Development of Protocols and Methods for Predicting the Remaining Economic Life of Wastewater Pipe Infrastructure Assets

Berk Uslu

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Performance prediction modeling is a crucial step in assessing the remaining service life of pipelines. Sound infrastructure deterioration models are essential for accurately predicting future performance that, in turn, are critical tools for efficient maintenance, repair and rehabilitation decision making. The objective of this research is to develop a gravity and force main pipe performance deterioration model for predicting the remaining economic life of wastewater pipe for infrastructure asset management. For condition assessment of gravity pipes, the defect indices currently in practice, use CCTV inspection and a defect coding scale to assess the internal condition of the wastewater pipes. Unfortunately, in practice, the distress indices are unable to capture all the deterioration mechanisms and distresses on pipes to provide a comprehensive and accurate evaluation of the pipe performance. Force main pipes present a particular challenge in performance prediction modeling. The consequence of failure can be higher for the force mains relative to the gravity pipes which increases the risk associated with these assets. However, unlike gravity pipes, there are no industry standards for inspection and condition assessment for force mains. Furthermore, accessibility issues for inspections add to this challenge. Under Water Environmental & Reuse Foundation (WE&RF)'s Strategic Asset Management (SAM) Challenge, there was a planned three-phase development of this performance prediction model. Only Phases 1 and 2 were completed for gravity pipes under the SAM Challenge. Currently, 37 utilities nationally distributed have provided data and support for this research. Data standards are developed to capture the physical, operational, structural, environmental, financial, and other factors affecting the performance. These data standards were reviewed by various participating utilities and service providers for completeness and accuracy. The performance of the gravity and force main pipes are assessed with incorporating the single and combined effects of these parameters on performance. These indices assess the performance regarding; integrity, corrosion, surface wear, joint, lining, blockage, I&I, root intrusion, and capacity. These performance indices are used for the long-term prediction of performance. However, due to limitations in historical performance data, an advanced integrated method for probabilistic performance modeling to construct workable transition probabilities for predicting long-term performance has been developed. A selection process within this method chooses a suitable prediction model for a given situation in terms of available historical data. Prediction models using time and state dependent data were developed for this prediction model for reliable long-term performance prediction. Reliability of performance assessments and long-term predictions are tested with the developed verification and validation (Ve&Va) framework. Ve&Va framework incorporates piloting the performance index and prediction models with artificial, field, and forensic data collected from participating utilities. The deterioration model and the supporting data was integrated with the PIPEiD (Pipeline Infrastructure Database) for effective dissemination and outreach.

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Utilities are operating under tight budgets with competing demands across every part of their operations not least of which understands and planning wastewater pipeline rehabilitation and replacement requirements. Wastewater systems in U.S. still face enormous infrastructure funding needs in the next 20 years to replace pipes and other constructed facilities that have exceeded their design life. With billions being spent yearly for water infrastructure, the systems face a shortfall of at least $21 billion annually to replace aging facilities and comply with federal water regulations. With the utilization of proper asset management practices, the problem the inability to sustain the performance levels as well as meeting the requirements of the federal standards and regulations can be resolved. Performance prediction modeling is a crucial step in assessing the remaining service life of pipelines. Sound infrastructure deterioration models are essential for accurately predicting future performance that, in turn, are critical tools for effective maintenance, repair and rehabilitation decision making. The objective of this research is to develop a gravity and force main pipe performance deterioration model for predicting the remaining economic life of wastewater pipe for infrastructure asset management.

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Participating Utilities

- Alexandria Renew Enterprises, Alexandria, VA
- Anchorage Water and Wastewater Utility, Anchorage, AK
- Arlington County, Arlington, VA
- Aurora Water, Aurora, CO
- Baltimore City, Baltimore, MD
- Baltimore County Public Works, Baltimore, MD
- Boston Water and Sewer Commission, Boston, MA
- City of Atlanta, Atlanta, GA
- City of Columbus, Columbus, OH
- City of Houston, Houston, TX
- City of Springfield, Springfield, MO
- Cobb County Water System, Marietta, GA
- County of Pulaski, Pulaski, VA
- Fairfax County, Fairfax, VA
- Gwinnett County, Lawrenceville, GA
- Hampton Roads Sanitation District, Virginia Beach, VA
- Johnson County Wastewater, Olathe, KS.
- Los Angeles County Sanitary District, Los Angeles, CA
- Metropolitan Sewer District of Louisville, KY
- Mount Pleasant Waterworks, Mount Pleasant
- Ocean County Utilities Authority, Bayville, NJ
- Orange County Sanitation District, Fountain Valley, CA
- Pittsburgh Water and Sewer Authority, Pittsburgh, Pennsylvania
- Prince William County Service Authority, Woodbridge, VA
- Seattle Public Utilities, Seattle WA
- Town of Blacksburg, Blacksburg, VA
- Washington Suburban Sanitary Commission, Washington, DC
- Western Virginia Water Authority, Roanoke

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Acronyms and Abbreviations

^{0}F	Fahrenheit Degrees
AC	Asbestos Cement
ADT	Average Daily Traffic
AIC	Akaike Information Criterion
ANN	Artificial Neural Networks
ASCE	American Society of Civil Engineers
CBR	Case Based Reasoning
CCTV	Closed Circuit Television
CI	Cast Iron
cm	Centimeter
COF	Consequence of Failure
CRI	Condition Rating Index
Cu	Cube
DI	Ductile Iron
ECT	Eddy Current Testing

EPR	Evolutionary Polynomial Regression
ETL	Extract, Transform, Load
FHWA	Federal Highway Administration
ft.	Feet
GIS	Geographical Information Systems
H2S	Hydrogen Sulfide
HDPE	High Density Polyethylene
I/I	Inflow and Infiltration
ID	Identification
K-M	Kaplan and Meier
l	Liter
Lbs.	Pounds
LGAM	Local Government Association of Queensland, AU
LOF	Likelihood of Failure
MCMC	Markov chain Monte Carl
MFL	Magnetic Flux Leakage
mg	Milligrams
MHA	Metropolis-Hastings Algorithm
Min	Minute

MLE	Maximum Likelihood Estimate
mV	Millivolts
NAASCO	National Association of Sewer Service Companies
O&M	Operation and Maintenance
PACP	Pipeline Assessment & Certification Program
PCCP	pre-stressed concrete cylinder pipe
PE	Polyethylene
POF	Probability of Failure
ppm	Parts per Million
PS	Performance State
psi	Pounds per Square Inch
PVC	Polyvinyl Chloride
RFEC	Remote Field Eddy Current
SCREAM	Sewer Condition Risk Evaluation Algorithm Model
Sec	Second
sq.	Square
SSURGO	Soil Survey Geographic
SVM	Support Vector Machines
TBL	Triple Bottom Line

USEPA	United States Environmental Protection Agency
VCP	Vitrified Clay Pipe
VFD	Variable Frequency Drives
WE&RF	Water Environmental & Reuse Foundation
WRc	Water Research Center

1. Introduction

1.1 Overview

The crumbling infrastructure we are facing today has a direct impact on people's personal and economic health, and nation's future prosperity. There has been an accelerating decline in the state of U.S. infrastructure over the past two decades, and these facilities may be inadequate both for current requirements and for projected future growth (Tafuri and Selvakumar 2002). Pipeline infrastructure in North America has become insufficient to sustain a growing economy (ASCE 2013). Large expenditures are needed to repair, rehabilitate, and replace public facilities (ASCE 2013). If the deterioration of pipeline infrastructure continues to deteriorate at this pace, local governments will suffer severe economic consequences. It is estimated that the cost of replacing all water mains in the United States would run to $348 billion (ASCE 2013). The estimated cost to upgrade the water transmission and distribution systems is $77 billion (ASCE 2013). Although more than $71 billion on wastewater treatment programs was spent since 1973, wastewater systems in U.S. still face enormous infrastructure funding needs in the next 20 years to replace pipes and other constructed facilities that have exceeded their design life (ASCE 2013). With billions being spent yearly for water infrastructure, the systems face a shortfall of at least $21 billion annually to replace aging facilities and comply with federal water regulations (ASCE 2013).

1.2 Role of Asset Management in the Deteriorating Infrastructure Problem.

With the utilization of proper asset management practices, the problem the inability to sustain the performance levels as well as meeting the requirements of the federal standards and regulations can be resolved. Efficient asset management brings many benefits for utilities. These advantages are, but not limited to the desired outcomes listed below (USEPA 2012):

- Prolonged remaining asset life through efficient O&M program
- Desired level of service for consumers with a focus on system sustainability
- Minimized cost through sound operational and financial planning
- Long-term budgets with a focus on activities critical to sustained performance
- Improved responses to emergencies
- Improved security and safety of assets.

1.3 Research Motivation

Performance prediction modeling is a crucial step in assessing the remaining service life of pipelines. Sound infrastructure deterioration models are essential for accurately predicting future performance that, in turn, are critical tools for effective maintenance, repair and rehabilitation decision making. The objective of this research is to develop a gravity and force main pipe performance deterioration model for predicting the remaining economic life of wastewater pipe for infrastructure asset management. For condition assessment of gravity pipes, the defect indices currently in practice use CCTV inspection and a defect coding scale to assess the internal condition of the wastewater pipes. Unfortunately, in practice, the distress indices are unable to capture all the deterioration mechanisms and distresses on pipes to provide a comprehensive and accurate evaluation of the pipe performance. Force main pipes present a particular challenge in performance prediction modeling. Consequences of failure are higher for the force mains about the gravity pipes which increases the risk associated with these assets. However, unlike gravity pipes, there are no industry standards for inspection and condition assessment for force mains. Furthermore, accessibility issues for inspections add to this challenge.

1.3.1 The Need for Data Standards

Adequate infrastructure asset management largely depends on the ability to share, exchange, and manage asset information efficiently. Although software tools are used to support almost every asset management process by stakeholders, data transfer is mainly performed using neutral file formats based on ad-hoc proprietary data models. Interoperability of infrastructure data is crucial to improve the information flow between various decision processes and to support better management. Data Standard models can be used to significantly improve the availability and consistency of asset data across different software systems, to integrate data across various disciplines, and to exchange information among the various stakeholders. Although these data standard models are beneficial for infrastructure asset management, there are substantial limitations on development and implementation of these data standards.

1.3.1.1 Lack of Data Interoperability

There is a variety of data across utilities, disciplines, data providers, and sectors related to water and wastewater infrastructure. Data sets are too large, distributed, and there are confidentiality issues which limit access. Infrastructure data are typically distributed in many documents and formats which include maps, drawings, maintenance records, and design documents. In many cases, some data may be outdated, inaccurate, or unavailable. These data limitations pose a serious problem, especially when dealing with buried infrastructure assets. Structural changes during construction or as a result of maintenance operations are rarely incorporated back into the maps or drawings. Outdated maps and drawings that do not reflect the current as-built status are very common among many utilities, especially for paper maps and drawings. Moreover, different documents may contain inconsistent or conflicting data.

1.3.1.2 High System Complexity

Pipeline asset management is becoming increasingly knowledge-intensive and requires accessing and managing a multitude of knowledge sources. Given the fact that it is a challenging and expensive for utilities to achieve expertise in all knowledge areas, the need for utilities to access “knowledge repositories” is becoming crucial. This knowledge needs to be formalized and structured in a format that would enable its efficient access, sharing, and reuse by various stakeholders to maximize its use. The infrastructure asset management process would be more accurate if it is supported by competent representation, management, sharing, and reuse of knowledge through implementing repositories that incorporate various forms of relevant knowledge. Techniques for data mining and knowledge discovery could be applied to the system to enable extracting useful knowledge from the stored infrastructure data.

The life cycle of pipe system consists of their planning; engineering; manufacturing; construction; operation and maintenance; and repair, rehabilitation, and replacement. Data Standard is needed to support advanced pipeline infrastructure asset management. Performance management is defined as managing the pipeline infrastructure to minimize the total cost of owning and operating while delivering service levels customer’s desire. Many factors are affecting the performance of the drinking water, wastewater, and stormwater pipes (see Figure 1-1). It is not fully understood how these factors are affecting the pipeline deterioration.

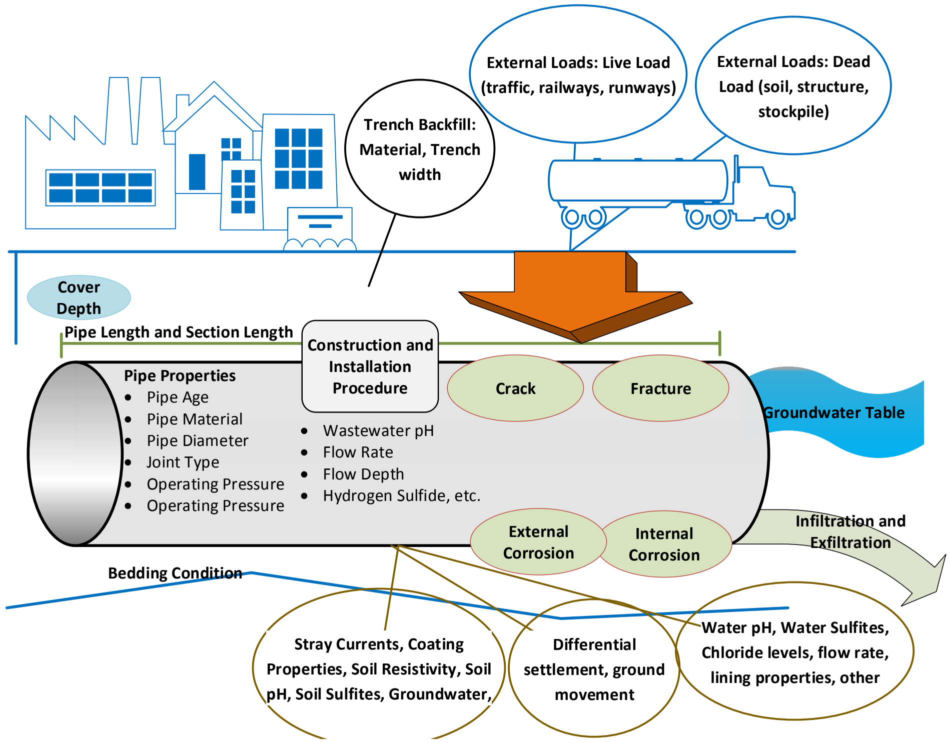


Figure 1-1. Factors Effecting Wastewater Pipeline Performance

1.3.2 Need for a Comprehensive Performance Index – not just Defect Index

PACP defect index, currently in practice, uses CCTV inspection and a defect coding scale to assess the internal condition of the wastewater pipes. Unfortunately, in practice, the distress indices are unable to capture all the deterioration mechanisms and distresses on pipes to provide a comprehensive and accurate evaluation of the pipe performance. The distresses, and deterioration of a pipe is the result of complex interactions of various mechanisms that occur within and around a pipeline. Pipelines are prone to particular types of failures based on the type of material, physical design, age or functionality, as well as its external and internal environment. The impact of the deterioration of the pipeline system depends upon its size, complexity, topography and service. Ideally, a comprehensive performance index should include consideration of the three aspects of pipe system: pipe condition, internal environment, and external environment. Unfortunately, in practice, the defect indices are unable to capture all of the deterioration mechanisms and stresses on pipes to provide a comprehensive and accurate evaluation of the pipe performance and remaining service life. The distresses and deterioration a pipe undergoes are the result of complex interactions of various mechanisms that occur within and around the pipeline. Pipelines performance deterioration is affected by various structural, environmental, operational, and other parameters. There is a need for a comprehensive performance index for wastewater pipes that incorporates the defect coding as well as other factors, as shown in Figure 1-2.

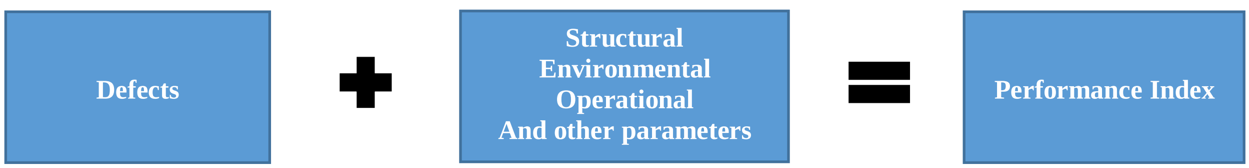


Figure 1-2. Fundamentals of Performance Index

The lack of performance index for force mains leads to limited applications of the performance prediction models. There are a limited number of prediction models available for force mains in the literature and practice (Sinha and Ge 2013). These models in literature and practice do not provide decision support for all of the level of decisions in infrastructure management.

1.3.3 Performance Index for Wastewater Pipeline

Water utilities are using a 5-point scale because it is a straightforward and easy way to aid decision- making. However, a 5-point scale is too coarse for predicting pipe remaining life. Higher granularity in the middle range of the performance index (Grade 3 to 8) provides the ability to prioritize assets in an efficient manner. Figure 1-3 represents the differences between an actual 5-point scale and the proposed 10-point performance scale. The 10-point scale gives more granularity of the performance data, especially in the middle of the assets life cycle. This higher detail in performance grades provides more accurate performance prediction in the next phase of the research. The 10-point scale has the advantage of a direct relationship to predict asset remaining life as shown in Figure 2. The proposed grading scale would be more appropriate for predictive modeling and proactive asset management compared to the 5-point scale.

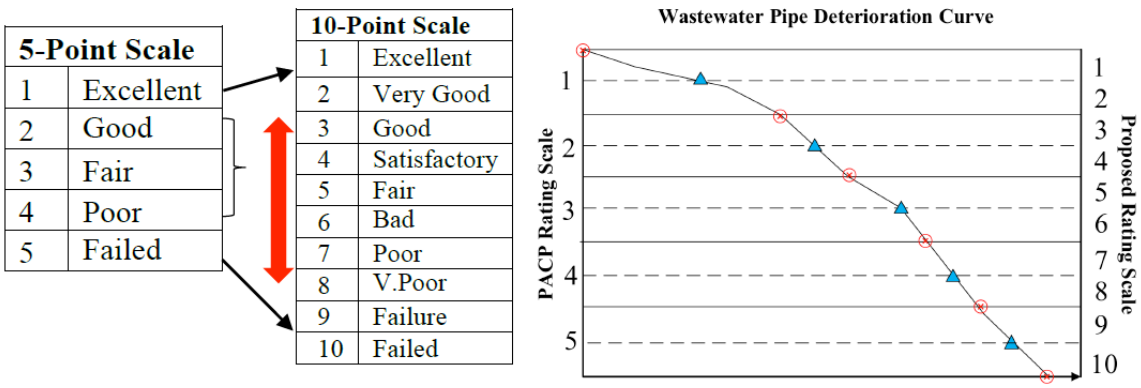
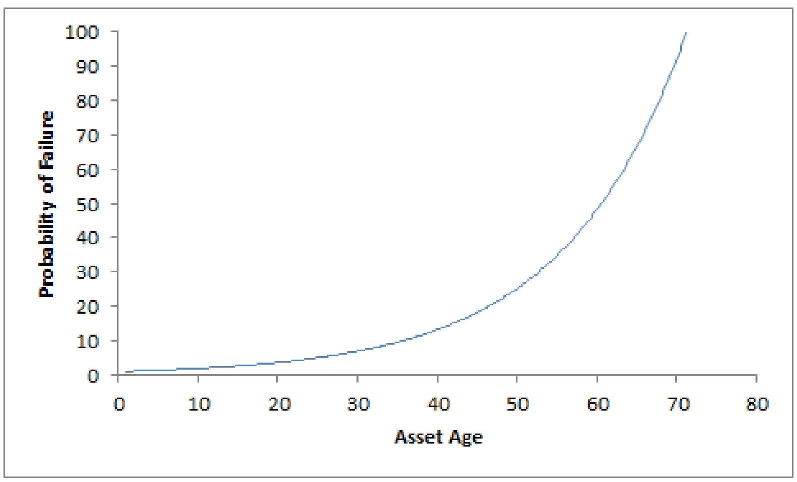


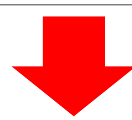
Figure 1-3. New 10-Grade Performance Scale

1.3.4 The Need for Practical and Efficient Performance Prediction Models

In a recent workshop which was held in Alexandria, Virginia, October 4th, 2014 and participants represented a diverse cross-section of researchers from academia, utility, consultant, industry, organization, and federal institutions and were all invited specifically for their expertise about water infrastructure needs. Experts within each subject area led the five breakout discussions; the moderated discussions permitted capturing the diverse opinions regarding "What are we concerned about, what do we want to measure, and how?" Polling of attendees then assisted with ranking the priority of the suggested research needs from each of the five discussion areas into the overall Top 10 identified needs. One of the top ten needs expressed by the workshop attendees was the need to develop models and tools for all three levels of pipeline infrastructure asset management: Strategic, Tactical, and Operational.

The current deterioration models in literature only address the probability of failure and are not be applicable for the proactive asset management. These probability of failure models only support the decision making process for the reactive asset management practices where utilities only concerned about the failures and fixing the failures. Reactive asset management practice is acceptable for low-risk assets can these models can only provide support for strategic level decision making. There is a need to develop models which would support proactive and predictive asset management practices which support the decisions on where, when and how the resources should be allocated. Figure 1-4 summarizes the motivation of this research to transform the asset management practices from reactive to proactive and predictive.





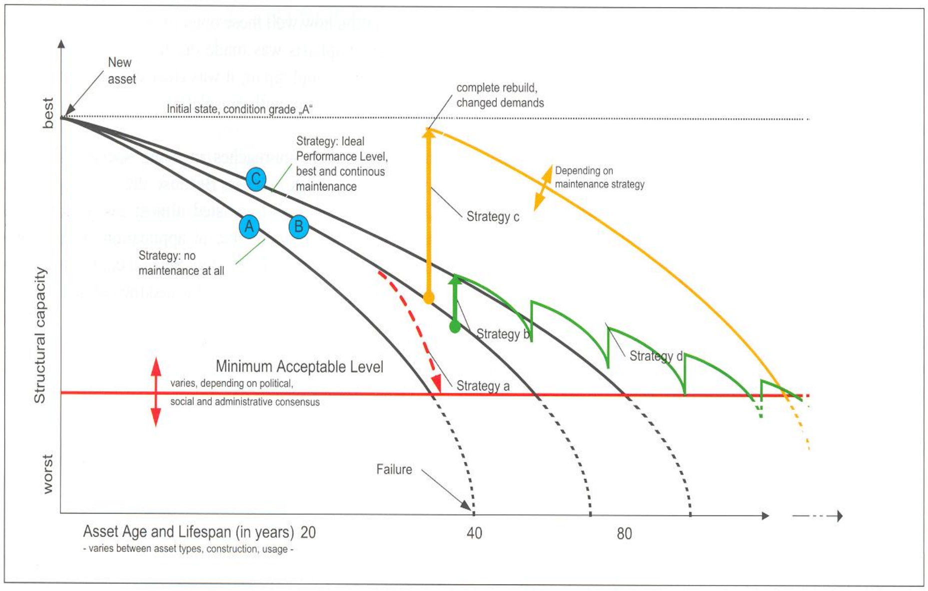


Figure 1-4 Predictive Infrastructure Asset Management.

1.4 Broader Impact of the Proposed Deterioration Modeling Research Project

The mere generation of models that are piloted within a limited number of participating utilities and limited data will always be incapable of achieving a significant and lasting change in utility asset management practices. Truly effective asset management, which leads to the promised cost-savings, improved service levels, and overall performance requires tactical and operational decisions to be driven by field- level data. Widespread implementation of such advanced asset management principles will need a culture change away from the top-down command and control management structure to one of a more integrated organization where field-level data collection drives enhanced decision-making, the better understanding of parameters, robust modeling, and validated models for acceptance. In other words, the utility management recognizes the importance of using data as the foundation to build the knowledge-driven utility and encourages active participation. This research has addressed these shortcomings in practice.

This research provides utility managers with a practical and accurate technique for the predicting wastewater pipeline performance and estimating end of the remaining life deterioration curve for decision making. A comprehensive understanding of the pipe deterioration parameters and process is presented regarding the performance index which captures the coupled effects of performance parameters. In turn, this better understanding reflects in high accuracies of future predictions (up to 70% accuracy) with the performance prediction models which leverage these performance indices.

1.5 Dissertation Outline

This dissertation captures the effort to develop the performance prediction models for the analysis of the remaining life of wastewater assets. The dissertation specifically has seven chapters. The summary of the content in these chapters is provided in figure 1-5.

Chapter 1. Introduction

- Research Motivation
- Previous WERF Studies

Chapter 2. Background

- Infrastructure asset management frameworks
- Fundementals about condition indices and prediction models
- State-of-the-art research review on wastewater pipe performance indices and prediction models
- State-of-the-art practice review on: Faliure modes and mechanisms, condition assessment technologies, and pipe defect indices

Chapter 3. Research Methodology

- Provides overview of the 3 phase research methodology followed for the research.

Chapter 4. Phase I

- Improvements on the previously developed gravity pipe data standards
- Newly developed force main data standards

Chapter 5. Phase II

- New 10-grade scale performance index
- Improvements on the previously developed gravity perforamance index
- Newly developed force main performance index
- Piloting performance indices with participating utilities

Chapter 6. Phase III

- Records selection process
- Development of state dependent prediction models
- Development of time dependent prediction models
- Integration of state and time dependent prediction models
- Piloting prediction models with participating utilities

Chapter 7. Conclusion and Recommedations

- Research conclusions
- Recommendations for future work

Figure 1-5. Dissertation Outline

2. Background

2.1 Infrastructure Asset Management Framework

An Infrastructure Asset Management framework that has acceptance in the water sector contains seven steps which is summarized in Figure 2-1.

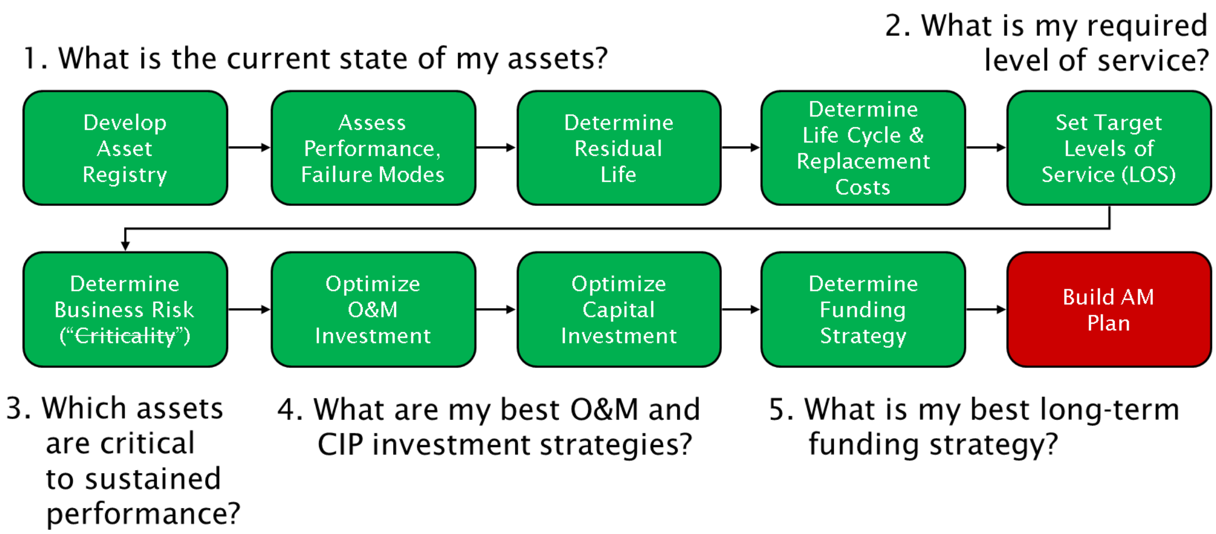


Figure 2-1. Advanced Asset Management Framework (USEPA 2014).

In the asset management framework presented above, the process starts with data collection. A wide array of options and depth levels exist for data collection. These data are from visual inspection, measurements, sensors, to real-time monitoring technologies. Selection of adequate data collection scope, methodology, and tools depends mostly on financial cost-benefit considerations. Basic methods such as visual inspection might be affordable, but the information that can be extracted from that data will be limited. In contrast, a sophisticated data collection method such as real-time monitoring may produce significant amounts of high-quality and detailed information, but it also requires a higher financial investment.

Once data have been collected, it is necessary to extract the contained information. The objective of the condition assessment step is to determine as accurately as possible, based on the data and extracted information, what is the specific condition of each asset in the system. In cases where extensive defect information is not available, asset age can be used as a proxy for asset condition. However, in many cases, the correlation between age and condition is not high enough to ensure the reliability of the condition. Therefore, condition assessment requires significant amounts of reliable information. Notice that although the inspection technologies are also known as condition assessment technologies, these technologies only provide the defect information required to perform condition assessment.

If there are sufficient data points in a time series of asset condition, it is theoretically possible to assemble a deterioration model. The deterioration models are useful for planning purposes and to generate curves. The ability to forecast asset condition at any future time would enable efficient asset renewal interventions. Never the less, obtaining a reliable deterioration model is challenging. The deterioration processes for any given asset have various factors with significant uncertainties and random variables. For example, a buried wastewater pipe will deteriorate in a particular way depending on pipe material, age, manufacturing quality, installation quality, soil conditions, external loads, and water quality, amongst other factors (Gay and Sinha 2014).

Based on condition assessment and the available information on asset deterioration, a decision is made whether the asset requires only routine maintenance or a renewal intervention. The renewal includes asset repair, rehabilitation, and replacement activities. Decision making is based on techniques such as life cycle analysis, financial methods, or risk-based methodologies. Good asset maintenance contributes to maintaining an acceptable asset deterioration rate and is expected to extend service life, but it is no substitute for renewal activities. Regardless of the maintenance performed, assets would require various renewal activities to be performed throughout their life cycle to keep it at an acceptable performance level.

When a decision has been made regarding the activity required on an asset, asset maintenance or renewal can be performed utilizing different technologies and methods. It is important to notice that the “do nothing” alternative is usually a valid option for analysis. An asset may not require immediate attention, or it may be more convenient to adopt a “run to failure” strategy where the asset is allowed to fail before replacing it. In the case of assets that are critical for sustaining system performance or whose failure implies unacceptably high risks, it is necessary to intervene before asset failure. Selection of a renewal method is currently based on financial or Triple Bottom Line (TBL) economic, social, and environmental considerations.

2.2 Advanced Asset Management

The monetary investments estimated to keep the nations is beyond the capacity of cities, municipalities, and utilities to shoulder alone. Without additional investment in the nation’s drinking water and wastewater infrastructure, the environmental and public health gains made during the last three decades could be at risk. However, monetary investment alone will not resolve this dilemma; it must be met with a new approach to sustainable water infrastructure engineering and management. There is a critical disconnect between the methodological remedies for infrastructure renewal problems and the current sequential or isolated manner of renewal analysis and execution.

Advanced infrastructure asset management is a crucial process in addressing the problem of rapidly deteriorating infrastructure and deciding where and when resources are needed to be spent. Water utility managers nationwide need to implement advanced infrastructure asset management strategies to tackle this ever challenging tasks. The main purpose of advanced asset management is to keep the level of service

Advanced asset management is centered on a framework of five core questions, which provide the foundation for many asset management best practices:

1) What is the current state of my assets?

2) What is my required "sustainable" level of service?

3) Which assets are critical to sustained performance?

4) What are my minimum life-cycle costs?

5) What is my best long-term funding strategy?

Performance evaluation and prediction models are efficient tools used by infrastructure asset managers to achieve this goal of achieving advanced asset management. These models are used to provide decision support to properly answer the crucial questions asked by the advanced asset management framework.

2.3 Performance Evaluation and Prediction Models for Decision Making

One of the core attributes of infrastructure asset management includes condition assessment and asset management risk-based prioritization activities. Even though asset management is a core activity for public utilities, the extent and efficiency of how it is performed vary from utility to utility. Utilities that have taken a leadership role to manage their assets better are familiar with the benefits of using risk-based decisions to help establish investment priorities. The popular industry mathematical expression of asset risk is the “likelihood of failure” (LOF) multiplied times the “consequence of failure” (COF). Therefore, the risk is quantified as shown by Equation 2-1:

Risk = [(Consequence) x (Likelihood)] or [COF x LOF] (Equation 2-1)

COF is often thought of as the "severity" or "criticality" of the potential failure. LOF is often thought of as the "probability" of failure, which primarily is influenced by the asset's condition score. The overall risk-based asset management is summarized in figure 2-2.

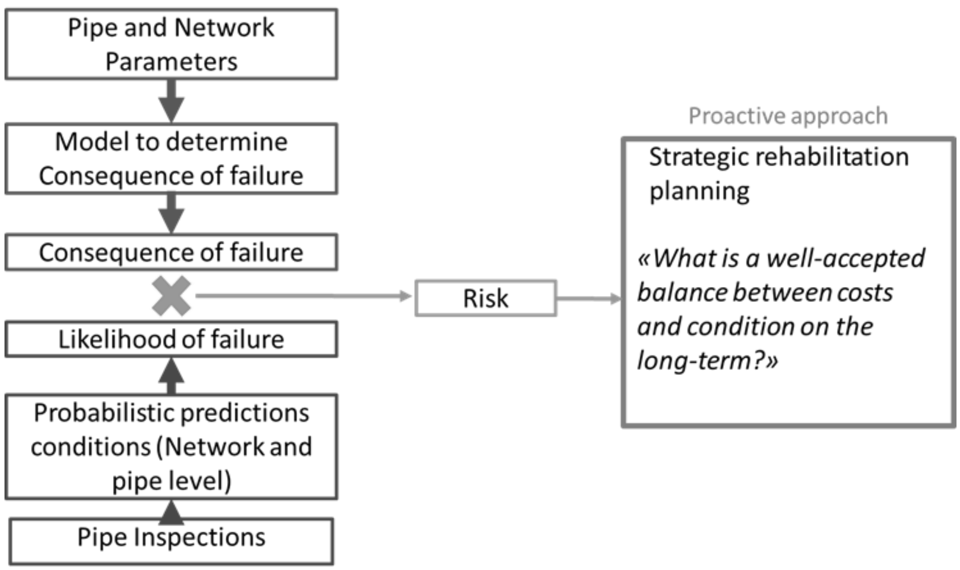


Figure 2-2. Risk Based Infrastructure Asset Management Framework.

There are many models used in condition evaluation and prediction, risk analysis, and renewal prioritization of drinking water and wastewater pipelines. These models can be used to;

- Condition evaluation and prediction provide utilities a better understanding of the current condition of the pipelines.
- The level of service is used together with the condition of the pipelines that is calculated using the models and tools.
- The risk analysis can help utilities in identifying the critical assets and assist utilities in making decisions on which asset to renewal and when to take proactive actions to guarantee the assets function at the level of service.

- The models and tools can provide analysis on the current state of the assets and predict their performance and risk. This can help utilities make decisions on renewal activities to minimize the cost of O&M.
- The long-term funding strategy can be developed based on the analysis of the condition curves of the assets using the models and tools, the risk analysis, and prioritization of the renewal activities.

2.4 Performance Indices

To evaluate the condition of an infrastructure system, the CRI is often used. Usually, the range for CRI is 0 to 100 (or 1 to 5), where 100 indicate an excellent condition and 0 indicates an inferior quality condition. Expert knowledge is used to provide relative weightings to the variables in the CRI evaluation model. Table 2-1 shows an example of a CRI that ranges from 0 to 100 where each color represents the condition of the pipe. Table 2-2 shows the condition index, condition description, and recommended action.

Table 2-1. Condition Rating Index

Grade	Semantic Representation	Range	Color Representation
1	Excellent	100-81	
2	Good	80-61	
3	Fair	60-41	
4	Poor	40-21	
5	Failed	20-0	

Table 2-2. Condition Index, Description, and Recommended Action.

Zone	Condition Index	Condition Description	Recommended Action
1	85 to 100	Excellent: no noticeable defects. Some aging or wear may be visible	Immediate action is not required
2	70 to 84	Good: Only minor deterioration or defects are evident	Economic analysis of repair is recommended for proper actions
	55 to 69	Fair: Some deteriorations or defects are evident, but function is not significantly affected.	
	40 to 54	Marginal: moderate deterioration. Function is adequate	

3	25 to 39	Poor: Serious deterioration in at least some portions of the structure. Function is inadequate.	Detailed evaluation is required to determine the need for renewal. Safety evaluation is recommended
	10 to 24	Very poor: Extensive deterioration. Barely functional	
	0 to 9	Failed: No longer function	

2.5 Performance Prediction Models

The deterioration of a pipe system is caused by the material degradation, the demands on the pipe, and its operating environment. The condition state of a pipe changes over time. Figure 2-3 illustrates the condition curve of a pipe system. The left diagram shows condition deterioration over time, and the right diagram shows an updated condition of the system when renewal actions such as repair and rehabilitation have been taken.

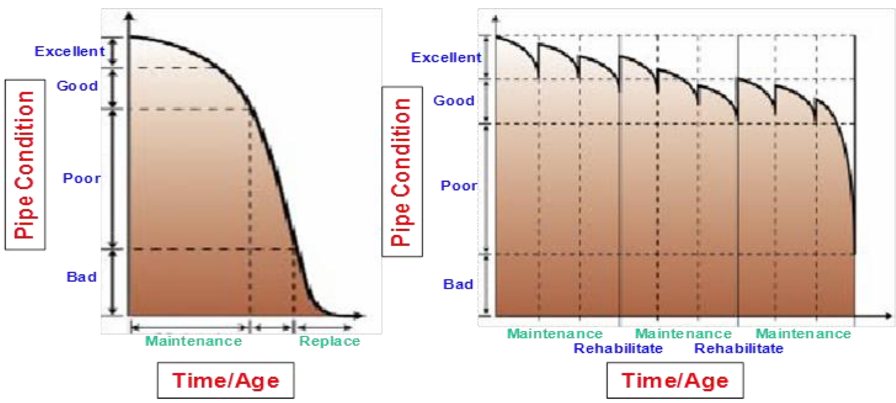


Figure 2-3. Condition/Performance Deterioration Prediction Model.

Condition curves are often used to determine the optimal renewal strategy of pipes. Different idealized strategies for the renewal of assets are shown schematically in Figure 2 4. Two graphs (A and C) describe theoretical levels of renewal, whereas (B) describes the likely reality of the situation:

- Graph A shows an asset reaching to a minimum acceptable level of service without appropriate renewal. The asset must be renewed or be operationally restricted until necessary renewal works are done.
- Graph B shows the lifecycle of an asset which is structurally and functionally adequate. It has various options for renewal:
    - No action is taken. It then reaches the graph of asset A (red dotted line, strategy a) relatively quickly.
    - The asset is specifically renewed (green arrow) to reach its ideal performance level at its actual age (strategy b).
    - The asset can be further improved (yellow arrow) to the performance level higher than the ideal performance level at its age (strategy c).
    - The asset could repeatedly be renewed, as the green saw-tooth graph shows, to maintain an acceptable level of performance over an extended time (strategy d).
- Graph C shows an asset that is perfectly constructed, installed, and maintained in its lifecycle. However, very few pipes have such lifecycle, because it is hard to guarantee perfect construction, installation, and maintenance.

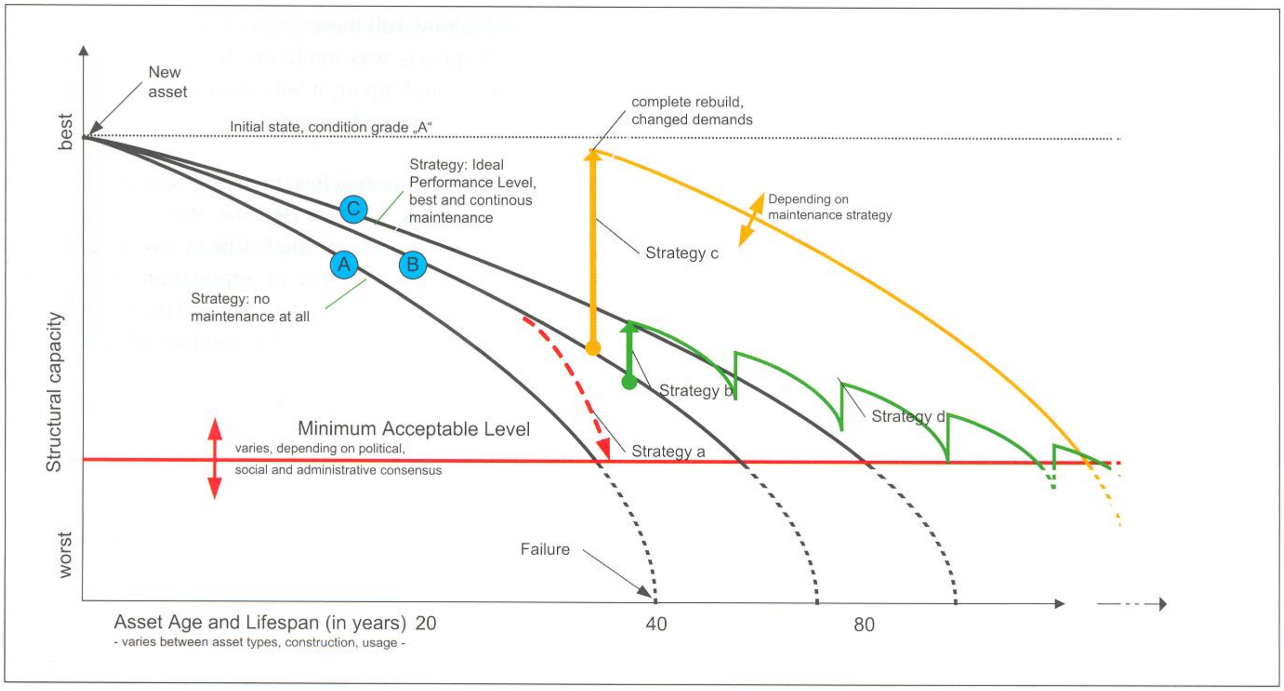


Figure 2-4. Condition Curves Applied to Renewal Strategies

2.6 Models Overview

A large number of deterioration models are described in the research literature. Various input regarding environmental, structural, functional, and economic factors are provided to be evaluated by the model to provide a decision on the management is provided. This working principle is summarized in figure 2-5.

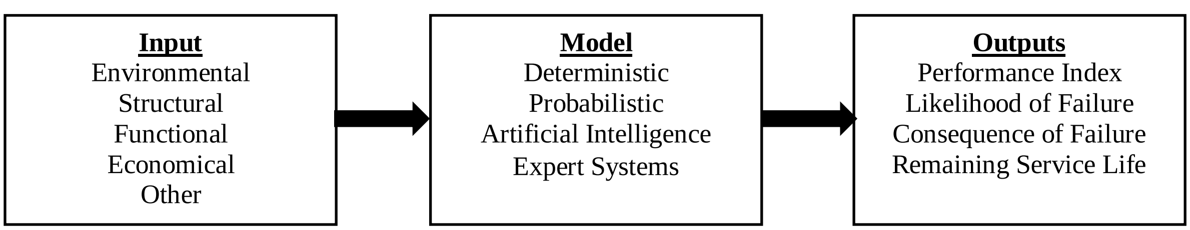


Figure 2-5. Wastewater Pipeline Performance Prediction Models

2.7 Research Review

A short overview of the models including the explanatory variables is available in the following sections. More detailed reviews can be found in Kleiner and Rajani (2001), Tran (2007), and Ana and Bauwens (2010). Deterioration models for predicting condition and performance of wastewater pipes in the literature can be grouped into three broad categories: Statistical, Probabilistic, and Advanced Mathematical, and heuristic models as represented in Table 2-3. Table 2-4 summarizes the advantages and limitation of these modeling techniques.

Table 2-3. Performance Prediction Models in Literature

Class	Type	References
Deterministic	Mechanical	Chughtay and Zayed (2007a, 2007b, 2008)
	Empirical	Wirahadikusumah et al. (2001)
Probabilistic/ Stochastic	Survival Function	Hörold and Baur (1999); Baur and Herz (2002); Baur et al. (2004); Ana (2009)
	Regression	Yang (1999) ; Davies et al. (2001b) ; Ariaratnam et al. (2001); Pohls (2001); Ana (2009); Wirahadikusumah et al. (2001) ; Micevski et al. (2002) ; Baik et al. (2006); Koo and Ariaratnam (2006); Newton and Vanier (2006); Tran (2007); Le Gat (2008)
	Semi-Markov Chains	Kleiner (2001); Dirksen and Clemens (2008); Ana (2009)
	Discriminant analysis	Tran (2007); Ana (2009)
Artificial Intelligence	ANN	Najafi and Kulandaivel (2005); Tran (2007); Ana (2009); Khan et al. (2010)
	Fuzzy Interference	Yan and Vairavamoorthy (2003); Kleiner et al. (2004a, 2004b, 2006)
	SVM	Mashford et al. (2011)
	EPR	Savic et al. (2006) ; Ugarelli et al. (2008); Savic et al. (2009)
Expert Systems	CBR	Fenner et al. (2007)
	Decision Support Trees	Syrachani et al.(2013)

2.7.1 <u>Deterministic Models</u>

Statistical models formalize the relationship between variables and deterioration in mathematical equations. These models rely on historical data collected about the deterioration of the wastewater pipes and try to put the effect of different variables with correlation approach. The statistical models can be grouped into three categories (linear, exponential, and regression models). Some good examples include; Duchesne et al. (2013), Salman and Salem (2012), Ana and Bauwens (2010), Savic et al. (2009), Chughtai and Zayed (2008), and Wirahadikusumah et al. (2001).

2.7.2 Probabilistic/Stochastic Models

These models assume a probabilistic relationship between variables and deterioration. Some good examples of probabilistic models are; stochastic duration models (Mahmoodian et al. 2014), and Markov chain models (Scheidegger et al. 2011, Le Gat 2008, Baik et al. 2006).

2.7.3 Artificial Intelligence Models

These models are data driven. Artificial learning algorithms are used to classify the evaluated asset into different categories. Some examples of advanced mathematical models are; fuzzy-based approaches (Angkasuwansiri and Sinha 2014, Kleiner et al. 2007) and neural networks (Tran 2010, Najafi and Kulandaivel 2005).

2.7.4 Expert Systems

Expert systems or heuristic models incorporate engineering knowledge rather than data parameters that affect a pipe to determine failure rates. Some examples of these models include; Syachrani et al. (2013), Bai et al. 2008.

Table 2-4. Advantages and Limitation of Pipe Deterioration Prediction Model Techniques.

	Types of Pipe Deterioration Prediction Models			
	Deterministic	Probabilistic / Stochastic	Artificial Intelligence	Expert Systems
Advantages	Provides insight into which factors most affect the deterioration process Resulting equation is very user-friendly Relatively easy to develop and understand	Can be easily incorporated into risk models (Ana et al. 2010) Output is discrete data (Tran 2010) Can inherent uncertainty of the deterioration process (Ens 2012)	Can model unknown, nonlinear, relationships between inputs and outputs Few underlying assumptions (Ens 2012) Can be used when data is imprecise, incomplete, and subjective (Flintsch et al. 2004)	Knowledge of expert staff can be captured to some extend before they move on. Graphical inference is user friendly The knowledge base can be updated and extended
Limitations	Developed with limited understanding and data Does not accurately represent the real world conditions	May require time dependent data which is not available (Baik et al. 2006) Cohords may need to be developed (Wirahadikusumah et al. 2001) Data used to calibrate may be partial representations which effects the accuracy (Egger et al. 2013)	Difficult to determine the significance of outputs (Olden et al. 2002) Can be a black box where path to solution is not transparent Large amount of data is needed for accurate training and calibration (Scheidegger et al. 2011)	Very narrow range of the knowledge is incorporated. There is no flexibility and ability to adapt to changing environments Cannot work when there is limited or uncertain data

2.8 Conclusions from Research Review

The literature review indicates that there is no shortage of modeling approaches. The models in literature were created with limited datasets, and there is a significant lack of methods and tools to evaluate and validate these models. The models in the literature differ in;

i) The mathematical description of the deterioration process,

ii) the data requirements,

iii) the mode of calibration.

These models all require some form of adjustment to real-world data to produce meaningful predictions of future condition states (Ana and Bauwens 2010, Scheidegger et al. 2011).

The main limitations of the current performance prediction models in literature are as follows:

1. Current models that are in literature and practice are aimed to predict the probability of failure (POF) of the wastewater pipes. POF models are not useful for the utility managers in tactical and project level decision making since the assets can be intervened long before the failure. Additionally, these models tend to be developed without understanding the root causes of deterioration factors and their effect on the deterioration rate.

2. The existing models only consider the factors affecting the deterioration in the service state. The distresses that are caused by improper manufacturing, transportation, and installation will be considered in determining the deterioration rates. The data about these stresses are readily available in utility and manufacturer reports.

3. Most of the models are not user-friendly, and utility managers need to be trained to use these models. User-friendliness can be assessed and improved by the input of the practitioners. The prototypes can be sent to utilities for reviews and comments to achieve this objective.

4. There is no accuracy assessment for the developed models. The accuracy of the models has not been tested for datasets which have not been used for development A verification and validation process needs to be defined to test, document, and improve the accuracy of the prediction models. Verification and validation process is a well-defined and followed process that is used in model and software development in other fields.

5. Data on all performance prediction parameters may not be available. Prediction models in literature are set to work only with a strict set of parameters and would not give results if some input parameters are missing. If the utility cannot provide enough pipe parameters to assess the condition of the pipe, models should still give results, but the confidence in these results should be low.

6. Current models in literature and practice are developed by certain mathematical techniques and do not consider the nature of the available data. These type of models have considered mathematical technique driven. These models tend to develop the modeling algorithm first and try to fit the data after the development stage.

7. To help practitioners on effectively share their decisions with other stakeholders, models need to have various visual reporting capabilities. The model should be developed with GIS capability for utilities to run analysis utilizing geospatial data and display results in GIS environment. Additionally, various bar charts, graphs, and visual aids should be developed to visualize the model results.

2.9 Practice Overview

To effectively manage the pipeline infrastructure, it is important to understand how the pipe fails and the key parameters that influence the performance of the pipe. The failure process of buried sewer pipes is more complex than expected. As the pipe age, the pipe deteriorates and causes structural and capacity (hydraulic) problems (Davies et al. 2001a), which eventually lead to failure of the pipe. There are many factors affecting the performance of the pipe including manufacture, construction, operational, and environmental factors. By better understanding, the failure mechanism and the factors that are influencing the performance of the pipe, the data collection, decision-making process, and the subsequent renewal activities will be more effective and efficient.

This section briefly covers the pipe performance influencing factors, failure modes and failure mechanism of wastewater pipelines. It will help municipal and utility engineers to understand the effects of various factors and improve the data collection practice for further decision-making. The failure mode of wastewater pipes are defined as the type of the failure; while failure mechanism is an event, which causes the pipe to reach one of combined strength and serviceability limit state (Farshad 2006). Limit states include ultimate limit state and serviceability limit state. The ultimate limit state defines a condition at which the strength of the pipe is reached. Examples of this state may be by the loss of water pressure, burst, and loss of stiffness. The serviceability limit state defines a condition at which a particular function of the pipe is no longer fulfilled. Examples of this state may be large deformations, change of color, buckling, clogging, abrasion, and local damages.

2.10 Failure of Wastewater Pipes

There are three general categories of wastewater pipe failures based on the analysis of failure causes: Physical Integrity, Hydraulic Restrictions, and Hydraulic Capacities.

2.10.1 Physical Integrity

The physical integrity of the system refers to its ability to have correctly functioning components and maintain a physical barrier between the water in the network and the external environment. Another definition of physical integrity is the ability of a distribution system to handle internal and external stresses in such a way that its components do not fail. Internal stresses include things like operating pressure variations, water hammer, and internal corrosion, while external stresses include soil stresses, external loading, and external corrosion. A water collection system consists of a complex combination of components, including pipes, fittings, pumps, manholes and valves that are all critical in maintaining physical integrity. At the same time, the collection system is constantly changing through aging, replacement of components and the addition of new extensions. The pipe structure can no longer function due to defects and the loadings. The general defects associated with structural failures include cracks, deformation, and joint problems, internal or external corrosion, etc.

2.10.2 Hydraulic restrictions failures

Hydraulic restrictions are the most common failure mechanism in wastewater collection systems. The accumulation of sediment, grease, and rags can create obstructions and rapid hydraulic restrictions for wastewater pipes, especially combined sewers, causing flooding to streets and basements. According to standards of hydraulic design, there is a minimum slope to guarantee to high flow velocities which minimize debris accumulation. However, there are many external conditions that can cause debris accumulation for example root, grease, pipe sags, etc. CCTV tools are usually used to detect the blockage of wastewater pipes. There is no evident direct cause for a blockage and most times, but for most conditions, the failure rate is slow over time. In current practice, there is a standard cleaning and flushing program to maintain the wastewater pipe and make sure that blockages are controlled. The types of defects for hydraulic restrictions include root intrusion, sediment accumulation, and grease build-up. Offset joints and pipe sags can directly impact pipe flow and result in deposits that can cause blockages.

2.10.3 Hydraulic capacity failures

When a pipe segment does not have adequate capacity due to increase demand, it fails. This failure can be caused by excessive I/I, pipe deformation, and inadequate slope. Groundwater and storm water can enter the collection system through direct connections or indirectly via cracks and defects, causing I/I problems, and reducing the capacity of the wastewater collection system. Pipe deformation and inadequate slope directly impact the hydraulic capacity of the pipe. Hydraulic flow can be calculated based on the Manning's equation for normal flow conditions. Many hydraulic models have been developed for capacity evaluation of the wastewater pipes. Since I/I problems are associated with cracks, leaking from the manhole, covers, etc., they serve as an indicator of the structural condition of the pipe.

2.11 Failure mode and mechanism of wastewater pipes based on material

Sinha et al. (2008) summarized the failure mode and mechanism of wastewater pipe based on materials.

2.11.1 <u>Concrete wastewater pipes</u>

Concrete pipes fail due to overloading and corrosion which causes defects such as cracks or deformation. There are some initial factors causing the failure such as design errors, or defects caused by construction. During the operation, the corrosion caused both inside and outside of the pipe will cause structural failure of the pipe, especially for the H2S inside the pipe. PCCP suffers the corrosion caused by the groundwater. The initial cracks in the coating are caused by the manufacture, construction, or overloading which provide a path for groundwater. The corrosion of the prestressing wires results in the hydrogen embrittlement failure of the wires, which in turn, causes the crack of concrete and cylinder yielding (Prices et al. 1998).

2.11.2 <u>DI wastewater pipes</u>

Most failures of ductile iron wastewater pipes are caused by internal or external corrosion. Internal corrosions are caused by the corrosive substances in the wastewater mainly from industry wastewater. Aggressive soil can cause external corrosions. Corrosion causes thinning of the pipe wall and even holes in it, resulting in pipe failure.

2.11.3 CI wastewater pipes

Cast iron contains more carbon compared with ductile iron; therefore, it has less tensile strength. This type of wastewater pipe mainly fails due to cracks caused by overloading. Small diameter pipes failure due to bending loads, while large pipes failure due to corrosion combined with external loading. There are two main forms of corrosion: general corrosion and localized pitting corrosion. The corrosion causes the thinning of the pipe wall, making it subject to structural failure and can even cause pitting holes in the pipe.

2.11.4 PVC wastewater pipes

PVC pipes are made of a material not sensitive to corrosion. They fail due to creep and extensive stress in the pipe. PVC pipes are stronger in the circumferential direction than the longitudinal direction due to the oriented structure of the pipe material. Bending stress along the pipe causes cracking. PVC pipe failures are caused by cyclic fatigues. Cyclic loading from turning pumps on and off can lead to premature failure in PVC pipe. During construction or transit, accidents may cut or damage the pipe surfaces both internally and externally. Poor installation and construction may result in damage to the pipe.

2.11.5 PE and HDPE wastewater pipes

PE and HDPE wastewater pipes fail due to many factors including overloading, chemical attack, temperature, and construction practices. There are three basic failure modes: ductile failure caused by high stress, brittle fracture at medium stress and cracking or stress corrosion at low stress.

2.11.6 Clay wastewater pipes (VCP)

Clay or vitrified clay pipes (VCP) are strong and chemical resistant because of their ceramic material properties. Since the material is brittle, crushing failure can happen. The age of the pipe does not affect the performance of the pipe because the properties of the clay do not change over time. Clay pipes fail due to cracks caused by loading, differential beddings, root intrusion, erosion of bedding due to infiltration, poorly constructed lateral connections, etc. During construction, if the beddings or foundation are poor, the pipe bell may crack and lateral shear. The differential settlement causes shear between the manhole and the pipe. Excessive point loading can cause a break in the clay pipes.

2.11.7 Brick wastewater pipes

Brick wastewater pipes fail due to abrasion, poor cleaning practice, chemical attack, and cracks caused by overloading or differential settlement. The failure of mortar causes I&I problems. The infiltration brings soil into the pipe, causing deposits in the pipe and loss of soil support.

2.12 Inspection Practices for Wastewater Pipes

Many inspection technologies have been developed to evaluate the condition of wastewater pipelines. These technologies are grouped into several major categories: CCTV, acoustic technologies, electrical and electromagnetic currents, laser profiling, and innovative methods. A brief description of each category is shown in the following subsections. Table 2-5 summarizes the inspection technologies used for wastewater pipes.

Table 2-5. Wastewater Pipe Inspection Technologies (Thuruthy et al. 2013)

Category	Description
Visual and Camera	These technologies primarily utilize visual images and observations as a way to understand pipeline condition, Includes CCTV and other cameras as well as visual assessment.

Acoustic Based	These technologies use sound waves to obtain data about pipeline condition. This includes ultrasonic technologies, acoustic monitoring technologies, and leak detection technologies.
Laser Based	These technologies use a laser to obtain pipeline condition related data.
Electromagnetic Based	These technologies use electricity or electromagnets to obtain data related to pipeline condition. Remove field technologies, ground penetrating radar, magnetic flux leakage, and sonde & receiver technologies are included in this category.
Flow Based	These technologies and methodologies measure flow volume and/or velocity.
Physical Force Based	This category includes technologies and methodologies that primarily use physical force to obtain data related to condition. This includes pressure related and deflection related technologies and methodologies.
Temperature Based	This category includes technologies and methodologies that use a measurement of temperature to obtain pipeline condition data. Included are infrared technologies and flow temperature measurements.
Environmental Testing	This category includes technologies and methodologies that assess the pipeline environment as part of the condition assessment process. This includes soil and water measurements and stray current analysis.
Other Methods	This category includes analysis of existing data, coupon sampling, and other technology that does not fit into the other categories.

2.12.1 Visual and Camera Based Methods

CCTV is used very often in the inspection of wastewater pipes. It can provide visual data on leaking, cracks, internal blockage, the location of service laterals, etc. The limitations of this technology are that it can only provide the image of the internal pipe surface and the deeper condition of the pipe cannot be detected such as the cracks in the pipe inner surface. It cannot measure the slope of gravity pipes. The quality of defect identification and pipe condition assessment highly depends on many factors such as operator interpretation, picture quality, and flow level. CCTV technologies include zoom cameras, digital inspections, push cameras, and advances in crawler technology.

2.12.2 Acoustic Based Methods

Acoustic technologies are used to detect signals emitted by defects in pipelines. There are three types of acoustic technologies that are often used for pipeline assessment:

- Leak detectors: detect the acoustic signals emitted by pipeline leaks;
- Acoustic monitoring systems: real-time monitoring of the signals emitted by breaking pre-stressed wires in PCCP;
- Sonic or ultrasonic systems: defect such as cracks, delamination, and wall thinning are detected by capturing high-frequency sound waves and measuring their reflection.

2.12.3 Laser Based Methods

Laser profiling is a technique using a laser to highlight the shape of wastewater pipe. This technique can detect the shape changes of the pipe caused by loading, corrosion or siltation. Since this technique is based on light, the portion of the pipe under the water cannot be detected. The inspection of the whole internal surface of a pipeline requires the pipe to be taken out of service. In practice, lasers are often used together with CCTV or sonic techniques.

2.12.4 Electrical or Electromagnetic Based Methods

The electrical leak location method is used in leak detection for surcharged non-ferrous pipes. Eddy Current Testing (ECT) and Remote Field Eddy Current (RFEC) are used for detecting defects in ferrous pipes. Magnetic Flux Leakage (MFL) inspection is used to detect cracks in ferrous pipelines.

2.12.5 Flow Based Methods

Sewer meters are used for the flow-based monitoring technologies. Magnetic Flow devices are accurate and reliable technologies used for measuring flow. They are durable and can usually be buried without issue. Magnetic flow meters are not affected by solids that may be in the flow stream. Magnetic flow meters can be affected by air pockets in the pipe and can give false readings of the pipe if it is not kept full. These meters can also be affected by stray currents.

Ultrasonic Flow Meters are another way for measuring flow in a closed pipe. They are easy to install and can yield an accuracy in the 1% range of flow. Ultrasonic flow devices are prone to be affected by solids in the flow.

2.12.6 Physical Force Based

Micro-Deflection method is used to check the general conditions and joint integrity of brick, concrete, and clay structures. In the condition assessment, the test materials are applied with a certain loading to generate slight deformation or deflection. Spectral Analysis of Surface Waves (SASW) and Impact Echo methods are acoustic wave techniques used to detect cracks, delamination, voids, and honeycombing in concrete and masonry pipes.

2.12.7 Temperature Based Methods

Infrared Thermography is a method where infrared cameras are used to measure the temperature differential across an object to detect leaks and voids.

2.12.8 Environmental Based Methods

Gamma-gamma logging is a method used for condition assessment of cast-in-place concrete pilings and the average bulk density of the concrete and the location of voids can be evaluated.

2.12.9 Other Methods

There are some technologies being used for larger diameter pipelines that use a combination of technologies (CCTV, HD Rapid Photography, Laser Profiling above water level, and Sonar Profiling below water level).

2.13 Wastewater Pipe Defect Indices

The WRc in the UK has been successfully using a method for sewer defect coding since 1980. This method is also used commonly in Manitoba, Ontario and British Columbia, and allows for the certification of CCTV operators to assure consistency and integrity in the coding of sewers. In the US, the NAASCO PACP codes are adopted from the WRc codes, and they are not further discussed in this section because of the similarities. The WRc Standard Codes for defect classification consists of 69 basic codes, broken down into three categories, as follows:

1. Structural defects: Describes the physical condition of the sewer and the severity of the damage. Examples include cracks, fractures, broken pipe, hole in the pipe and deformations.

2. Service defects: Describes the capability of a sewer to meet its service requirements. Examples include roots, encrustation, debris, obstruction, and water level.

3. Construction features: Defines features related to the construction of the sewer.

The coding of defects as applied through the WRc method is the first step in a sewer condition assessment. The structural and service condition ratings are established directly from the inspection data. Weights are assigned based on the defect type and the severity. Tables 2-6 and 2-7 show the service and structural defect codes and their weights.

Table 2-6. WRc Service Codes and Weights (McDonald and Zhao 2001)

Defect Type	Code	Weight
Roots		
Fine roots, restricting flow <10%	RL	2
10% to 25% diameter loss	RM	8
> 25% diameter loss	RS	10
Debris		
< 10% flow restriction	DEL	5
10% - 25% diameter loss	DEM	8
> 25% diameter loss	DES	10
Encrustation		
< 10% flow restriction	EL	2
10% - 25% diameter loss	EM	8
> 25% diameter loss	ES	10
Protruding service connection		
< 10% flow restriction	PL	2
10% - 25% diameter loss	PM	8

> 25% diameter loss	PS	10
Infiltration		
Seeping, dripping	IL	2
Running, trickling	IM	5
Gushing, spurting	IS	10

Table 2-7. WRc Structural Codes and Weights (McDonald and Zhao 2001)

Defect Type	Code	Weight
Longitudinal fracture		
< 10 mm wide	FLL	5
10 mm - 25 mm wide, or 2 - 3 fractures	FLM	10
> 25 mm wide, > 3 fractures	FLS	15
Circumferential fracture		
< 10 mm wide	FCL	5
10 mm - 25 mm wide	FCM	10
> 25 mm wide	FCS	15
Diagonal fracture		
< 10 mm wide	FDL	5
10 mm - 25 mm wide	FDL	10
> 25 mm wide, Multiple occurrence	FDS	15
Multiple Fractures	FM	20
Broken Pipe		
> 100 diameter or 100 square	B	15
Longitudinal Crack		
No leakage	CLL	3
With leakage	CLM	5
With leakage, multiple	CLS	10
Circumferential Crack		
No leakage	CCL	3
With leakage	CCM	5
Diagonal crack		
No leakage	CDL	3
With leakage	CDM	5
Deformed Pipe		
< 5% diameter change	DL	5
5% - 10% diameter change	DM	10
> 10% diameter change	DS	15
Collapsed	X	20
Joint Opening		
< 10 mm	JOL	3
10 mm - 50 x wall thickness	JOM	10
> 50 x wall thickness	JOS	15

Joint Displacement		
< V4 pipe wall thickness	JDL	3
V4 - Yz pipe wall thickness	JDM	10
> Yz pipe wall thickness	JDS	15
Surface Damage		
< 5 mm pipe wall thickness spalled or worn out, pitting on metal pipe	HL	3
5 mm - 10 mm pipe wall thickness lost, exposed reinforcement or aggregates, extended corrosion in metal pipe	HM	10
More than 10 mm pipe wall thick- ness lost, corroded reinforcement, corroded through metal pipe	HS	15
Sags		
< 50 mm	SL	4
50 mm - 100 mm	SM	10
> 100 mm	SS	15

2.14 Conclusions from Practice Review

WRc (and related PACP) defect coding uses the CCTV inspection and provides a defect coding to be evaluated to assess the internal condition grade for the wastewater pipes. The distresses, and deterioration of a pipe is the result of complex interactions of various mechanisms that occur within and around a pipeline. Pipelines are prone to certain types of failures based on structural, operational, environmental, and other factors. The impact of the deterioration of the pipeline system depends upon its size, complexity, topography and service.

Ideally, a well-developed sewer condition rating system should include consideration of the three aspects of sewer condition: internal, pipe, and external conditions. Hydraulic considerations such as the infiltration/inflow, capacity, and blockage should be considered (Wirahadikusumah et al. 2001). Infiltration refers to the water entering a sewer system from the ground through means of defective pipes, pipe joints, damaged lateral connections, or manhole walls. Infiltration is most often related to a high ground water level but can also be influenced by storm events. Inflow is extraneous storm water discharged to a sewer system through roof leaders, storm drain, or manhole covers. The additional wastewater volume in a sewer line contributed by the combination of I/I reduces hydraulic capacity, increases the potential of surcharge that contributes to sewer deterioration, which as it progresses, increases the potential for collapse. Most rating systems are based on the assessment of structural conditions with little consideration of hydraulics, and I/I condition because hydraulic and I/I conditions cannot be easily evaluated. They require hydraulic modeling and simulations (which include comprehensive input data) and in-depth investigations of I/I, which can be expensive (Wirahadikusumah et al. 2001).

3. Research Methodology

3.1 Overview

To develop the performance prediction model, data standards for gravity and force main pipes were develop. These data standards were used to develop the performance indices for gravity and force main performance indices, which would give the performance state at the time when the participating utility provided the data. These performance indices were moved with time statistically to develop the performance prediction models. Due to limitations of the data, a records selection process was developed to support the state dependent and time-dependent prediction models developed. The developed models were piloted with participating utilities and validated with piloting sites from these participating utilities. This chapter gives an overview of the research goal, objectives, and methodology. Following chapters provide the details on the methodology for all the research tasks.

3.2 Research Objective

The overall objective of this research is to develop the prediction models for determining the remaining life of wastewater pipes.

3.3 Research Goals

To develop the proposed prediction models, the research has been divided into three main objectives. Figure 3-1 summarizes the overall research approach.

- In Phase 1, the research team identified and developed: identified deterioration parameters for gravity and wastewater pipes and established units and ranges.
- In Phase 2, the research team developed and piloted indices for gravity and force main pipes to determine the performance at the time of inspection.
- In Phase 3 research team is developed and piloted time dependent and state dependent models for strategic and operational level remaining life analysis.

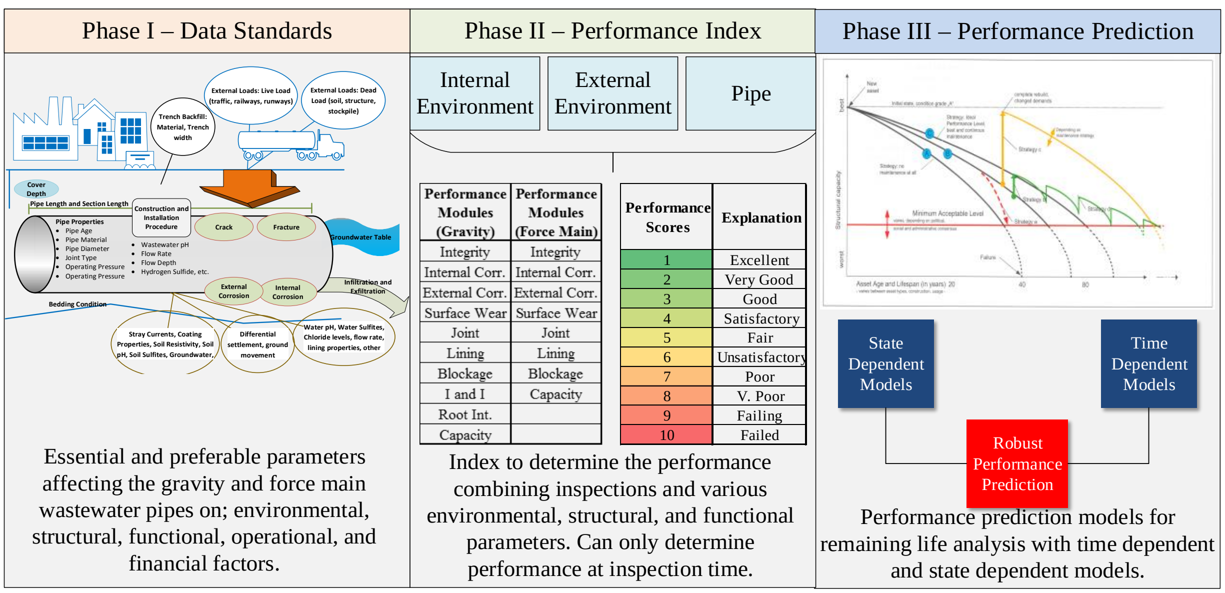


Figure 3-1. Research Objectives

3.4 Research Tasks

There are 11 specific tasks followed to deliver the 3 phases developed to meet the project goals. Figure 3-2 summarizes the research tasks followed.

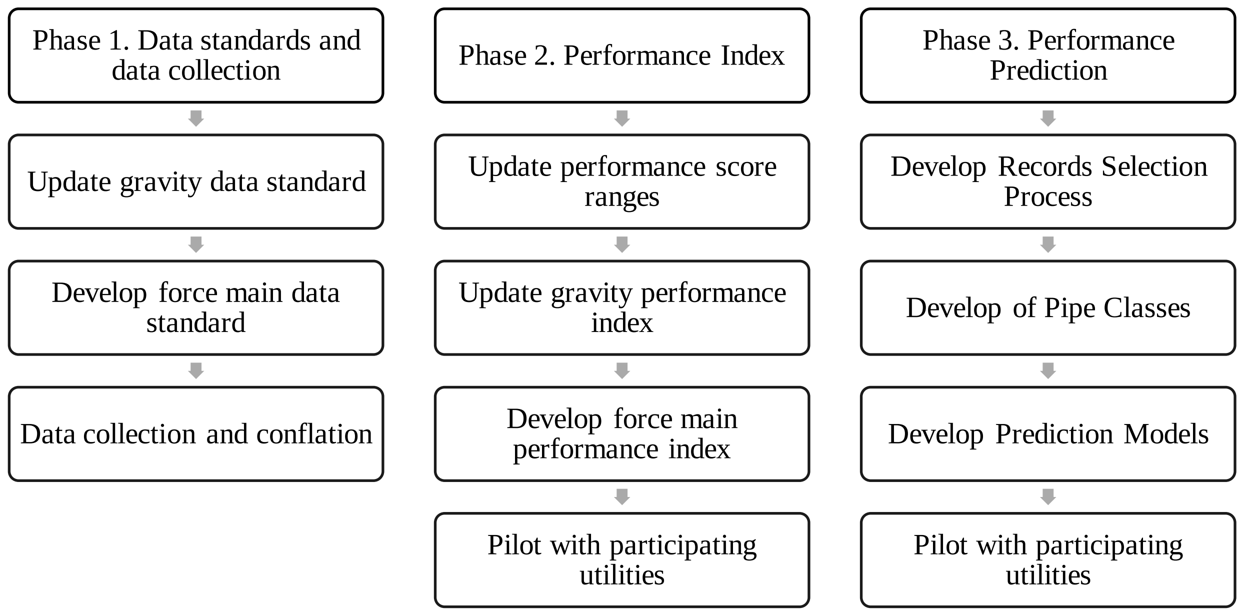


Figure 3-2. Research Tasks

4. Phase 1 – Data Standards and Data Collection

4.1 Overview

The research team has updated the previously developed data standard for the gravity index (Sinha et al. 2008) and developed a new data standard for the force mains. These data standards identify numerous possible parameters which may affect pipe infrastructure. The lists of parameters have been sent to participating utilities within and out of the U.S. to get feedback for improving the data structures. From the feedbacks received, changes and updates have been made. The goal is to eventually create a national standard data structure for the wastewater pipe infrastructure. This standard data structure was developed to aid the decision-making process in asset management program. Also, this data structure has been used for developing the performance indices and prediction models. The parameters were divided into five classes based on their characteristics: Physical/Structural, Operational/Functional, Environmental, Financial, and Others. These classes are presented in Figure 4-1.

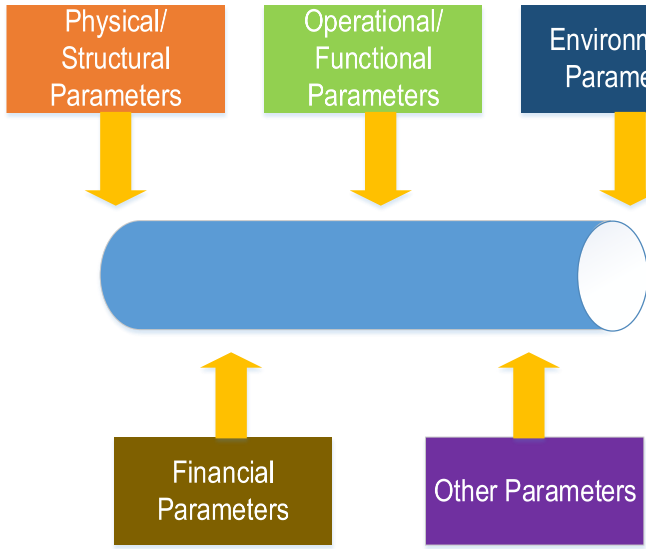


Figure 4-1. Classification of Pipe Parameters.

Ultimately, for the purpose of this study, most of the parameters are needed to develop a reliable prediction model, and it is critical that the utility companies provide the essential data. Due to time constraints of the utilities, some of the preferable parameters were acquired by other means such as the research team organizing and researching past documents within the city data, or deriving from other sources. For example, utilities may not have soil parameters for a wastewater data structure; therefore, the research teams had evaluated and utilized data from external sources such as U.S. Department of Agriculture (USDA) Soil Survey Geographic Database (SSURGO) Database.

4.2 Update Gravity Data Standard

The list of parameters affecting the gravity pipe performance was developed in earlier research (Sinha et al. 2008, Sinha and Angkasuwansiri 2010). After the additional parameters are defined, the units and the ranges of these parameters are defined to be used to update the performance index. This list of parameters is updated with the feedback of participating utilities and service providers. The detailed explanations of these parameters and units ranges are provided in Appendix A and B.

Table 4-1. Gravity Pipes Essential Data List

No	Parameter	Unit	Brief Explanation
			Physical/Structural
1	Node Identification Number	Node	ID for each pipe segments (Manhole-Manhole)between nodes
2	Pipe Material	Type	Different pipe materials deteriorate at different rates
3	Pipe Diameter	Inch	Different pipe sizes may fall in different failure modes
4	Pipe Installation Year	Year	Older pipes may deteriorate faster than newer pipe
5	Pipe Depth	Feet	Pipe Depth affects pipe loading and deteriorating rate
6	Pipe Wall Thickness	Inch	Wall thickness affects rupture resistance and corrosion penetration rates
7	Pipe Location	Area	Some locations may receive roadway salt intrusion; urban, sub urban, rural, other
8	Pipe Shape	Type	Different pipe shapes may result in different failure modes and deterioration
9	Pipe Joint Type	Type	Some types of joints may undergo premature failure
10	Pipe Bedding	Type	Inadequate bedding may cause premature pipe failure, special bedding use
11	Trench Backfill	Type	Some backfill materials are more corrosive or frost susceptible
12	Pipe Slope	Gradient	Slope affects the velocity of gravity flow and may result in different pipe deterioration rates
13	Design Life of Pipe	Year	The pipe design life
14	Design Strength of Pipe	psi	Original design strength of each pipe.
15	Node Length	Feet	Length of Node (Manhole-Manhole)
16	Pipe Lining	type	Presence of pipe lining significantly reduces internal corrosion
17	Pipe Lining pH	pH	The pH of lining can be used as an indicator for the deterioration.
			Operational/Functional
18	Pipe Hydraulics	Gallon/Min	Capacity of the sewage gravity conveying pipe
19	Pipe Surcharging	Yes/No.	Surcharging in gravity sewers in dry & wet weather should be considered
20	Operational& Maintenance Practices	Type	Poor practices can compromise structural integrity and water quality
21	Pipe Renewal Record	Type	All records of pipes renewal-type of renewal method

22	Pipe Defect Type	Type	Record of Defects observed
23	Pipe Defect Level	Level	The level of defects observed at pipe.
24	Pipe Defect Location	Orientation	Locations of the defects observed
25	Infiltration/Inflow	Level-Gal/Min	infiltration/inflow may cause soil erosion, and increasing flow volume
26	Exfiltration	Level	Exfiltration may cause erosion of soil and change soil loading on pipe
27	Blockage/stoppage	Yes/No-Type	Blockage make the pipeline network inoperative, sewer pipe is no longer functional
28	Sediments	Ton/Feet	Sediments per unit length
29	Inspection record	Type	Record of inspection, method use, date of inspection
30	Flow Velocity	Feet/Second	Low velocity accumulate deposits; excessive velocity accelerate deterioration at invert
		Environmental	
31	Soil Type	Type	Corrosive, expansive,& compressible; hydrocarbons &solvents cause deterioration
32	Soil Corrosivity	Level	Condition of the soil related to pipe deterioration
33	Soil Moisture Content	Percent	Moisture percentage in the soil may affect loading and pipe deterioration
34	Stray Currents	Yes/No	Stray currents may cause electrolytic corrosion of metal pipes
35	Groundwater Table	Feet	Affecting soil loading on the pipes and pipe deterioration rate
36	Ground Cover	Type	Paved ground or vegetation cover result in different deterioration mode and rate
37	Loading Condition (Dead Load)	Lbs. / sq. ft.	Dead load can be determined from infrastructure loading
38	Loading Condition (Live Load)	ADT-Level	Live load can be determined from average daily traffic volume and railway loading etc.
39	Rainfall/ Precipitation	Inch/year	Rainfall in the areas should be monitored
40	Climate Temperature	^{0}F	Frost action in cold regions and seasonal soil water content variation in warmer regions
41	H2S	ppm	Concentration of Hydrogen Sulfide can increase pipe internal deterioration rate
42	Frost Penetration	Yes/No-depth	Soil ever frozen around the pipe, depth of penetration in feet.
43	Proximity to Trees	Feet	Average distance between sewer and trees
44	Tidal Influences	Yes/No	Sewers in Coastal areas may be subjected to tidal influence affecting bedding of the pipe
		Financial	
45	Annual Capita cost	$/Year	Utility annual capital Cost and allocation criteria
		Other	
46	FOG	Level	Fats, Oils, and Grease entering the sewer system

Table 4-2 Gravity Pipes Preferable Data List

No	Parameter	Unit	Brief Explanation
Physical/Structural			
1	Pipe Section Length	Feet	Length of pipe section(Joint-joint)
2	Dissimilar Materials	Yes/No	Dissimilar metals/materials are more susceptible to galvanic corrosion
3	Pipe External Coating	Type	External coating prevents corrosion of the pipe
4	Pipe Cathodic Protection	Yes/No	Technique used to control he corrosion of a metal surface
5	Pipe Vintage	Year	Pipes made at different time and place may deteriorate differently
6	Pipe Manufacturer Name	Name	Defects in pipe walls produced by manufacturing errors can make pipes vulnerable to failure
7	Pipe Manufacture Class	Class	Manufacturing class determine the rate of deterioration for pipes
8	Pipe Manufacture Date	Year	Manufacture date determines some deterioration characteristics
9	Pipe Trench Width	Feet	Trench width may affect soil loading on the pipes and deterioration rate
10	Cathodic Protection Design Potential	mV	The cathodic protection design potential
11	Cathodic Protection Present Potential	%	As pipes age the cathodic protection potential decreases suggesting wall thickness loss
12	Pipe Thrust Restraint	Type	Inadequate restraint may increase longitudinal pipe stresses
13	Type of Dissimilar Materials	Type	Different types of dissimilar materials effect the corrosion rates
14	Height of Bedding	Inches	Height of bedding is an important factor in deterioration
15	Lateral Connections	Record	Condition of lateral connections and other related information such as type of connection
16	Lateral Connection Type	Type	Type of Lateral connection can be a determining factor for deterioration rates.
17	Lateral Connection Location	Location	Location of Lateral Connections influences the blockage and capacity.
18	Lateral Connection Height of Drop	Feet/10	The height of the lateral connection effects the deterioration
19	Lateral Connection Flow Rate	Gal/min	The flow rate for the lateral connections effects the blockage and capacity performance
20	Lateral Connection Size	Inches	The size of the lateral connections effect the performance by increasing the amount of water conveyed.
21	Lateral Connection Slope	%Grade	The slope of the lateral connections effect the surface wear and corrosion rates.
22	Distance to WWTP	Miles/10	The distance the Wastewater treatment plant indicates how much time the conveyed water spends in the system.
23	Wastewater TSS	ppm	The total suspended solids can increase the Corrosivity of the conveyed water.
24	Concrete Encasement	Yes/No	The presence of concrete encasement can protect the pipe against external corrosion.
Operational/Functional			

25	Sewer Flooding	Yes/No	Flooding may change property of surrounding soil and loading on pipe
26	Flow Depth/Diameter	Ratio	Pipes with different flow depth over diameter ratios deteriorate differently
27	Maintenance Frequency	Level	Frequent maintenance performed will increase the life of the pipe
28	Type of Cleaning	Type	Type of cleaning can affect the blockage and internal corrosion
29	Cleaning Frequency	Frequency	The cleaning frequency can determine the defects such as the blockage and surface defects.
30	Sewer Odors	Yes/No	Solids build- ups, poor system hydraulics, flat grade, etc.
31	Sewer Overflow(SSO/CSO)	Yes/No	Overflow may inundate surrounding soil and change loading on pipe
32	Backup Flooding	Number	Number of properties affected by flooding in Dry & Wet weather
33	Dry Weather Flow	Gal/Min	The high dry weather flow rates indicate capacity problems.
Environmental			
34	Extreme Events	Yes/No- Type	Information related to extreme events
35	Soil Disturbance	Yes/No	Disturbance of soil may cause damage or change soil support or loading to the pipe
36	Soil Chloride	%	Low chloride levels in high pH(>11.5) environments can lead to serious corrosion
37	Soil Sulfate	%	Possible food source for sulfate reducing bacteria in anaerobic conditions under loose coatings
38	Soil Redox Potential	mV	Redox potential of soils directly effects the external corrosion of pipes.
39	Soil Resistivity	Ohm-cm	External corrosion of pipes are reduced with higher resistivity of soil
40	Wastewater pH	pH	Low pH(<4) and high alkaline conditions (pH>8)means conveyed water likely promotes corrosion;
41	Wastewater Sulfate	mg/l	Possible food source for sulfate reducing bacteria in an aerobic conditions under loose linings.
42	Wastewater Dissolved Oxygen	mg/l	Higher concentrations contribute to oxidization
43	Wastewater Temperature	F°	Lower temperatures of wastewater contribute to failures
44	Foreign Anode Bay Distance	ft.	Distance of the foreign anode bay causing stray current is proportional to external corrosion
45	Runoff Rate	Cu. Ft/ Sec.	Excess water flow which can be caused by rainfall, evaporation, snow melting, etc.
46	Non-Uniform Soil	Yes/No	Non-uniform soil support in longitudinal axis may increase shear and bending stresses
47	Non-Uniform slope	Yes/No	non-uniform slope may reduce the operating performance
48	Unstable Slope	Yes/No	Pipes in unstable slope may be subjected to downslope creep displacement
49	Soil pH	pH	Low pH(<4) and high alkaline conditions (pH>8)are likely to promote corrosion;
50	Soil Sulfide	%	Sulfate reducing bacteria giving off sulfides which are excellent electrolytes
Financial			
51	Annual Maintenance Cost	$/Year	Routine Cleaning,Etc.;Method and Cost of Maintenance

52	Annual Renewal Cost	$/Year	Method and Cost of Preservation and Improvement like grouting, lining, etc.
53	Installation and Replacement Cost	$	Original cost of installation and replacement cost
54	Annual Operational Cost	$/Year	Cost spent each year for operating and functioning sewer system
55	Depreciated Value	%	Depreciated value and method of calculation
Other			
56	Density of Connections	Number/Mile	Number of properties connected to the sewer per mile
57	Third Party Damage	Yes/No	Information related to third party damage
58	Other Information	-	Information relevant for pipe condition assessment and deterioration modeling
PACP Inspection Data(Please Refer to NASSCO PACP Coding Manual)			
59	Survey Date	Date	Date which the CCTV inspection was conducted
60	Upstream manhole ID	ID	Reference number for the upstream manhole
61	Upstream rim to invert	Feet and 1/10	Distance between rim level of manhole and invert level of pipe
62	Upstream grade to invert	Feet and 1/10	Depth between the grade (ground) and the invert
63	Upstream rim to grade	Feet and 1/10	Depth between the rim of the manhole and grade (ground)
64	Downstream manhole ID	ID	Reference number for the upstream manhole
65	Downstream rim to invert	Feet and 1/10	Distance between rim level of manhole and invert level of pipe
66	Downstream grade to invert	Feet and 1/10	Depth between the grade (ground) and the invert
67	Downstream rim to grade	Feet and 1/10	Depth between the rim of the manhole and grade (ground)
68	Direction of Survey	Upstream/Down stream	Indicate the direction of the survey
69	Flow Control	Type	Indicate how the flow has been controlled during the survey
60	Size 1	inch	pipe diameter if circular ,height if not circular
61	Size 2	inch	Maximum sewer width
62	Total length Surveyed	Feet and 1/10	Distance Surveyed
63	Purpose of survey	Type	Predominant reason survey was conducted
64	Pre-Cleaning	Type	Type of cleaning conducted for the CCTV Survey
65	Date Cleaned	Date	Date cleaned in year, month, day,
66	Weather	Type	Weather conditions duringsurvey
Form Details Section(Repeated per Observation/ Defect)			
67	Distance	Feet and 1/10	Distance of the defector the observation from the access point or the start of the survey.

68	Group/Description	PACP Code	NASSCO PACP code to indicate general description of defect
69	Modifier/severity	Code	NASSCO PACP code indicating further details on the location and severity of defect
80	Continuous Defect	Type	If the observation/defect is continuous and type.
81	Value	Dimensions	Dimensions of defects. These defects are captured in various dimension types
82	Joint	Yes/no	If the observed defect is within 8" of the pipe joint.
83	Circumferential location (at/from)	Clock	Defect beginning location for pipe cross section e.g. 8 o'clock
84	Circumferential location (at/from)	Clock	Defect end location for pipe section in clock positions e.g. 4 o'clock

4.3 Develop Force Main Data Standard

The list of parameters affecting the force pipe performance was developed. List of parameters and units are developed by literature review and was reviewed by participating utilities and service providers. The detailed explanations of these parameters and units ranges are provided in Appendix C and D.

Table 4-3. Force Main Pipes Essential Data List

No	Parameter	Unit	Brief Explanation
Physical/Structural			
1	Node Identification Number	Node	ID for each pipe segments (Manhole-Manhole) between nodes
2	Pipe Material	Type	Different pipe materials deteriorate at different rates
3	Pipe Diameter	Inch	Different pipe sizes may fall in different failure modes
4	Pipe Age	Year	Older pipes may deteriorate faster than newer pipe
5	Pipe Depth	Feet	Pipe Depth affects pipe loading and deteriorating rate
6	Pipe Wall Thickness	Inch	Wall thickness affects rupture resistance and corrosion penetration rates
7	Pipe Location	Area	Some locations may receive roadway salt intrusion; urban, sub-urban, rural, costal, etc.
8	Pipe Shape	Type	Different pipe shapes may result in different failure modes and deterioration
9	Pipe Joint Type	Type	Some types of joints may undergo premature failure
10	Pipe Bedding	Type	Inadequate bedding may cause premature pipe failure, special bedding use

11	Trench Backfill	Type	Some backfill materials are more corrosive or frost susceptible
12	Pipe Slope	Gradient	Slope affects the velocity of gravity flow and may result in different pipe deterioration rates
13	Design Life of Pipe	Year	The pipe design life
14	Design Strength of Pipe	psi	Original design strength of each pipe.
15	Node Length	Feet	Length of Node (Manhole-Manhole)
16	Pipe Lining	type	Presence of pipe lining significantly reduces internal corrosion
17	Pipe Lining pH	pH	The low pH of the pipe liners indicate deterioration of the liners
Operational/Functional			
18	Operational & Maintenance Practices	Type	Poor practices can compromise structural integrity and water quality; very good, good, fair
19	Pipe Renewal Record	Type	All records of pipes renewal- type of renewal method
20	Pipe Defect Type	Type	Record of Defects observed
21	Pipe Defect Level	Level	The level of defects observed at pipe.
22	Pipe Defect Location	Orientation	Locations of the defects observed
23	Blockage/stoppage	Yes/No-Type	Blockage make the pipeline network inoperative, sewer pipe is no longer functional
24	Sediments	Ton/Feet	Sediments per unit length
25	Inspection record	Type	Record of inspection, method use, date of inspection
26	Water Corrosivity	level	Water present may be corrosive and may affect pipe material
27	Hazen Williams C Factor	c factor	Hazen Williams C factor is used to determine the head loss in flow
28	Operation Pressure	psi	Operational pressure pipe is designed for.
29	Pipe Break	Number	The historical break records can be used to assess the probability of failure
30	Pipe Break<5 Years	Yes/No	The current pipe breaks indicate an ongoing problem with the pipe.
31	Leak	Gal/Min	The presence of leak indicates exfiltration
32	Tuberculation	Yes/No	The presence of tuberculation indicates a surface wear/internal corrosion problem
33	Pressure Exceeded	Yes/No	Pipes operating on higher pressure is prone to structural failures
34	Pressure Surges	Yes/No	Pipes operating on higher pressure is prone to structural failures
35	Distance to WWTP	Miles	The distance to the Wastewater treatment plant indicate the time spend by the conveyed water in the system.
36	Surcharging	Yes/No	The presence of surcharging indicate capacity and blockage problems.
37	Number of Gas Pockets	Number	Number of gas pockets indicate gas accumulation and internal corrosion problems

38	Length of Gas Pockets	Feet	Length of gas pockets indicate gas accumulation and internal corrosion problems
39	Factor of Safety	Ratio	The factor of safety left at the pipe ins an indicator for deterioration.
Environmental			
40	Soil Type	Type	Corrosive, expansive, & compressible; hydrocarbons & solvents cause deterioration
41	Soil Corrosivity	Level	Condition of the soil related to pipe deteriorate; low, medium, high
42	Soil Moisture Content	Percent	Moisture percentage in the soil may affect loading and pipe deterioration
43	Stray Currents	Yes/No	Stray currents may cause electrolytic corrosion of metal pipes
44	Groundwater Table	Feet	affecting soil loading on the pipes and pipe deterioration rate; above, below sewer, fluctuating
45	Ground Cover	Type	Paved ground or vegetation cover result in different deterioration mode and rate
46	Loading Condition (Dead Load)	Lbs/sq.ft.	Death load can be determined from infrastructure loading
47	Loading Condition (Live Load)	ADT-Level	Live load can be determined from average daily traffic volume and railway loading etc.
48	Rainfall/Precipitation	Inch/year	Rainfall in the areas should be monitored
49	Climate - Temperature	^oF	Frost action in cold regions and seasonal soil water content variation in warmer regions
50	H2S	ppm	Concentration of Hydrogen Sulfide can increase pipe internal deterioration rate
51	Frost Penetration	Yes/No-depth	Soil ever frozen around the pipe, depth of penetration in feet.
52	Tidal Influences	Yes/No	Sewer in Coaster area may be subjected to tidal influence affecting bedding of the pipe
Financial			
53	Annual Capital Cost	$/Year	Utility annual capital Cost and allocation criteria
Other			
54	FOG	Level	Fats, Oils, and Grease entering the sewer system

Table 4-4. Force Main Pipes Preferable Data List

No	Parameter	Unit	Brief Explanation
Physical/Structural			
1	Pipe Section Length	Feet	Length of pipe section (Joint - joint)
2	Dissimilar Materials	Yes/No	Dissimilar metals/materials are more susceptible to galvanic corrosion
3	Pipe External Coating	Type	external coating prevents corrosion of the pipe

4	Pipe Cathodic Protection	Yes/No	Technique used to control the corrosion of a metal surface
5	Pipe Vintage	Year	Pipes made at different time and place may deteriorate differently
6	Pipe Manufacturer Name	Name	Defects in pipe walls produced by manufacturing errors can make pipes vulnerable to failure
7	Pipe Manufacture Class	Class	Manufacturing class determine the rate of deterioration for pipes
8	Pipe Manufacture Date	Year	Manufacture date determines some deterioration characteristics
9	Pipe Trench Width	Feet	Trench width may affects soil loading on the pipes and deterioration rate
10	Cathodic Protection Design Potential	mv	The cathodic protection design potential
11	Cathodic Protection Present Potential	%	As pipes age the cathodic protection potential decreases suggesting wall thickness loss
12	Pipe Thrust Restraint	Type	Inadequate restraint may increase longitudinal pipe stresses
13	Type of Dissimilar Materials	Type	Different types of dissimilar materials effect the corrosion rates
14	Height of Bedding	Inches	Height of bedding is an important factor in deterioration
15	Lateral Connections	Record	Condition of lateral connections and other related information such as type of connection
Operational/Functional			
16	Sewer Flooding	Yes/No	Flooding may change property of surrounding soil and loading on pipe
17	Maintenance Frequency	Level	Frequent maintenance performed will increase the life of the pipe
18	Type of Cleaning	Type	Type of cleaning can affect the blockage and internal corrosion
19	Sewer Odors	Yes/No	Solids build-ups, poor system hydraulics, flat grade, etc.
20	Sewer Overflow (SSO/CSO)	Yes/No	Overflow may inundate surrounding soil and change loading on pipe
21	Backup Flooding	Number	Number of properties affected by flooding in Dry & Wet weather
22	Name of Treatment Plant	Name	Name of treatment plan indicate the location and sewer shed of the pipes.
Environmental			
23	Soil Disturbance	Yes/No	Disturbance of soil may cause damage or change soil support or loading to the pipe
24	Soil Chloride	%	Low chloride levels in high pH(>11.5) environments can lead to serious corrosion
25	Soil Sulfate	%	Possible food source for sulfate reducing bacteria in anaerobic conditions under loose coatings
26	Soil Redox Potential	mV	Redox potential of soils directly effects the external corrosion of pipes.
27	Soil Resistivity	ohm cm	External corrosion of pipes are reduced with higher resistivity of soil
28	Wastewater pH	pH	Low pH (<4) and high alkaline conditions (pH>8) means conveyed water likely promotes corrosion;
29	Wastewater Sulfate	mg/l	Possible food source for sulfate reducing bacteria in anaerobic conditions under loose linings.
30	Wastewater Dissolved Oxygen	mg/l	Higher concentrations contribute to oxidization

31	Wastewater Temperature	F°	Lower temperatures of wastewater contribute to failures
32	Foreign Anode Bay Distance	ft.	Distance of the foreign anode bay causing stray current is proportional to external corrosion
33	Runoff Rate	Cu. Ft/Sec.	Excess water flow which can be caused by rainfall, evaporation, snow melting, etc.
34	Non-Uniform Soil	Yes/No	Non-uniform soil support in longitudinal axis may increase shear and bending stresses
35	Non-Uniform slope	Yes/No	non-uniform slope may reduce the operating performance
36	Unstable Slope	Yes/No	Pipes in unstable slope may be subjected to downslope creep displacement
37	Soil pH	pH	Low pH (<4) and high alkaline conditions (pH>8) are likely to promote corrosion;
38	Soil Sulfide	%	Sulfate reducing bacteria giving off sulfides which are excellent electrolytes
Financial			
39	Annual Maintenance Cost	$/Year	Routine Cleaning, etc.; Method and Cost of Maintenance
40	Annual Renewal Cost	$/Year	Method and Cost of Preservation and Improvement like grouting, lining, etc.
41	Installation and Replacement Cost	$	Original cost of installation and replacement cost
42	Annual Operational Cost	$/Year	cost spent each year for operating and functioning sewer system
43	Depreciated Value	%	Depreciated value and method of calculation
Other			
44	Third Party Damage	Yes/No	Information related to third party damage
45	Other Information	-	Information relevant for pipe condition assessment and deterioration modeling

4.4 Data Collection and Conflation

Data on the list of parameters was collected from various participating utilities and other data sources. This collected data was utilized to develop, verify and validate the models developed. A protocol was developed to collect data from participating utilizes in an effective manner. As represented in figure 4-2, an initial meeting was held with participating utilities to discuss the list of parameters needed as well as the units and ranges these parameters were recorded. A secure FTP site is created for utilities to submit the requested data. The initially submitted dataset was evaluated, and issues were discussed at a follow-up meeting with the participating utilities. After the issues are resolved, the submitted data was transformed into a standardized format and was added to the final database which was relied on for the development of the performance index and the prediction model. Figure 4-2 summarizes the data collection protocol. Figure 4-3 summarizes the data conflation process.

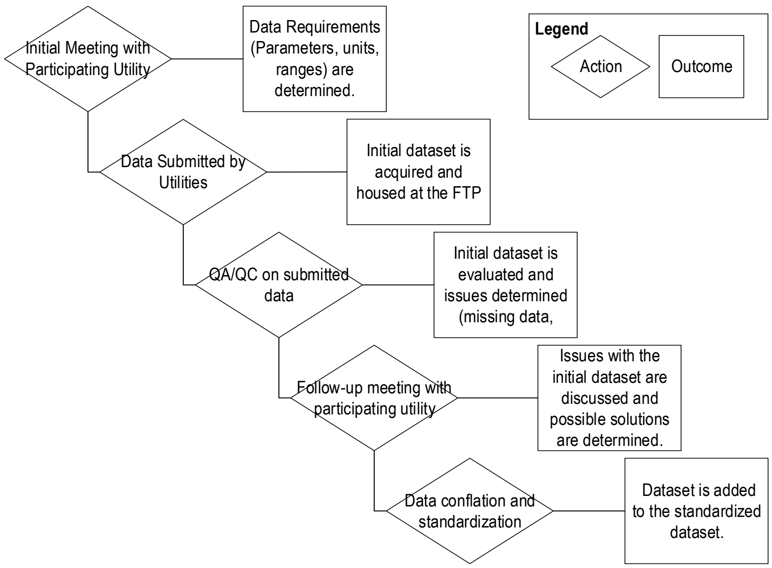


Figure 4-2. Data Collection Protocol

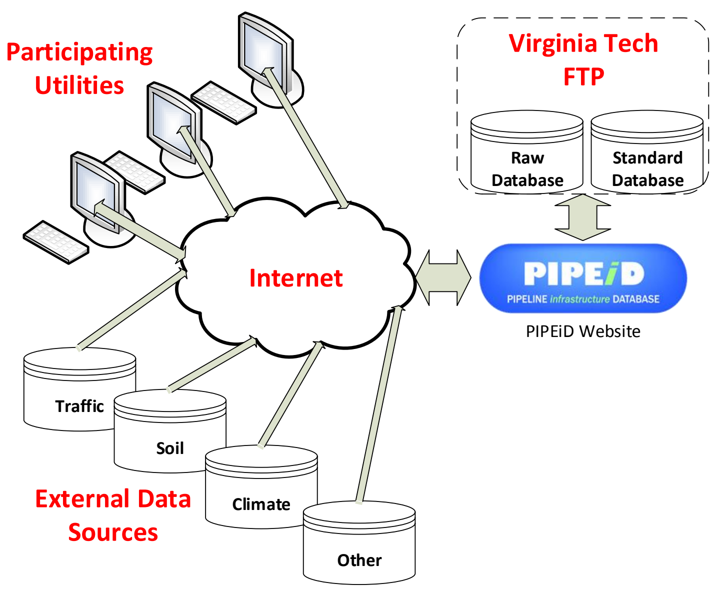


Figure 4-3. Data Conflation Process

4.5 Participating Utilities and Data Collected

Numerous utilities have provided data and feedback for the piloting of the performance indices and prediction models. Figure 4-4 summarizes the participating utilities and their distribution geographically.

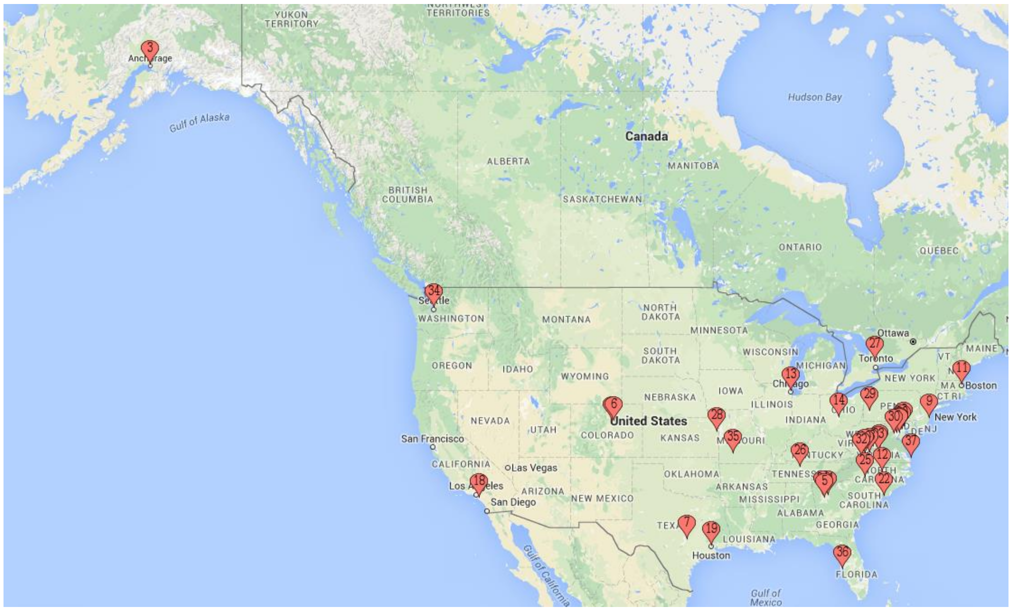


Figure 4-4. Participating Utilities and Geographical Distribution

Tables 4-5 and 4-6 represent the participating utilities, which have provided data for the piloting, verification, and validation process. Figures 4-5 and 4-6 represent the geographical distribution of participating utilities by USEPA Regions.

Table 4-5. Piloting Overview – Gravity

No	Utility	EPA Region	City	State
1	Alexandria Renew	3	Alexandria	VA
2	Anchorage Water and Wastewater	10	Anchorage	AK
3	Arlington County	3	Arlington	VA
4	Baltimore County	3	Baltimore	MD
5	Blacksburg	3	Blacksburg	VA
6	City of Atlanta	4	Atlanta	GA
7	City of Boston	1	Boston	MA

8	City of Columbus	5	Columbus	OH
9	City of Houston	6	Houston	TX
10	City of Springfield, MO	7	Springfield	MO
11	Cobb County	4	Marietta	GA
12	County of Pulaski	3	Pulaski	VA
13	Fairfax County	3	Fairfax	VA
14	Gwinnett County	4	Lawrenceville	GA
15	Hampton Roads Sanitation District	3	Virginia Beach	VA
16	Johnson County	7	Olathe	KS
17	Ocean County	2	Bayville	NJ
18	Orange County Sanitation District	9	Fountain Valley	CA
19	Pittsburg	3	Pittsburg	PA
20	Prince William County	3	Prince William	VA
21	Seattle Public Utilities	10	Seattle	WA
22	Town of Amherst	3	Amherst	VA
23	WSSC	3	Laurel	MD
24	WVWA	3	Roanoke	VA

Table 4-6. Piloting Overview – Force Main

No	Utility	EPA Region	City	State
1	Baltimore County	3	Baltimore	MD
2	City of Houston	6	Houston	TX
3	Fairfax County	3	Fairfax	VA
4	Hampton Roads Sanitation District	3	Virginia Beach	VA
5	Johnson County	7	Olathe	KS
6	Mount Pleasant Waterworks, NC	4	Mount Pleasant	NC
7	Pulaski County	3	Pulaski	VA
8	WSSC	3	Laurel	MD
9	WVWA	3	Roanoke	VA

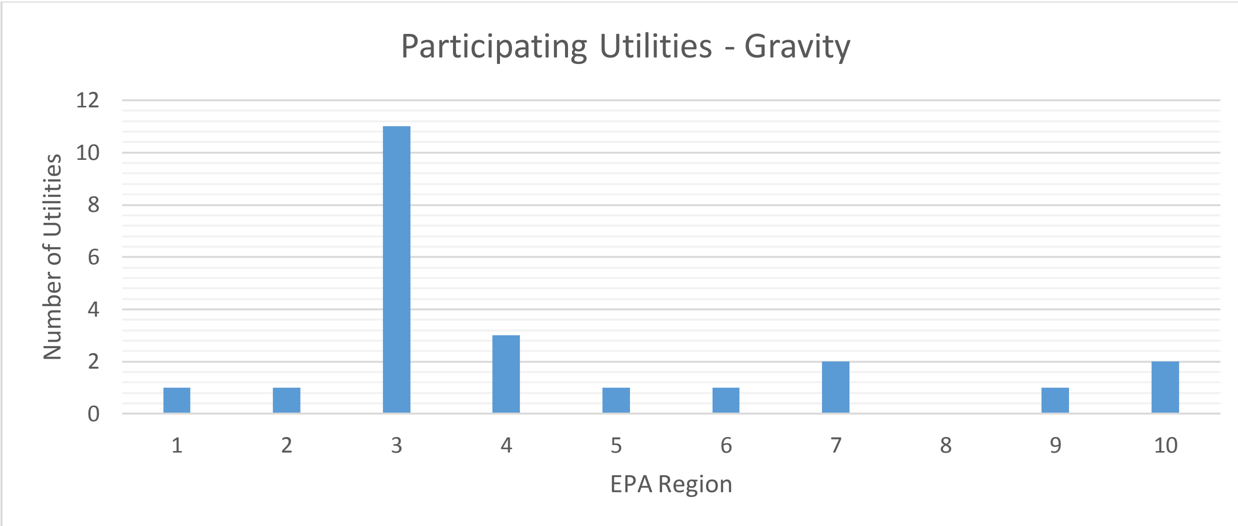


Figure 4-5. Geographical Distribution of Participating Utilities (Gravity) per USEPA Region

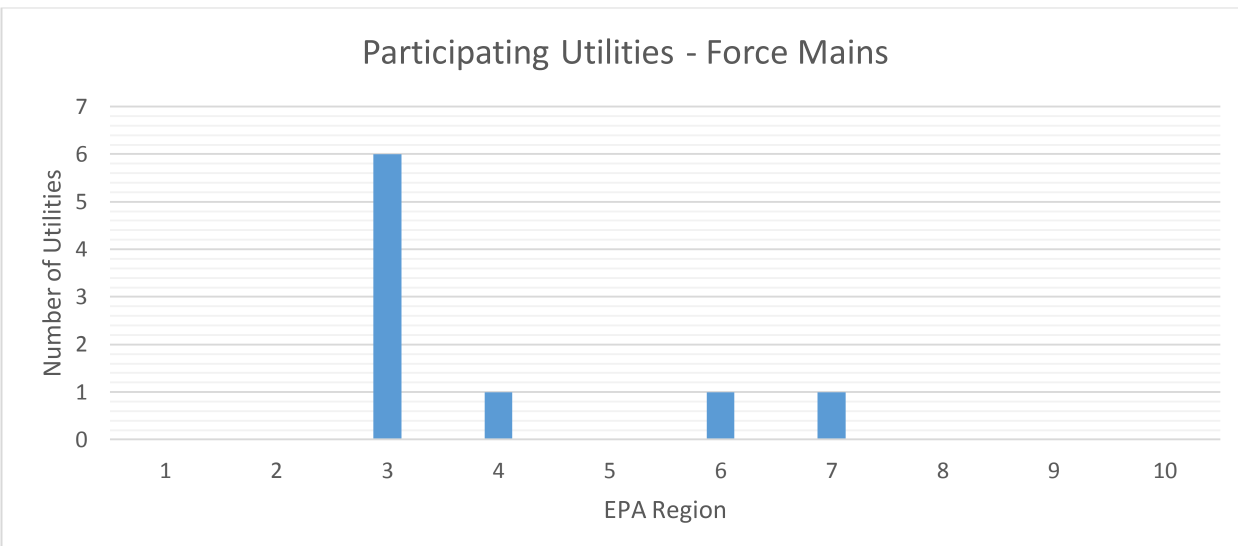


Figure 4-6. Geographic Distribution of Participating Utilities (Force Main) per USEPA Region

4.6 Conclusions from Phase I

The data models provide a standard template for the many disparate datasets created and maintained by water utilities across the United States. Such models will be informed by industry best practices and the needs of the research community. Beyond the database design aspects about the storage of spatially referenced data describing the engineered water infrastructure, we also propose to incorporate relationships between aspatial, and even unstructured information resources to the infrastructure feature themselves. Additionally, security is designed into the system before the ingestion of any data sets, as water infrastructure is a critical component of the built environment, and local water utilities rightly consider this data to be sensitive. An infrastructure for the upload of data, before ETL into the standard data model, was designed with this in mind. On top of the infrastructure for data management, which consists of physical repositories for the data itself and standardized data structures within the repository, must be overlaid a well-defined set of ETL rules and processes to automate, as much as possible, assimilation of data into the model.

Utilization of the data standards and promises more than a unifying repository for data; rather, the data repository is a foundational building block for the real value-adding contribution of the infrastructure asset management. These value-adding prospects can be summarized as;

- A set of interfaces to the data to enable the plug-and-play application of engineering models to data in the repository.

- A discovery infrastructure to enable information resources to be identified from within the massive central data set(s)

- A visualization framework to facilitate intuitive interpretation of model results.

In short, standardized data platform will generate real, actionable insight over the period of performance for the water industry. The main benefit for the standardized data is the leverage of this standardized data to be used for the standardized models and tools which the reliability and applicability can be judged across various datasets.

5. Phase 2 – Performance Indices

5.1 Overview

The research team developed indices for gravity and force main pipes to determine the performance at the time of inspection. In the first task for this phase, the feasibility of improving the 5-point scale used by in practice was investigated. A new 10-point scale was developed and used for this survey. The data standards established for the previous phase 1 were used to develop the performance indices for gravity and force main performance indices which would give the performance state at the time when the participating utility provided the data.

5.2 Fuzzy Logic Technique

Performance index algorithms for gravity and force main pipes utilizing the fuzzy logic technique are developed to determine the performance of the pipes at the time of inspection. In fuzzy rule-based modeling, the relationships between variables are represented as a result of fuzzy if-then rules of the form "If antecedent proposition then consequent proposition." The antecedent proposition is always a fuzzy proposition of the type "x is A" where x is a linguistic variable, and A is a constant linguistic term. The proposition's truth value (a real number between zero and 1) depends on the degree of similarity between x and A. Following section discuss the modules parameters and if and then rules developed for the performance indices.

Membership Function: Each parameter has its membership function presenting linguistic expression and degree of membership. An example of membership functions is shown in figure 5-1.

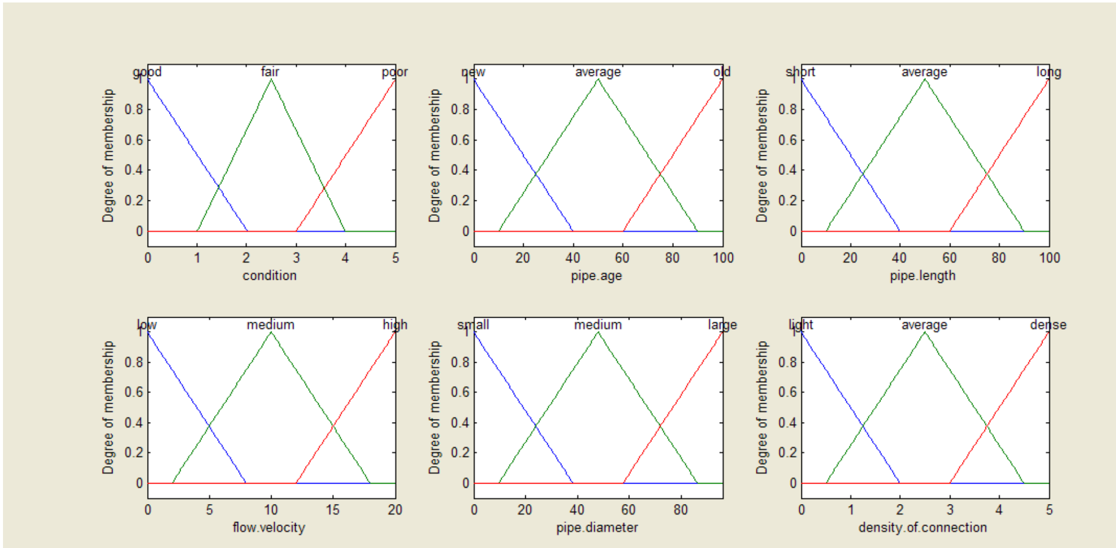


Figure 5-1. Example of Membership Functions

Fuzzy If-Then Rules:Fuzzy if-then rules were used to represent the knowledgebase in the F-PIE. Unlike weighted factors, fuzzy inference system can take independency of parameters into account and has multiple effects to the system. In wastewater pipe performance case for example, if the pipe condition and bending condition is poor, the structure failure will be likely possible. Figure 5-2 and 5-3 show example of the fuzzy rules.

1. If (condition is good.) then (structure, failure is good.) (1)
2. If (condition is fair.) then (structure, failure is fair.) (1)
3. If (condition is poor.) then (structure, failure is poor.) (1)
4. If (condition is fair.) and (bedding is poor.) then (structure, failure is poor.) (1)
5. If (condition is fair.) and (location is poor.) and (pipe, depth is shallow.) then (structure, failure is poor.) (1)
6. If (condition is fair.) and (soil, type is worst.) and (groundwater, table is above, pipe.) then (structure, failure is poor.) (1)
7. If (condition is fair.) and (ground, cover is worst.) then (structure failure is poor.) (1)

Figure 5-2. Example of Knowledge Based Fuzzy Rules

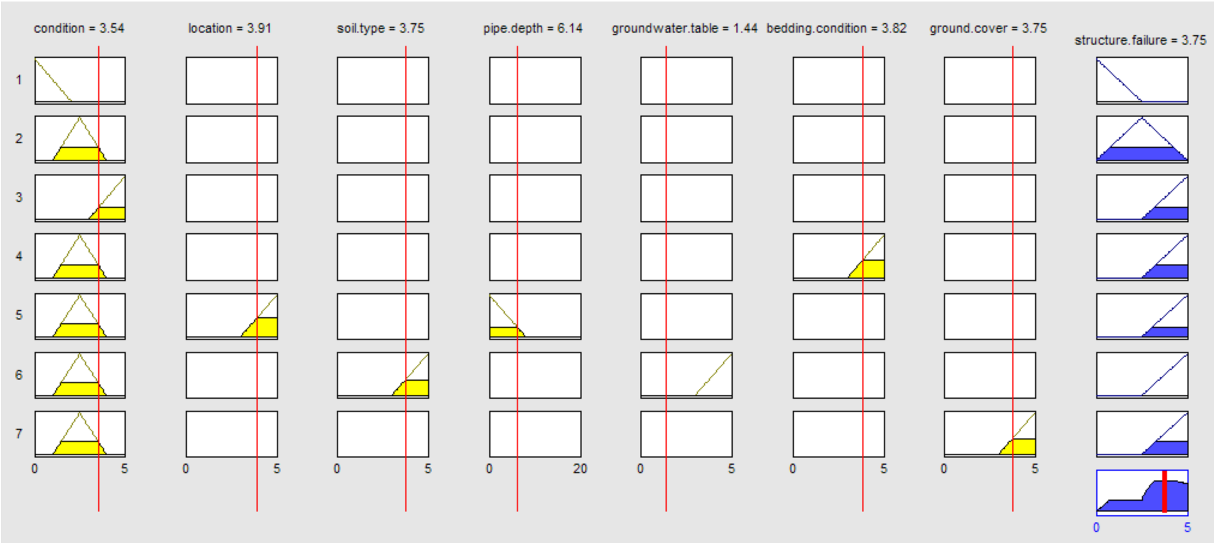


Figure 5-3. Graphical Representation of the Fuzzy Rules

Output: Figure 5-4 illustrates the non-linear relationship between the selected parameters with respects to the index. In this example, a blockage will likely be possible if the length of the pipe is high and the pipe age is very high.

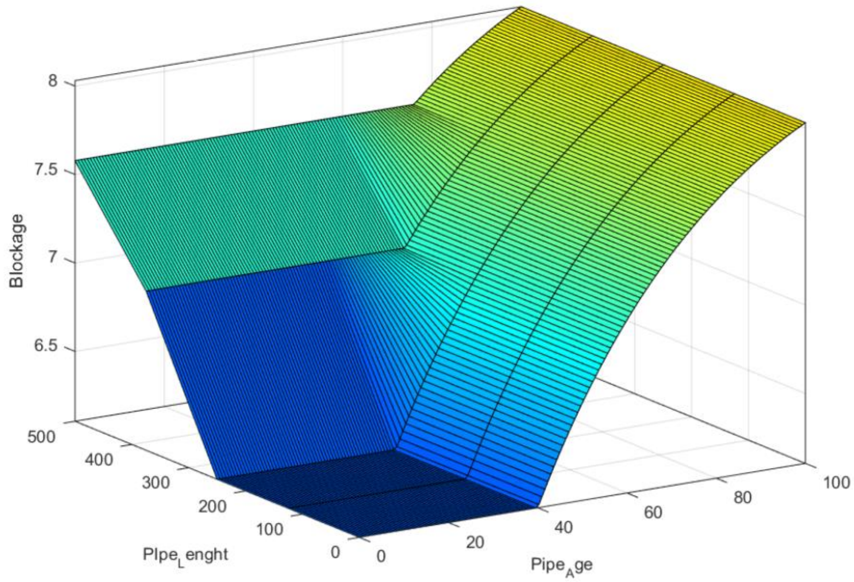


Figure 5-4. Example of Parameter Relationship

5.3 Updating Performance Score Ranges.

Condition indices provide the tool to measure the overall health of the wastewater pipes and correlate to maintenance requirements and the needed budget levels (Uzarski et al. 1997). Additionally, condition indices present utilities the ability to form a basis for measuring rates of deterioration and prediction of condition for wastewater pipes.

To effectively manage infrastructure assets, renewal activities such as maintenance, repair, and rehabilitation (MR&R) must be timed to satisfy the safe condition of pipes actively and to maximize the financial benefits to wastewater utilities. Currently, wastewater utilities rely on internal inspection results performed with CCTV cameras with instant follow-up measures taken to decide the maintenance strategies (Lee et al. 2005). This approach is a reactive approach which would not be effective or economical in the long run.

Condition grades are normally a scale of numerical values derived from defect severity and impact on service life. Condition assessment protocols examined in the literature and practice calculates the condition grades based on the defect coding and deduct values (WRc, PACP, CH2M Hill SCREAM). Typical condition grades for sewer pipes vary from 1 to 5: 0-1 for excellent, 2 for good, 3 for fair, 4 for poor, and 5 for collapsed or collapse imminent condition. Table 5-1 summarizes the point scale used in US practice today. There is a debate in international infrastructure asset management community including;

- How many discrete condition rating categories a system should use?
- Whether a low number or a high number is good/bad, etc?

5, 10 & 11 Category Condition Rating Systems are the most common, but other systems have been used, and each system has its pros & cons.

Table 5-1. 5 Point Condition Scale Used in Practice

Condition Grade	Linguistic Term	Explanation
1	Excellent	Excellent; minor defects
2	Good	Good; has not begun to deteriorate
3	Fair	Fair; moderate
4	Poor	Poor; will become Grade 5 in near future
5	Failed	Immediate attention needed

Utilities using 5-point scale argue that they are simple to apply in the field and that it is too difficult to identify the difference between assets in adjoining condition categories in a ten category system. However, a 5-point scale is too coarse for proactive infrastructure renewal decision support. In 5-point scale, if one is brand new and five is unserviceable there are only three other scores to choose. Most of the renewal decisions and determination of the level of service is made in middle range (good-fair-poor) by wastewater utilities. Higher granularity in the middle region of the condition index provides utilities the ability to prioritize their assets for renewal activities in a more effective manner. Figure 7-5 represents the differences between a 5 point and 10-point condition scale.

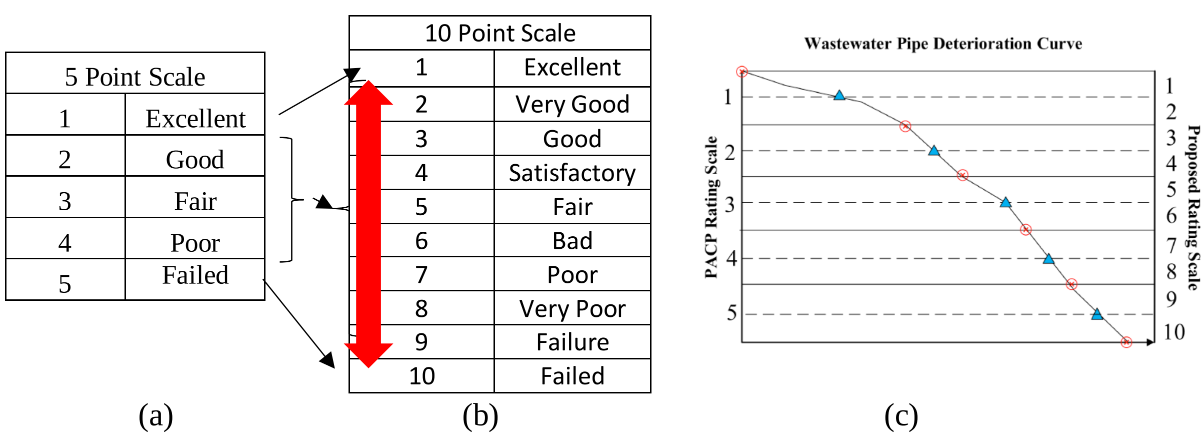


Figure 5-5. 5-Point Scale vs. Proposed 10-Point Scale for Performance Prediction

A 10-point grading system provides more granularity in the middle region of the condition scale (3-points vs. 8-points). This granularity promotes effective decision support and better prioritization of the assets for renewal activities. There are various infrastructure systems use 10-point scale systems. For example; a point scale from 0 to 9 is commonly used numerical condition rating for bridge components by the FHWA (2002).

There are some innovative wastewater utilities in Australia which are moving to the 10-point grading system. The Local Government Association of Queensland asset management program in Australia promotes an 11-point system. Table 5-2 summarizes the condition grading system used by this utility.

Table 5-2. Condition Scale from Practice (LGAM 2012)

Condition Grade	Explanation
0	A new asset or an asset recently rehabilitated back to new condition.
1	A near new asset with no visible signs of deterioration often moved to condition 1 based upon the time since construction rather than observed condition decline.
2	An asset in excellent overall condition. There would be only very slight condition decline but it would be obvious that the asset was no longer in new condition.
3	An asset in very good overall condition but with some early stages of deterioration evident, but the deterioration still minor in nature and causing no serviceability problems.
4	An asset in good overall condition but with some obvious deterioration evident, serviceability would be impaired very slightly.
5	An asset in fair overall condition deterioration in condition would be obvious and there would be some serviceability loss.
6	An asset in Fair to poor overall condition. The condition deterioration would be quite obvious. Asset serviceability would now be affected and maintenance cost would be rising.
7	An asset in poor overall condition deterioration would be quite severe and would be starting to limit the serviceability of the asset. Maintenance cost would be high
8	An asset in very poor overall condition with serviceability now being heavily impacted upon by the poor condition. Maintenance cost would be very high and the asset would at a point where it needed to be rehabilitated.
9	An asset in extremely poor condition with severe serviceability problems and needing rehabilitation immediately. Could also be a risk to remain in service
10	An asset that has failed is no longer serviceable and should not remain in service. There would be an extreme risk in leaving the asset in service

Cairns Regional Council in Australia uses another 11 point rating system, but in reverse order (LGAM 2012):

10 = Brand new

9 = Excellent Condition (90% of life remaining)

7 = Very Good Condition (70% of life remaining)

5 = Good Condition (50% of life remaining)

3 = Fair Condition (30% of life remaining)

1 = Poor Condition (10% of life remaining)

0 = Unserviceable (No useful life remaining)

5.3.1 Proposed Condition Grading Scale

Researchers used a 10 point (1=excellent, 10=failed) condition grading scale. The 10-point scale has the advantage of a direct relationship to remaining useful life and therefore performance prediction. This grading scale would be more appropriate for predictive modeling and proactive asset management compared to the 5-point grading scale currently used by the utilities US wide. Table 5-3 represents the new condition grading scale to be used for this research.

Table 5-3. New Condition Grading Scale

Condition Grade	Linguistic Representation	Explanation
1	Excellent	A near new asset with no visible signs of deterioration
2	Very Good	An asset in excellent overall condition. There would be only very slight condition decline but it would be obvious that the asset was no longer in new condition.
3	Good	An asset in very good overall condition but with some early stages of deterioration evident, but the deterioration still minor in nature and causing no serviceability problems.
4	Satisfactory	An asset in good overall condition but with some obvious deterioration evident, serviceability would be impaired very slightly.
5	Fair	An asset in fair overall condition deterioration in condition would be obvious and there would be some serviceability loss.
6	Bad	An asset in Fair to poor overall condition. The condition deterioration would be quite obvious. Asset serviceability would now be affected and maintenance cost would be rising.
7	Poor	An asset in poor overall condition deterioration would be quite severe and would be starting to limit the serviceability of the asset. Maintenance cost would be high
8	V. Poor	An asset in very poor overall condition with serviceability now being heavily impacted upon by the poor condition. Maintenance cost would be very high and the asset would at a point where it needed to be rehabilitated.
9	Failure	An asset in extremely poor condition with severe serviceability problems and needing rehabilitation immediately. Could also be a risk to remain in service
10	Failed	An asset that has failed is no longer serviceable and should not remain in service. There would

		be an extreme risk in leaving the asset in service

5.3.2 Comparison of 10 and 5 Point Grading Scales

A random selection of 142 pipe segments from a participating utility database from USEPA Region #3 was conducted to compare the 10 point grading scale and 5 point grading scale results. . Extracted data from utility records are summarized in the following table.

Table 5-4. Parameters Extracted from Utility Data

	Parameter	Lower Range	Higher Range	Unit
1	Pipe Age	0.4575	110.901	Years
2	Pipe Condition	0	5	PACP Index
3	Pipe Depth	0.5	27.5	Feet
4	Pipe Diameter	4	48	Inches
5	Pipe Length	0.96	898.133	Feet
6	Pipe Location	Field, not-road, Pavement, Road		Type
7	Pipe Slope	0.00128	95.573	Percent Grade
8	Surcharging Height	0	131.99	Feet
9	Lining Present?	Yes	No	Yes/No
10	Lining age	0	19	Years
11	Lining Material	EXP, PVC, HDPE		
12	Lining Type	CP, FI, FF		
13	Flow Depth/Diameter	0	26	%
14	Concrete Encasement	Yes	No	Yes/No
16	Ground Cover	Field, not-road, Pavement		Type
17	Pipe Shape	Circular		Type
18	Pipe Material	AC, CAS, CP, DIP, HDPE, PE, PP, PVC, RCP, VCP		Type
19	Pipe Function	Collector, trunk, interceptor		Type

5.3.2.1 Performance Index Piloting Results Discussion

After the model run with the dataset, the results between the PACP index and the model outputs are compared. It is important to note that the results from the index used by the utility were normalized by multiplying by 2 to have a comparable scale with the index outputs (10-grade scale). The results differences between the utility defect index and performance index output range between 0-4. There are also some pipe segments which do not have inspection records but significant defects included in the evaluation. Table 5-5 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table 5-5. Final Piloting Results

Total Number of Segments	Segments with 0 difference	Segments with 1 difference	Segments with 2 Difference	Segments with 3 Difference	Segments with 4 Difference	Segment with Unknown Condition
142	9	44	47	18	11	13
100%	6.34%	30.99%	33.10%	12.68%	7.75%	9.15%

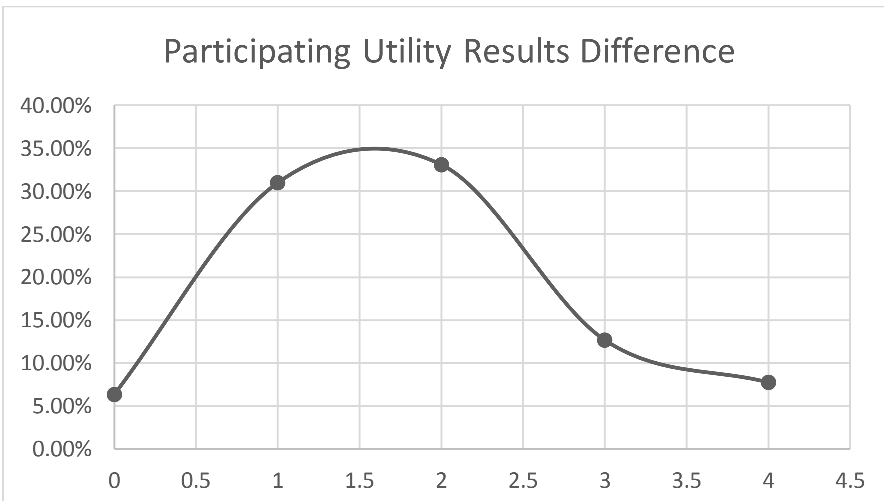


Figure 5-6. Utility #19 Results Difference

5.3.2.1.1 Results with 2 Difference

There are 29 (20.57%) pipe segments with two difference between the normalized PACP index and the performance index output. Pipe segments where are two difference are summarized in the following table.

Table 5-6. Segments with 2 Points Difference

Explanation	PIPEiD	Index	PACP Norm	Difference	Module
High flow depth	8236	6	4	2	Capacity

Moderate age under pavement	5688	6	4	2	Integrity
Moderate age under pavement	6750	6	4	2	Integrity
High length	6162	6	4	2	Blockage
DIP, High age, low slope, low flow depth	8782	3	1	2	Internal Corrosion
High length	6935	6	4	2	Blockage
PVC, low slope, low flow depth	8776	3	1	2	Surface Wear
VCP, High age, low slope, low flow depth	7859	6	4	2	Surface Wear
PVC, low slope, low flow depth	7845	6	4	2	Surface Wear
High length	6088	6	4	2	Blockage
Moderate age, Shallow Depth, under unpaved road	7317	6	4	2	Integrity
PE, moderate age, low flow depth, low slope	658	3	1	2	Surface Wear
PVC, moderate age, low flow depth, low slope	6751	6	4	2	Surface Wear
AC, high age, high slope	859	6	4	2	Surface Wear
DIP, high age, under unpaved road	588	3	1	2	Integrity
VCP, shallow, under unpaved road.	7807	3	1	2	Integrity
PVC, High length, low slope	1640	3	1	2	Blockage
VCP, moderate age, low slope	4776	3	1	2	Surface Wear
CIP, high age, low slope	8784	3	1	2	Surface Wear
VCP, high age, moderate depth, under traffic.	779	4	2	2	Integrity
CP, moderate age, under traffic	576	6	4	2	Integrity
CP, high age, low slope	6874	3	1	2	Surface Wear
VCP, high age, low slope	8791	3	1	2	Surface Wear
CP, moderate age, low slope	6569	6	4	2	Surface Wear
VCP, high length	7613	3	1	2	Blockage
VCP, high age, low slope	233	3	1	2	Surface Wear

5.3.2.1.2 Results with 3 Difference

There are 13 (9.22%) pipe segments with three difference between the normalized utility index and the performance index output. Pipe segments where results are three difference between the normalized utility index and the performance index output is summarized in the following table.

Table 5-7. Segments with 3 Points Difference

PIPEiD	Index	PACPNorm	Difference	Module
7511	4	1	3	Capacity
7512	4	1	3	Capacity
6244	4	1	3	Capacity
4030	4	1	3	Blockage
8774	5	2	3	Integrity
8777	7	4	3	Blockage
5230	4	1	3	Blockage
5230	4	1	3	Blockage
739	4	1	3	Blockage
739	4	1	3	Blockage
8780	7	4	3	Blockage
7795	4	1	3	Blockage
7795	4	1	3	Blockage

5.3.2.1.3 Case Studies (Segments with 3 Points Difference)

Table 5-8. PIPEiD: 7511

	Parameter	Value	Unit
	Network ID	16-3233.0 to 16-3230.0	ID
1	Pipe Age	7.19	Years
2	Pipe Condition (PACP)	0	Utility Index
3	Pipe Depth	10.16	Feet
4	Pipe Diameter	8	Inches
5	Pipe Length	9.66	Feet
6	Pipe Location	Not Road	Type
7	Pipe Slope	5.48	Percent Grade
8	Flow Depth/Diameter	26.04	%
9	Pipe Surcharging height	0	Percent
10	Ground Cover	Not Road	Type
11	Pipe Shape	Circular	Type
12	Pipe Material	VCP	Type

PACP Normalized vs. Performance Index: 1 (Excellent) vs. 4 (Satisfactory)

Module with maximum result: Capacity

Reason: High flow depth/ diameter ratio.

Discussion: This young aged vitrified clay pipe has a high flow depth/diameter ratio (26.04%). This high ratio indicates this pipe is prone to capacity issues.

Table 5-9. PIPEiD: 4030

	Parameter	Value	Unit
1	Network ID	05A-4080.0 to 05A-2066.0	ID
2	Pipe Age	6.48	Years
3	Pipe Condition (PACP)	0	Utility Index
4	Pipe Depth	15.785	Feet
5	Pipe Diameter	8	Inches
6	Pipe Length	481.381	Feet
7	Pipe Location	Pavement	Type
8	Pipe Slope	2.39	Percent Grade
9	Flow Depth/Diameter	2.08	%
10	Pipe Surcharging height	0	Percent
11	Ground Cover	Pavement	Type
12	Pipe Shape	Circular	Type
13	Pipe Material	V	Type

PACP Normalized vs. Performance Index: 1 (Excellent) vs. 4 (Satisfactory)

Module with maximum result: Blockage

Reason: High pipe length, low flow depth/diameter, moderate pipe slope.

Discussion: This young aged PVC pipe has a high length (481.381 feet) and low flow depth over diameter (2.08%) and moderate slope. These factors indicate pipe segment is prone to blockage issues.

Table 5-10. PIPEiD: 8774

	Parameter	Value	Unit
1	Network ID	20B-3211.5 to 20B-3211.0	ID
2	Pipe Age	110.55	Years
3	Pipe Condition (PACP)	1	Utility Index
4	Pipe Depth	6.135	Feet
5	Pipe Diameter	18	Inches
6	Pipe Length	183.04	Feet

7	Pipe Location	Pavement	Type
8	Pipe Slope	0.74	Percent Grade
9	Flow Depth/Diameter	2.08	%
10	Pipe Surcharging height	0	Percent
11	Ground Cover	Pavement	Type
12	Pipe Shape	Circular	Type
13	Pipe Material	Vitrified Clay	Type

PACP Normalized vs. Performance Index: 2 (Very Good) vs. 5 (Fair)

Module with maximum result: Integrity

Reason: High aged pipe under traffic load.

Discussion: This high aged (110.55 years) vitrified clay pipe with a shallow depth (6.135 feet) in under pavement. The location and depth of this pipe indicate that it is under high dynamic loads and would be prone to integrity issues.

5.3.2.1.4 Results with 4 Difference

There are 13 (9.22%) pipe segments with three difference between the normalized utility index and the performance index output. Pipe segments where results are three difference between the normalized utility index and the performance index output is summarized in table G19-11.

Table 5-11. Segments with 4 Points Difference

PIPEiD	Index	PACPNorm	Difference	Module
635	6	2	4	Integrity
8216	6	2	4	Integrity

5.3.2.1.5 Case Studies (Segments with 4 Points Difference)

Table 5-12. PIPEiD: 635

	Parameter	Value	Unit
1	Network ID	01B-3885.0 to 01B-3884.5	ID
2	Pipe Age	85.53	Years
3	Pipe Condition (PACP)	1	Utility Index

4	Pipe Depth	7.325	Feet
5	Pipe Diameter	8	Inches
6	Pipe Length	141.127	Feet
7	Pipe Location	Pavement	Type
8	Pipe Slope	13.68	Percent Grade
9	Flow Depth/Diameter	0.0833	%
10	Pipe Surcharging height	0	Percent
11	Ground Cover	Pavement	Type
12	Pipe Shape	Circular	Type
13	Pipe Material	PVC	Type

PACP (Normalized) vs. Performance Index: 2 (good) vs. 6 (poor)

Module with maximum result: Integrity

Reason: High aged PVC pipe under traffic with moderate depth.

Discussion: This PVC pipe segment is aged high (85.53) under pavement and moderate depth (7.325 ft.). With the assumption of this high aged pipe is under dynamic loading due to its location, it would be prone to integrity issues.

Table 5-13. PIPEiD: 8216

	Parameter	Value	Unit
1	Network ID	200-3064.0 to 200-3065.0	ID
2	Pipe Age	87.54	Years
3	Pipe Condition (PACP)	1	Utility Index
4	Pipe Depth	6.35	Feet
5	Pipe Diameter	8	Inches
6	Pipe Length	45.47	Feet
7	Pipe Location	Pavement	Type
8	Pipe Slope	39.39	Percent Grade
9	Flow Depth/Diameter	0	%
10	Pipe Surcharging height	0	Percent
11	Ground Cover	Pavement	Type
12	Pipe Shape	Circular	Type
13	Pipe Material	PVC	Type

PACP (Normalized) vs. Performance Index: 2 (good) vs. 6 (poor)

Module with maximum result: Integrity

Reason: High aged PVC pipe under traffic with moderate depth.

Discussion: This cast iron pipe segment is aged high (87.54) under pavement and moderate depth (6.35ft.). With the assumption of this high aged pipe is under dynamic loading due to its location, it would be prone to integrity issues.

5.4 Upgrading Gravity Performance Index

This performance index uses the recorded defects as well as time invariant parameters to estimate the performance of gravity wastewater pipes at a given time. Modules capturing failure modes and mechanisms as well as additional parameters will be incorporated in the performance index. Figure 5-6 summarizes the modules representing the failure modes and mechanism of gravity wastewater pipes. Additional parameters determined at phase 1 were added to the existing modules. Additional modules will also be added for the failure modes mechanisms omitted for the previous research was also be added. The performance index modules which was added to update the performance index is highlighted in Figure 5-6. Specifically, modules to estimate the lining and joint performance was added to the current performance index algorithm. Detailed list of modules and the parameters to be included in each module is provided in Appendix F.

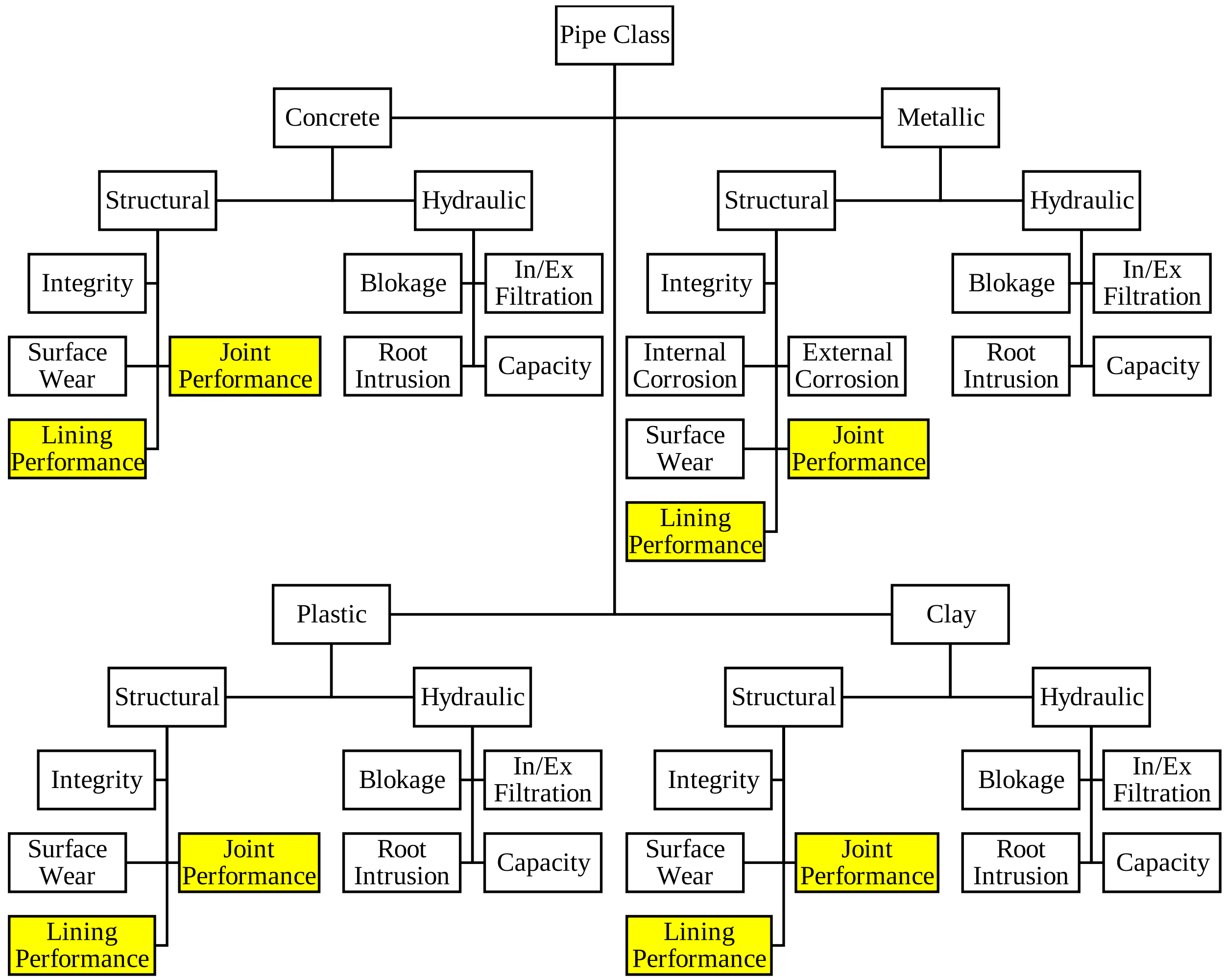


Figure 5-7. Deterioration Modules.

5.5 Develop Force Main Performance Index

Figure 5-7 summarizes the modules representing the force main performance index. The outputs of the fuzzy logic modules were divided into three categories: Integrity, Internal and External Performance Indices. Parameters, units, and ranges used for determining the pipeline performance by these modules are provided in Appendix F.

5.5.1 Integrity Performance Index

Pipe performance index is used to assess the performance of the pipe integrity. It is incorporating deterioration factors such as the remaining wall thickness, roughness index (Hazel-Williams C factor), tuberculation, pressure surges, pipe break history, and other factors such as the presence of cathodic protection, lining, coating, etc.

5.5.2 Internal Performance Index

Internal performance index is incorporating the internal factors affecting the pipeline performance such as the wastewater parameters, H2S concentrations, flow velocity, and distance to treatment plant. The modules for this index are; internal corrosion, surface wear, and blockage.

5.5.3 External Performance Index

External performance index is incorporating the external factors effecting the pipeline performance such as soil parameters, environmental factors (such as frost penetration, groundwater, other), external factors (traffic loads, root penetration, other). The modules for this index are; external corrosion, infiltration and inflow, root intrusion, and external load.

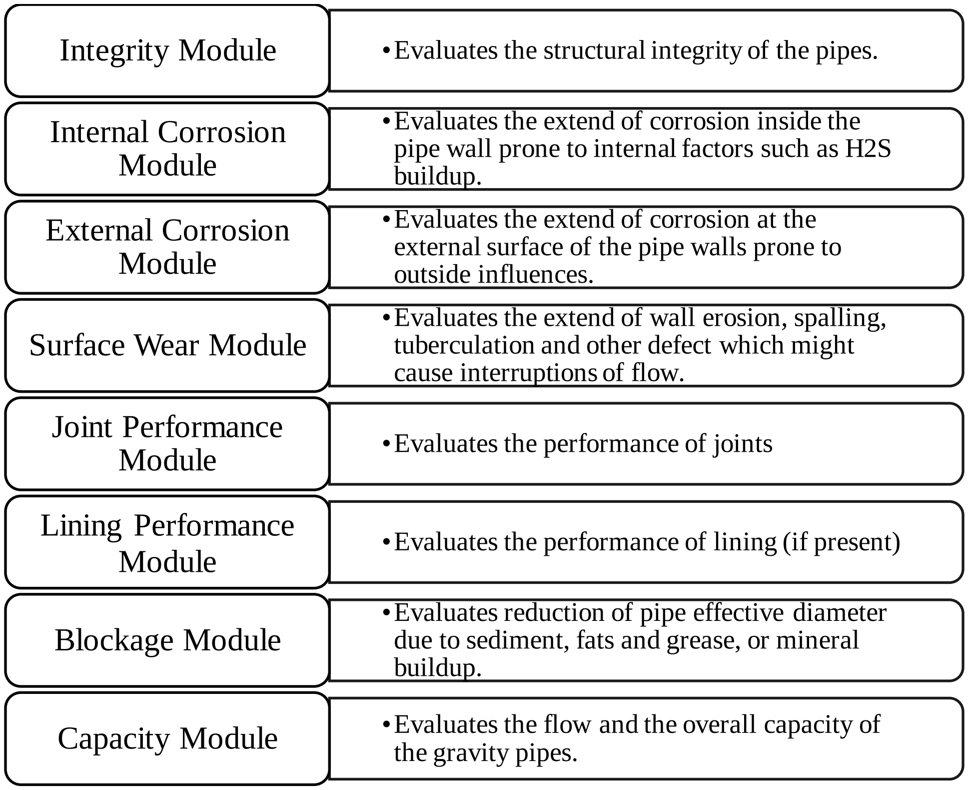


Figure 5-8. Fuzzy Logic Force Main Pipeline Performance Index Modules

5.6 Piloting Performance Indices

The piloting of the performance index has been carried with the data submitted by the participating utilities. It is important to acknowledge that the data submitted by these participating vary in detail and content. The research team followed a three-tiered approach for piloting with the data submitted by the participating utilities (summarized in figure 5-8):

- Preliminary Analysis: Comparing the generic data submitted by participating utilities with the index results.
- Detailed Analysis: Data previously collected by participating utilities which can be used as ground truth (wall thickness, flow values, etc.) compared with the index results.

- Piloting: Forensic studies include numerous soil, pipe, and water tests run at the selected sites by the participating utilities. The results of these forensic tests are used as ground truth as a comparison with the index.

The detail of the data and the reliability of the data increases as moved up from the preliminary analysis to piloting. Thus, the reliability of the tests increases. Figure 5-8 summarizes the different level of their data and their reliability for the piloting.

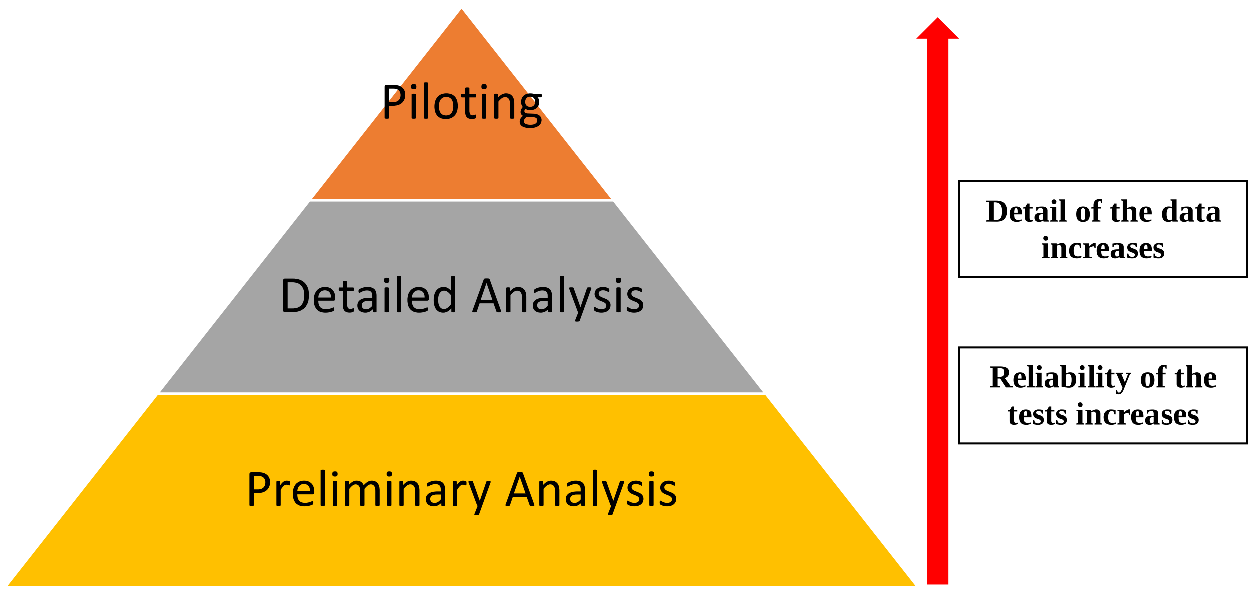


Figure 5-9. Three-Tiered Piloting Approach

5.6.1 Preliminary Analysis

Performance index verification was conducted with the preliminary analysis method. Initial data collected from the participating utilities was run with the performance index. The conveyance system level results were evaluated for the selection of specific pipe segments which are regions of interest for further analysis. The regions of interest were selected by comparing the results of the indices with standardized condition assessment indices(PACP, SCREAM, etc.). The segments which give the highest difference between the indices and standardized indices were selected. For networks with no defect indices, segments with the highest ratings were further evaluated. Figure 5-10 and figure 5-11 gives an example of a preliminary analysis. Appendix G contains the detailed discussions on the preliminary result analysis for all participating utilities.

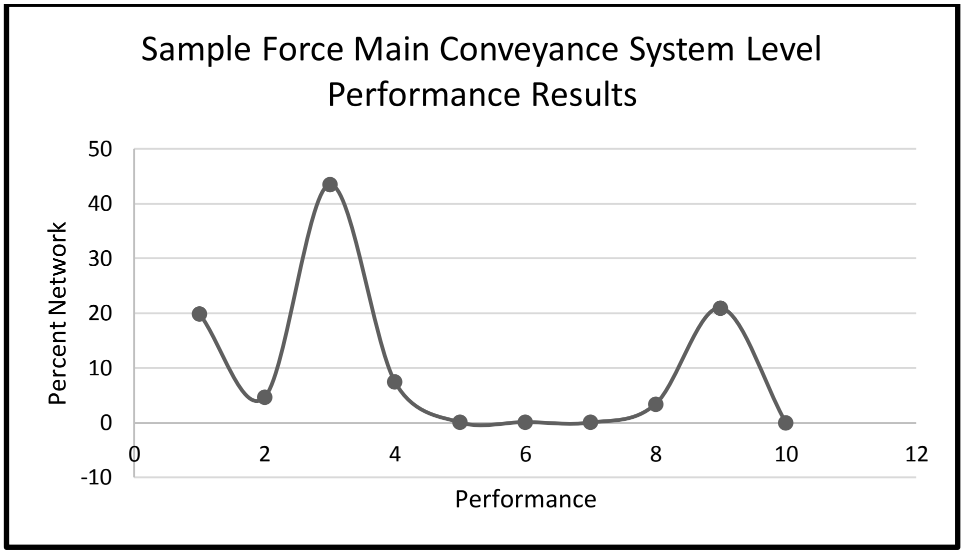


Figure 5-10. Piloting of the Performance Index

Number	Parameter	Value	Unit
1	PIPEiD	SF-031-4972	ID
2	Break <5 Years	No	Yes/No
3	Cathodic Protection	No	Yes/No
4	External Coating	NO	Yes/No
5	Flow Velocity	Unknown	Ft/Sec
6	Foreign Anode Distance	33	Ft.
7	Ground Cover	Gravel	Type
8	H2S	Unknown	ppm
9	Live Load	High	Type
10	Node Length	356.32	Feet
11	Operating Pressure	Unknown	PSI
12	Pipe Age	36	Years
13	Pipe Break	No	Yes/No
14	Pipe Depth	10	Feet
15	Pipe Diameter	8	Inch
16	Pipe Joint Type	Unknown	Type
17	Pipe Lining	No	Yes/No
18	Pipe Location	Railroad	Type
19	Pipe Material	Ductile Iron	Type
20	Pipe Renewal	No	Yes/No
21	Pipe Shape	Circular	Type
22	Pipe Slope	Unknown	%
23	Proximity to Trees	30	Feet
24	Stray Currents	Yes	Yes/No
25	Tidal Influences	No	Yes/No
26	Wall Thickness	Unknown	%
27	Gas Pockets	Unknown	Number
28	Factor of Safety Left	Unknown	Factor

Index Output = 9 (Failing)
Module = External Corrosion
Reason = Presence of Railroad and Possible stray current

Figure 5-11. Case Studies with Selected Sites.

5.6.2 <u>Field Testing</u>

The validation of the performance indices was conducted with comparing the index results with available forensic studies conducted by the participating utilities.

Field Study #1 – Sewer Metering Tests for Blockage Module (Gravity Pipes)

A participating utility from the USEPA Region #3 was conducting blockage performance analysis with sewer flow meters. There was a total of 2534 reading collected from their system indicating; 132 pipe blockages, 238 pipes in poor flow, 603 has fair flow, and 1561 has good flow. Figure 5-12 summarizes the geographical distribution of the sewer flow monitoring study.

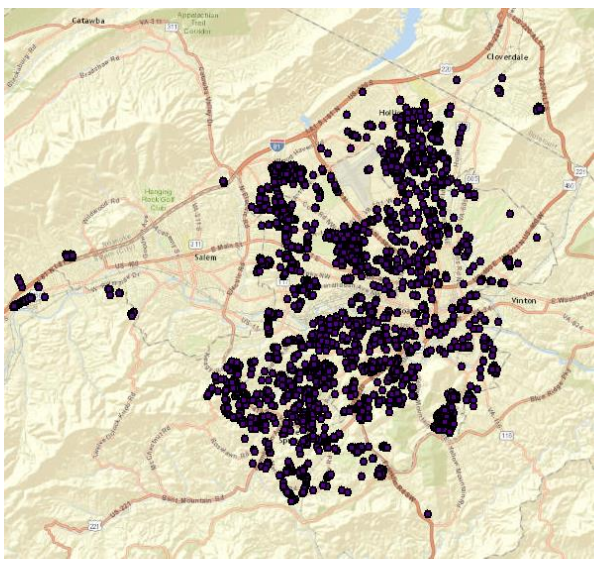


Figure 5-12. Sewer Flow Monitoring Study from Participating Utility.

The performance index was run for the same segments, and the results of the forensic study and the performance index were compared. For the normalization purposes, index results were combined for certain ranges as shown in Table 5-4 under column "Index Result Range" As summarized in Table 5-14, the accuracies are ranging between 69.70 % and 48.92% depending on the range evaluated.

Table 5-14. Blockage Forensic Study Results Comparison

No	Number in Performance State	Index Result Range	Number in Performance State	Performance Index Accuracy
blockage	132	10 to 9	92	69.70%
poor	238	8 to 6	131	55.04%
fair	603	4 to 5	295	48.92%
good	1561	1 to 3	1043	66.82%

Field Study #2– Remaining Wall Thickness on Ductile Iron Pipe

A participating utility at USEPA Region #3 has conducted remaining wall thickness tests with the Broadband Electromagnetic (BEM) testing method on 38 of their ductile iron force main segments. Table 5-5 summarizes the segments which these tests were conducted. The field measured remaining wall thickness values are normalized to a 1 to 10 grading scale for comparison with the performance index. The piloting results indicate 60.53% accuracy when index results are compared with the normalized wall thickness readings. Table 5-15 summarizes these results.

Table 5-15. Force Main Segments for Field Testing

Segment Number	Pipe Size (in)	Pipe Age	Nominal Wall Thickness (in)	Measured Min Wall Thickness (%)	Normalized Grade (1-10)	Index Results (1-10)	Difference	Difference?
1	4	12	0.39	0.87	1.30	2	0.70	No
2	8	12	0.39	0.9	1.00	2	1.00	Yes
3	8	12	0.39	0.91	0.90	2	1.10	Yes
4	4	18	0.39	0.79	2.10	2	0.10	No
5	6	23	0.39	0.8	2.00	2	0.00	No
6	6	23	0.39	0.86	1.40	2	0.60	No
7	8	12	0.472	0.73	2.70	2	0.70	No
8	8	12	0.472	0.79	2.10	2	0.10	No
9	8	14	0.472	0.78	2.20	2	0.20	No
10	8	18	0.472	0.84	1.60	2	0.40	No
11	8	23	0.472	0.77	2.30	2	0.30	No
12	16	48	0.472	0.51	4.90	3	1.90	Yes
13	10	10	0.5	0.7	3.00	1	2.00	Yes

14	10	19	0.5	0.67	3.30	2	1.30	Yes
15	10	19	0.5	0.64	3.60	2	1.60	Yes
16	10	19	0.5	0.91	0.90	2	1.10	Yes
17	10	22	0.5	0.83	1.70	2	0.30	No
18	10	22	0.5	0.82	1.80	2	0.20	No
19	10	26	0.5	0.7	3.00	3	0.00	No
20	10	39	0.5	0.79	2.10	3	0.90	No
21	12	51	0.5	0.83	1.70	3	1.30	Yes
22	10	56	0.5	0.77	2.30	3	0.70	No
23	10	56	0.5	0.81	1.90	3	1.10	Yes
24	10	56	0.5	0.84	1.60	3	1.40	Yes
25	6	9	0.551	0.75	2.50	1	1.50	Yes
26	6	11	0.551	0.64	3.60	1	2.60	Yes
27	16	15	0.551	0.77	2.30	2	0.30	No
28	8	18	0.551	0.71	2.90	2	0.90	No
29	20	25	0.551	0.86	1.40	3	1.60	Yes
30	20	25	0.551	0.77	2.30	3	0.70	No
31	16	39	0.551	0.72	2.80	3	0.20	No
32	36	8	0.72	0.99	1.00	1	0.00	No
33	36	8	0.72	0.94	0.60	1	0.40	No
34	36	22	0.72	1	1.00	2	1.00	Yes
35	36	22	0.72	0.83	1.70	2	0.30	No
36	18	46	0.72	0.49	5.10	3	2.10	Yes
37	16	48	0.72	0.67	3.30	3	0.30	No
38	16	48	0.72	0.69	3.10	3	0.10	No

Table 5-16. Field Test Results

Number of Matches Between Index and Ground Truth	Number of Non-Matches Between Index and Ground Truth	Total Number of Segments	Accuracy Percentage
23	15	38	60.53%

Field Study #3– Remaining Wall Thickness on Asbestos Cement Pipe

One on the participating utilities from US EPA Region #3 has conducted forensic studies to determine the remaining life of their force main AC pipes with remaining wall analysis. Various testing methods were evaluated but the phenolphthalein test was selected from available testing methods due to its cost efficiency and effectiveness. The forensic tests evaluated are summarized in figure 5-13.

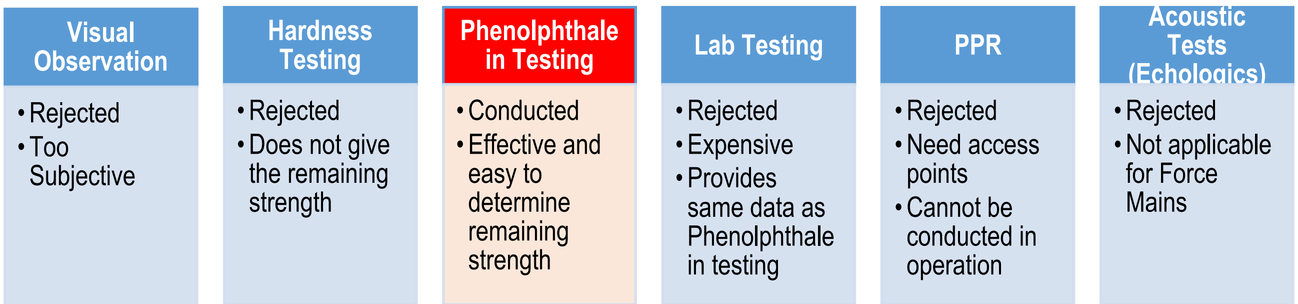


Figure 5-13. Forensic Studies Evaluated by the Participating Utility

The working principle of the Phenolphthalein Testing is that the free lime in new AC pipe will have a pH of 14 and will, therefore, show up as purple. When free lime leech out, the test will give a clear result. Core samples were collected among the evaluated pipe segment, and remaining wall analysis was conducted. According to the analysis, there was 65% of the wall thickness was remaining after the pipe was in service for 44 years. It was estimated that only six years of life was remaining in 2012. Figure 5-14 summarizes the analysis conducted.

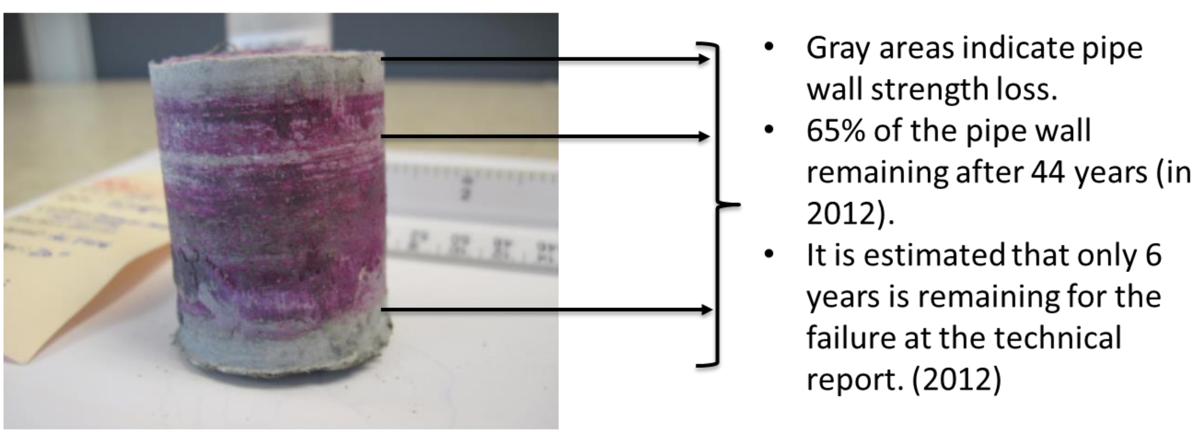


Figure 5-14. Test Results for the Phenolphthalein Test.

When the performance index for the force mains was run with the data provided by the participating utility, the index indicated that the pipe was in failing condition (performance state #9). Thus, when the ground truth from the forensic study and the index results were compared, there was agreement. Figure 5-15 summarizes this validation test results.

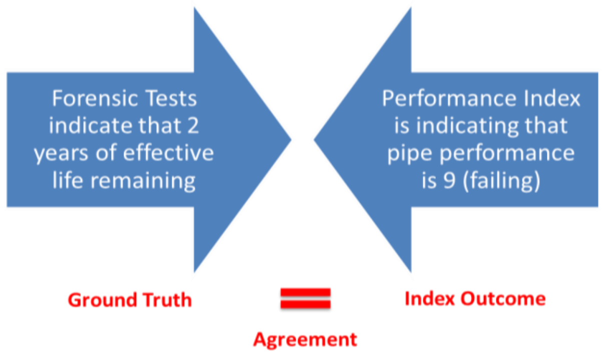


Figure 5-15. Validation Test Results with the Forensic Studies.

5.6.3 <u>Forensic Studies</u>

Detailed forensic studies were conducted by selecting specific sites of interest through perpetual data analysis and gathering more pertinent information through the process summarized in figure 5-16. This process was followed to identify six sites at a participating utility varying in age, location, material, environmental, and operating conditions.

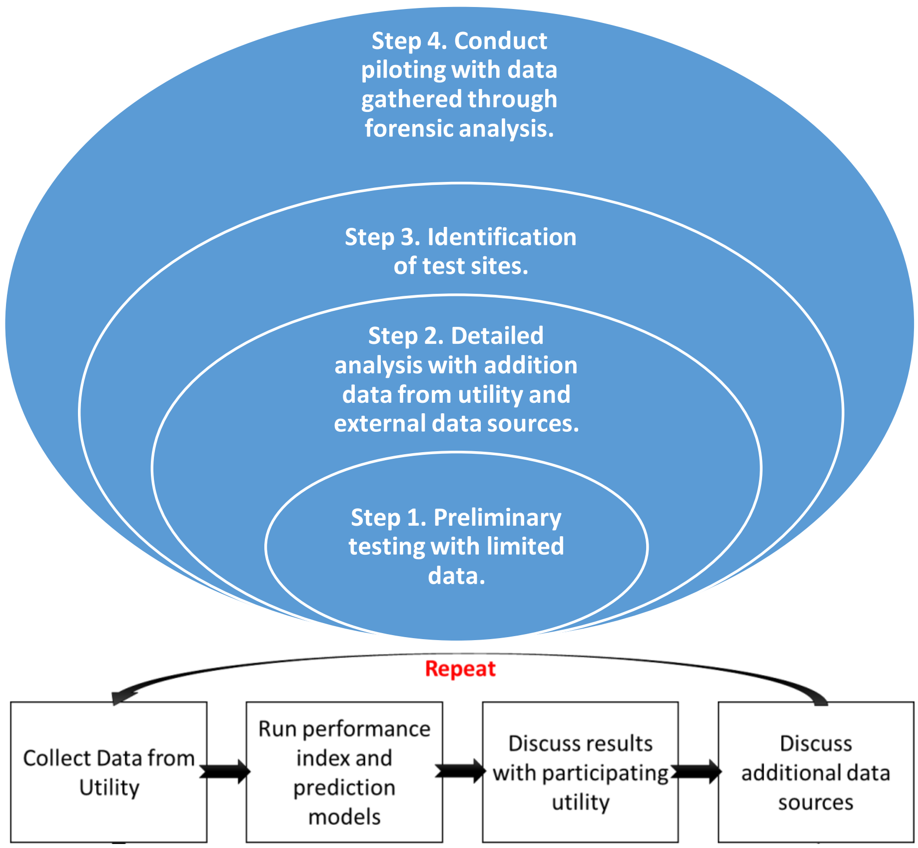


Figure 5-16. Site Selection Process through Testing

5.6.3.1 Selected Piloting Sites

After three perpetual runs, 21 parameters were collected from various sources. These parameters were used to run the index and determine regions of interest for the forensic tests and piloting. Table 5-17 summarizes the parameters used for site selection. Table 5-18 summarizes the six specific sites to run the forensic analysis and pilot the performance index.

Table 5-17. Collected Parameters for Site Selection.

No	Parameter	Data Source
1	PipeID	GIS
2	Line Number	GIS
3	Pipe Material	GIS
4	Pipe Diameter	GIS
5	Pipe Age	GIS

6	Line Number	GIS
7	Pipe Joint Type	GIS
8	Pipe Slope	GIS
9	Node Length	GIS
10	Pipe Lining	GIS
11	Failure Type	Failure Data
12	Cathodic Protection	GIS
13	Soil Corrosivity	USGS Database
14	Pipe Break Rate	Failure Data
15	Pipe Break <5 Years	Failure Data
16	Operating Pressure	Sahara Inspections
17	Flow Velocity	Sahara Inspections
18	Treatment Plant	GIS
19	Number of Gas Pockets	Sahara Inspections
20	Length of Gas Pockets	Sahara Inspections
21	Remaining factor of Safety	BEM Inspections

Table 5-18. Selected Piloting Sites and Characteristics

Site Number	Pipe Material	Pipe Vintage	Pipe Diameter (Inches)
1	Asbestos Cement	1968	14
2	Asbestos Cement	1968	16
3	Asbestos Cement	1968	20
4	Reinforced Concrete	1966	36
5	Ductile Iron	2002	30
6	Cast Iron	1949	1949

5.6.3.2 Forensic Tests for Piloting Sites

Numerous forensic tests are conducted at the piloting sites to compare the results with the performance index. Figure 5-17 summarized the forensic tests conducted at the piloting sites.

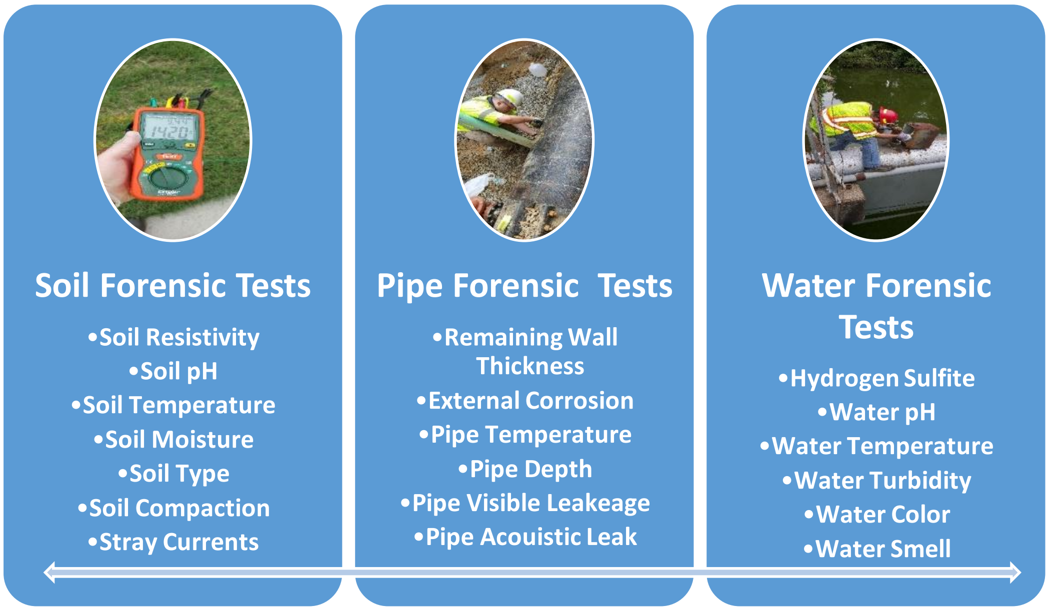


Figure 5-17. Forensic Tests for the Piloting Sites

5.6.3.3 Piloting Results

Site #1

First selected site was a 48-year-old, 14” diameter asbestos cement pipe. The phenolphthalein testing indicated 62% of the wall thickness was remaining. The results of the forensic analysis are summarized in Table 5-19. The results of the wall thickness tests and the performance index results using the data collected with the forensic analysis agree. Figure 5-18 summarizes this agreement between the ground truth and the index results.

Table 5-19. Site #1 Forensic Test Results

Parameter	Value
Pipe Material	AC
Pipe Diameter	14 inches
Pipe Age	48 years
Pipe Depth	5 ft
Pipe Location	Right of Way
Pipe Shape	Circular
Soil Type	Sandy Clay
Soil Moisture	Low
Stray Currents	No
Ground Water Table	Below Pipe
Ground Cover	Yard
H2S	30 ppm
Tidal Influences	Yes
FOG	No
Cathodic Protection	No
Thrust Restraint	No
Height of Bedding	3 ft.
Soil Resistivity	17881 ohm/cm
Wastewater pH	7.5
Soil pH	6.9

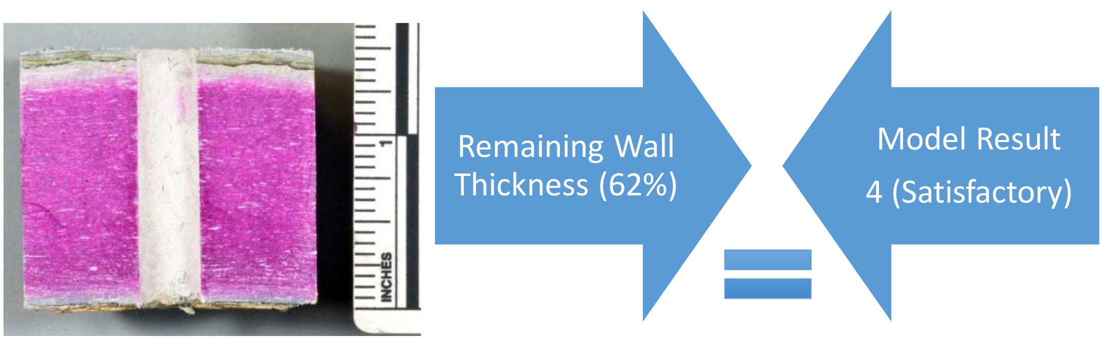


Figure 5-18. Piloting Site #1, Ground Truth and Index Results Agree.

Site #2

Second selected site was a 48-year-old, 16” diameter asbestos cement pipe. The phenolphthalein testing indicated 50% of the wall thickness was remaining. The results of the forensic analysis are summarized in Table 5-20. The results of the wall thickness tests and the performance index results using the data collected with the forensic analysis agree. Figure 5-19 summarizes this agreement between the ground truth and the index results.

Table 5-20. Site #2 Forensic Test Results

Parameter	Value
Pipe Material	AC
Pipe Diameter	16 inches
Pipe Age	48 years
Pipe Depth	3 ft
Pipe Location	ROW
Pipe Shape	Circular
Soil Type	Sandy Clay
Soil Moisture	Low
Stray Currents	No
Ground Water Table	Below Pipe
Ground Cover	Yard
H2S	15 ppm
Tidal Influences	No
FOG	No
Cathodic Protection	No
Thrust Restraint	No
Height of Bedding	3 ft.
Soil Resistivity	15, 076 ohm/cm
Wastewater pH	7.5
Soil pH	6.9

Figure 5-19. Piloting Site #2, Ground Truth and Index Results Agree.

Site #3

Third selected site was a 48-year-old, 20” diameter asbestos cement pipe. The phenolphthalein testing indicated 61% of the wall thickness was remaining. The results of the forensic analysis are summarized in Table 5-21. The results of the wall thickness tests and the performance index results using the data collected with the forensic analysis agree. Figure 5-20 summarizes this agreement between the ground truth and the index results.

Table 5-21. Site #3 Forensic Test Results

Parameter	Value
Pipe Material	AC
Pipe Diameter	20 inches
Pipe Age	48 years
Pipe Depth	3 ft.
Pipe Location	ROW
Pipe Shape	Circular
Soil Type	Sandy Clay
Soil Moisture	Low
Stray Currents	No
Ground Water Table	Below Pipe
Ground Cover	Yard
H2S	15 ppm
Tidal Influences	No
FOG	No
Cathodic Protection	No
Thrust Restraint	No
Height of Bedding	6 ft.
Soil Resistivity	15, 076 ohm/cm
Wastewater pH	7.5
Soil pH	6.9

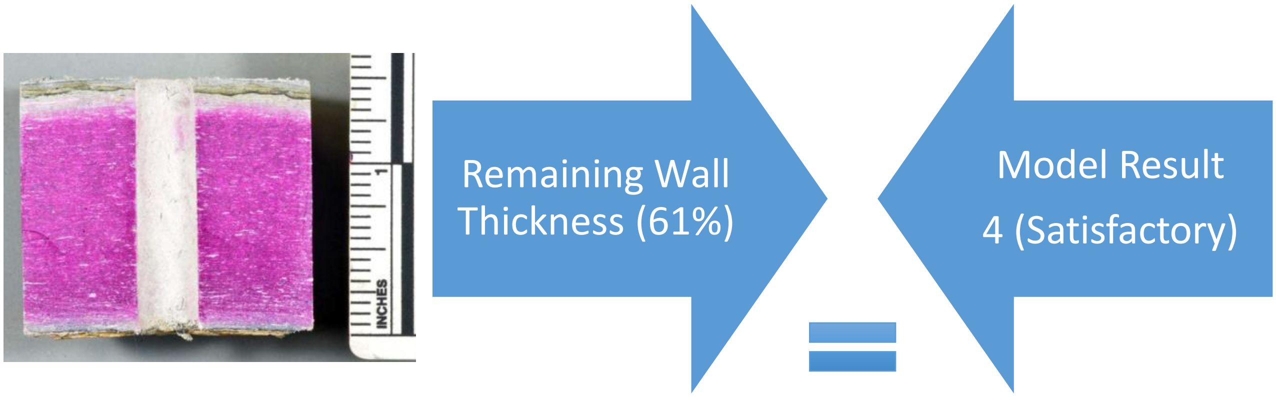


Figure 5-20. Piloting Site #3, Ground Truth and Index Results Agree.

Site #4

Fourth selected site was a 50-year-old, 36” diameter reinforced concrete pipe. There were no remaining wall thickness tests were conducted for this segment. The results of the forensic analysis are summarized in Table 5-22. Figure 5-21 summarizes this agreement between the ground truth and the index results.

Table 5-22. Site #4 Forensic Test Results

Parameter	Value
Pipe Material	RC
Pipe Diameter	36 inches
Pipe Age	50 years
Pipe Depth	15 ft.
Pipe Location	Highway
Pipe Shape	Circular
Soil Type	Sand
Soil Moisture	Very Low
Stray Currents	No
Ground Water Table	Below Pipe
Ground Cover	Ditch
H2S	30 ppm
Tidal Influences	No
FOG	No
Cathodic Protection	No

Thrust Restraint	No
Height of Bedding	0
Soil Resistivity	43,253 ohm/cm
Wastewater pH	7.5
Soil pH	7.1

Figure 5-21. Piloting Site #4, Ground Truth and Index Results.

Site #5

Fifth selected site was a 14-year-old, 30” diameter ductile iron pipe. Ultrasound tests were conducted to determine the remaining wall thickness. The results of the ultrasound tests are summarized in figure 5-22. The results of the forensic analysis are summarized in Table 5-23. The results of the wall thickness tests and the performance index results using the data collected with the forensic analysis agree. Figure 5-23 summarizes this agreement between the ground truth and the index results.

Table 5-23. Site #5 Forensic Test Results

Parameter	Value
Pipe Material	DI
Pipe Diameter	30 inches
Pipe Age	14 years
Pipe Depth	15 ft.
Pipe Location	ROW (Railroad)

Pipe Shape	Circular
Soil Type	Sandy Clay
Soil Moisture	Low
Stray Currents	No
Ground Water Table	With Pipe
Ground Cover	Ditch
H2S	10 ppm
Tidal Influences	No
FOG	No
Cathodic Protection	No
Thrust Restraint	No
Height of Bedding	0
Soil Resistivity	66,751 ohm/cm
Wastewater pH	7.5
Soil pH	7.1

Flow Direction →

10x10 Grid

	1	2	3	4	5	6	7	8
A	0.69	0.77	0.77	0.62	0.76	0.76	0.79	0.69
B	0.69	0.75	0.77	0.77	0.76	0.78	0.8	0.79
C	0.62	0.78	0.76	0.69	0.65	0.69	0.73	0.79
D	0.78	0.78	0.76	0.69	0.72	0.74	0.69	0.79
E	0.78	0.78	0.78	0.67	0.77	0.68	0.78	0.8
F	0.8	0.78	0.8	0.75	0.76	0.69	0.81	0.8

Figure 5-22. UT Tests Results

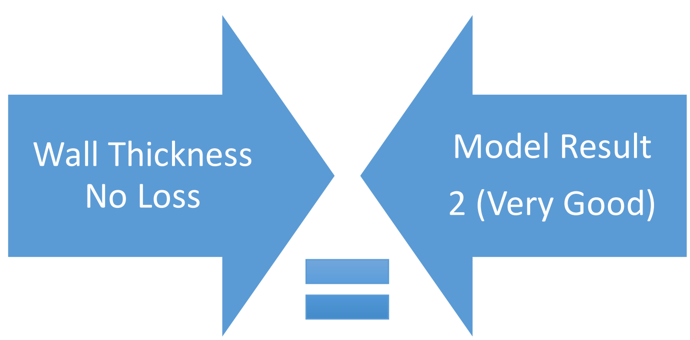


Figure 5-23. Piloting Site #5, Ground Truth and Index Results.

Site #6

Sixth selected site was a 67-year-old, 18" diameter cast iron pipe. This specific segment was failed a year before analysis and was replaced. The results of the forensic analysis are summarized in Table 5-24. Figure 5-24 summarizes this agreement between the ground truth and the index results.

Table 5-24. Site #6 Forensic Test Results

Parameter	Value
Pipe Material	RC
Pipe Diameter	36 inches
Pipe Age	50 years
Pipe Depth	15 ft.
Pipe Location	Highway
Pipe Shape	Circular
Soil Type	Sand
Soil Moisture	Very Low
Stray Currents	No
Ground Water Table	Below Pipe
Ground Cover	Ditch
H2S	30 ppm
Tidal Influences	No
FOG	No
Cathodic Protection	No
Thrust Restraint	No
Height of Bedding	0
Soil Resistivity	3,253 ohm/cm
Wastewater pH	7.5
Soil pH	7.1

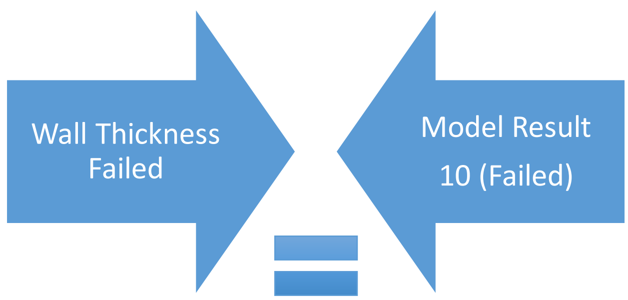


Figure 5-24. Piloting Site #6, Ground Truth and Index Results.

5.7 Conclusions from Phase 2

The new 10-point scale to assess the performance of the pipes is a new approach which was investigated for the first task in developing the performance indices. Although the practitioners in U.S. are currently using a 5-point scale, the extended indices are in use by some of the utilities internationally. This 10-point scale provides better granularity in the mid-range (good to very poor) of the scale which provides better decision support for the repair and replacement decision are made for assets in this region. Moreover, this granularity provides better accuracy for the prediction models developed for the 3rd phase of this research.

Developed performance indices are comprehensive rating systems which evaluate the performance of gravity and force main wastewater pipes. The methodology considers defects identified from inspections, such as cracks, holes, and corrosions and other parameters affecting wastewater pipe condition and performance. The indices consist of parameters from wastewater pipe systems including physical/structural, operational/functional, environmental and others. Moreover, the mathematical technique used in the development of these indices capture the coupled effects of these parameters in contrast with the weighted indices in practice and literature which captures a linear relation between these parameters. The incorporation of these performance parameters and capturing the coupled effects allow better modeling of the deterioration process, and in return improves the accuracy of the model developed.

6 Phase 3 – Performance Prediction Models

6.1 Overview

To develop deterioration models, the Markov chain is one of the modeling methods most utilized in predicting infrastructure deterioration. For a set of states, $S = \{s_0, s_1, s_2, \ldots s_t\}$, the deterioration process starts in one of these states and moves through subsequent states until it reaches a state whereby no further deterioration is possible. If the chain is currently in state s_i, it then moves to state s_j at the next step with a probability denoted by p_{ij}. The Markovian property establishes that, for the conditional distribution of any future s_{t+1}, for given past states s_1, s_2… and the current state s_t, the subject is independent of the previous states, and depends only on the present state (Ross 1997). Equation 6-1 expresses it as;

$$\mathbf{P\{s_{t+1}, = j|S_t = i, S_{t-1} = i_{t-1} \ldots S_2 = i_2, S_1 = i_1\} = P\{S_{t-1} = j|S_t = i\} = p_{ij}} \quad \text{(Equation 6-1)}$$

The probabilities p_{ij} are called the transition probabilities and are therefore nonnegative. The process can remain in the same state, and this occurs with probability p_{ii}.. Then;

$$\mathbf{P_{ij} \geq 0,\ i,\ j \geq 0,\ \sum P_{ij} = 1,\ i=1,2\ldots} \quad \text{(Equation 6-2)}$$

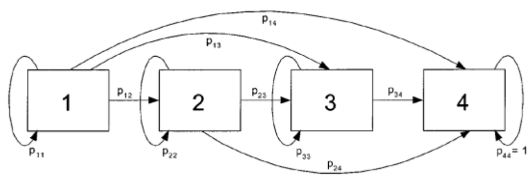
If either the value of the initial state or the present state is known, we can obtain the future state value by multiplying the present or initial state vector by the transition matrix. At any time t, the value s_t is computed by multiplying the initial vector s_0 by the *t*th power of the transition matrix P.

$$\mathbf{S_t = S_0 P^t} \quad \text{(Equation 6-3)}$$

Sewer's estimated rating condition at any age is obtained by multiplying the condition state vector by a condition rating vector, as shown in equation 6-4.

$$\mathbf{C_t = S_t R'} \quad \text{(Equation 6-4)}$$

Where C_t is the estimated condition rating at time t, S_t is the condition state vector at time t, and R' is the transpose of the condition rating vector R. In the deterioration model, the initial state, and the rating vector are often known; only transition matrix P in equation 6-3 has to be determined to get the system's expected future condition. Figure 6-1 represents an example 5 state transition probability matrix. Figure 6-2 is an example output from MATLAB script.



$$\mathbf{P} = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ 0 & P_{22} & P_{23} & P_{24} & P_{25} \\ 0 & 0 & P_{33} & P_{34} & P_{35} \\ 0 & 0 & 0 & P_{44} & P_{45} \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 6-1. Example Transition Probably Matrix for 5 States

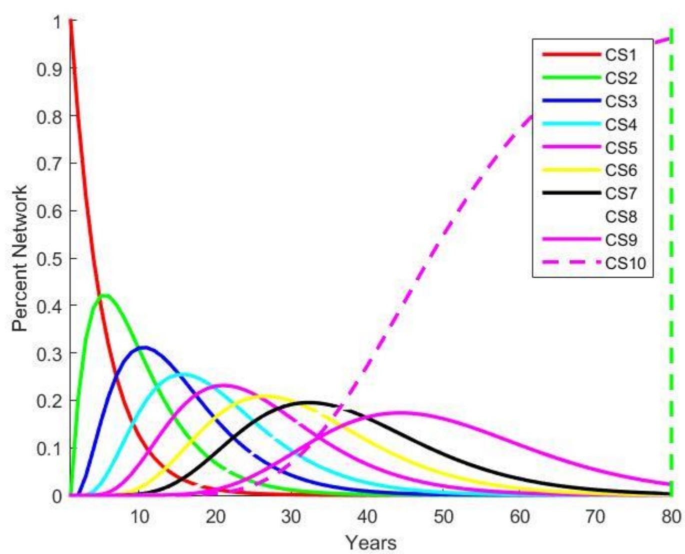


Figure 6-2. Example Results from MATLAB Script (Artificial Data)

6.2 Calibrating Transition Probability Matrices

The calibration of Markov model is the task of applying the selected calibrating technique on a calibration dataset to estimate the model parameters or the transition probability. There are several methods for deriving a transition probability matrix. Two methods are applied when calculating transition probabilities: state dependent and time dependent. The state-based models predict long-term performance using transition probabilities obtained from the difference between the two performance states (PSs) at a given discrete time interval. Markov-chain models are the most common example of state-based models (Morcous and Akhnoukh 2006). The key prerequisite for Markov-chain models is to generate accurate and reliable transition probabilities for infrastructure facilities to predict future condition ratings. Numerous methods were discussed in the literature to calibrate transition probability matrices, including the expected value method (Jiang et al. 1988), Poisson regression (Madanat and Ibrahim 1995), and ordered probit model (Madanat et al. 1995, 1997). The approaches discussed in literature suffer limitations such as ignorance of the hidden nature of the deterioration, and failure to account for maintenance issues (Madanat et al. 1995; DeStefano and Grivas 1998). Furthermore, a classification process is usually required by these models to achieve accurate deterioration models.

The time-dependent models employ a probability density function of time, referring to the state duration time required for each pipe element to deteriorate from an initial PS to its next lower state. Time-dependent models are also called duration models; they were developed to estimate infrastructure deterioration. For example, DeStefano and Grivas (1998) presented a time-based deterioration model for bridge decks in which the Kaplan and Meier (K-M) method was used to estimate the nonparametric distribution functions of the duration time. Prozzi and Madanat (2000) applied parametric models to estimate time to failure in the pavement deterioration process. Mauch and Madanat (2001) used semiparametric hazard rate modeling to develop time-dependent models for a bridge deck. The main limitation in time-dependent models is that they require uncensored data throughout the life of the asset. In other words a constant and frequent inspection of condition ratings are needed over a long observation period for these deterioration models to be developed.

6.3 Development of Prediction Models

In order to mitigate the previously mentioned shortcomings, this research presents an integrated Markov-based method incorporating both state-dependent and time-dependent models, which is more effective as compared with the models utilizing only one of the aforementioned methods. A selection process is embedded in the integrated method to automatically select a suitable prediction approach (either state-dependent or time-dependent) for a given dataset. Figure 6-3 summarizes the prediction model types.

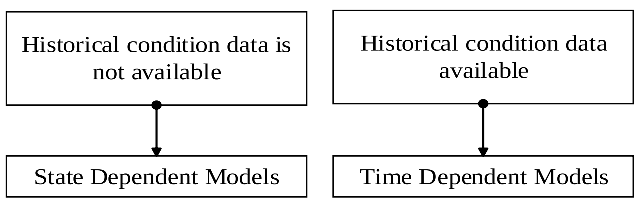


Figure 6-3. Types of Prediction Models and Data Selection Process

Developed state-dependent models will be calibrated with available time-dependent models to provide long-term performance predictions. The following list and figure 6-4 summarizes the prediction model development process. Following sections provide details and examples from the current data analysis process from collected utility data.

- Task 3.1 Records Selection Process – Select eligible records to be evaluated by time or state dependent models.
- Task 3.2 Pipe Class Selection Process – Separate pipe records according to similar deterioration patterns.

- Task 3.3 Develop State Based Models
- Task 3.4 Develop Time Based Models

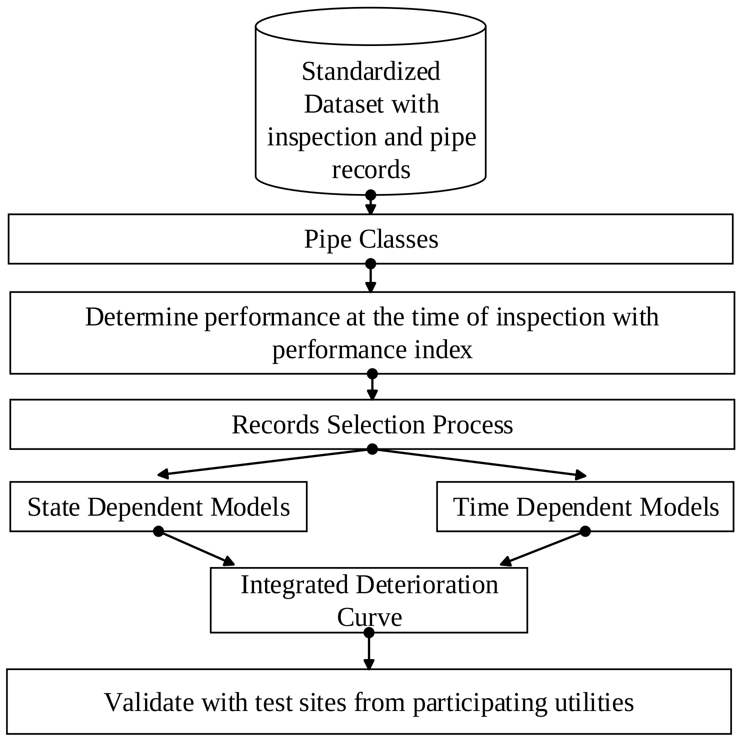


Figure 6-4. Overall Research Flow Diagram Summary

6.4 Records Selection Process

Pipe records were investigated to be used in the time-dependent or state-dependent models. Figure 6-5 summarizes the records selection process.

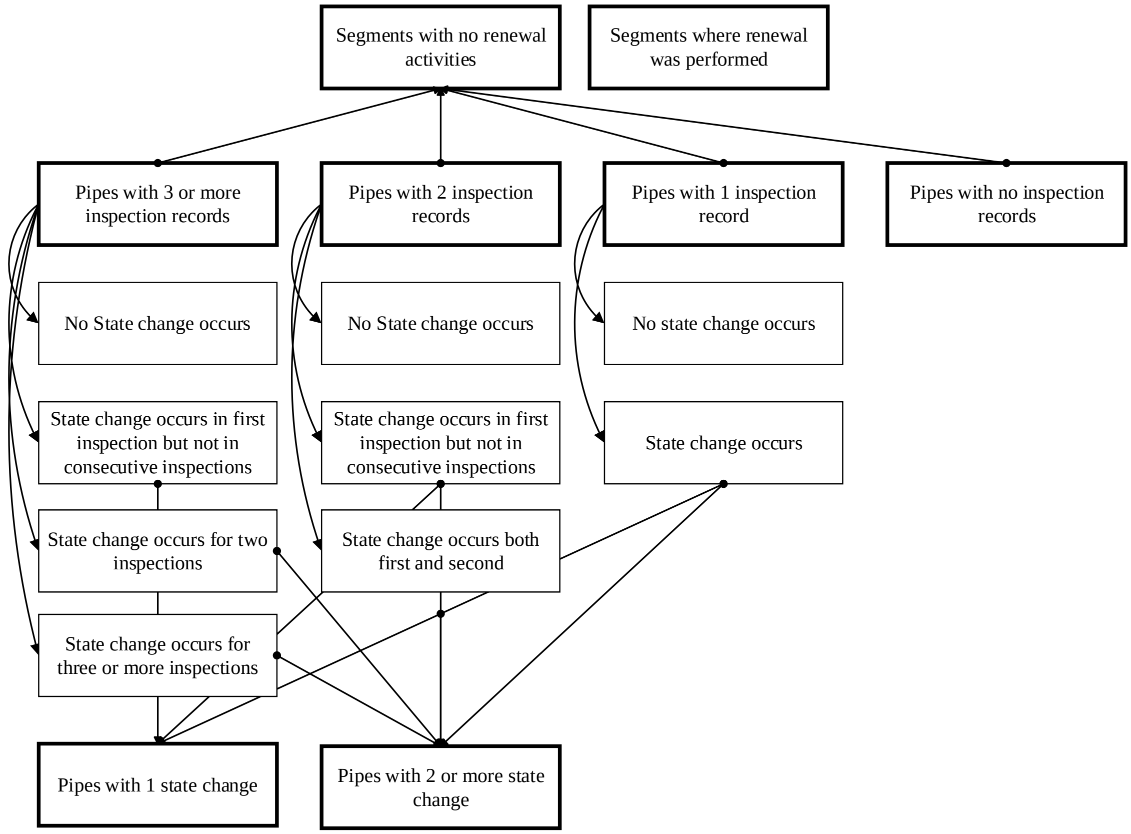


Figure 6-5. Records Selection Process

6.5 Pipe Class Selection Process

Pipe records are divided into pipe classifications according to (Please refer to Appendix H for detailed pipe class information);

- Sewer Shed – Varies by utility
- Sewer Type – Gravity, Force Main
- Pipe Type – Lateral, Main, Trunk, Interceptor, Outfall
- Pipe Material – Various (19 Classes total)
- Construction Era – Varies by material
- Size – Varies by material
- Shape – Varies by material

6.6 Develop State Dependent Models

State-dependent models determine probability of a pipe segment being in a certain performance state at a given time. This type of calibration technique is suitable for scenarios where time dependent data is not available. Considering the limitations with the historical data availability for the sewer pipes, development of the state-dependent models is required to address this limitation. The research team developed several state dependent prediction models to evaluate the better fitting model among them for the data from participating utilities.

6.6.1 State Dependent Model #1

The calibration technique called Bayesian Markov Chain Monte Carlo (MCMC) simulation was used in this study since it was the proven technique that can be used with snapshot data currently available for stormwater pipes (Micevski 2002 et al., Tran 2007).

The Metropolis-Hastings Algorithm (MHA), a member of the MCMC simulation (Gelman et al. 1995), was chosen to perform sampling from the posterior distribution. MCMC simulation allows sampling from most types of posterior distributions with reliable results and easy coding for computer simulations. The basic idea behind MCMC simulation is the use of a Markov chain whose stationary probabilities are identical to the target posterior distribution (Ross 1997). This Markov chain is then run a large number of times until it converges to the stationary probability. After discarding the warm up runs, the remaining values can be used as the sampling data for the posterior distribution.

The Bayesian theorem has been widely used to estimate random variables via their conditional distribution in many engineering problems (Brooks 1998). It is formulated in Equation 6-5:

$$P(\theta|D) = \frac{P(D|\theta) \times P(\theta)}{\int P(D|\theta)P(\theta)d\theta} \qquad \text{(Equation 6-5)}$$

where: θ = random variable whose value to be estimated

D = random variable whose value or probability distribution is known

P(θ|D) = posterior distribution of θ given D which relates to θ via a model

$P(D|\theta)$ = likelihood to observe D

$P(\theta)$ = is prior probability of θ

$\int P(D \mid \theta)P(\theta)d\theta$ = normalizing factor and always resulted in a value

This Bayesian approach allows estimating true values of θ from both prior knowledge about θ and current knowledge obtained from data, depending on which ones are closer to the true values. For estimating the transition probabilities, the Bayesian approach can be used to estimate P_{ij} based on the observed pipe condition and prior knowledge of P_{ij}. This was done via sampling a large number of P_{ij} from its posterior distribution as shown in Equation 6-6.

$$\pi (P \mid Y, M) \approx L(Y \mid P, M) \times \pi_0 (P) \qquad \text{(Equation 6-6)}$$

Where: $\pi (P \mid Y)$ = posterior distribution of P_{ij}

$L(Y \mid P, M)$ = likelihood to observe a set of Y pipe conditions

$\pi_0(P)$ = is the prior distribution of P_{ij}

The prior distribution π_0 (P) was arbitrarily chosen as a uniform distribution in interval [0, 1], since there was no available knowledge about the proper distribution of P_{ij}. As a result, the posterior distribution π (P | Y) is proportional to the likelihood function L(Y | P, M) which was determined. From the joint probability theory, the likelihood to observe Y can be expressed in Equation 6-7, which was then transformed into logarithm format as in Equation 6-8.

$$L(Y|P,M) = \prod_{t=1}^{T} \prod_{i=1}^{10} (C_i^t)^N \qquad \text{(Equation 6-7)}$$

$$\log[L(Y|P,M)] = \prod_{t=1}^{T} \prod_{i=1}^{10} N_i^t \log(C_i^t) \qquad \text{(Equation 6-8)}$$

where: t = pipe age in years

T = largest age found in the dataset

N_i^t = number of pipes in condition *i* at year *t*

C_i^t = probability in condition *i* at year *t*

Figure 6-6 gives an example of strategic level time-dependent data and model for a participating utility from USEPA Region #3 at sewer shed #1 PVC pipe class #3 (collection, less than 18" diameter, construction era 1998 to present).

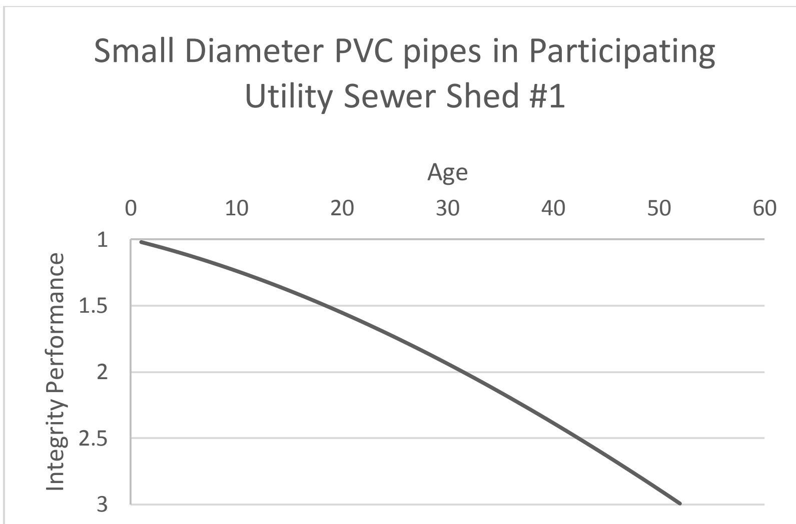


Figure 6-6. State Dependent Deterioration Model Example.

6.6.2 State Dependent Model #2

The calibration technique called logistic regression was used in second state-dependent deterioration model. Logistic regression has been extensively used in medical applications, especially in dealing with dose response tests. In such instances, the dependent variable is a dichotomy, i.e., it can take only two classes, and the independent variables are of any type. This approach aims at predicting the outcome of an event by providing the likelihood of success and failure. An application of the binary logistic regression for a sewer deterioration model can be found in Koo and Ariaratnam (2006) as well as Salman and Salem (2010).

In this research, the Ordinal Logit model for the multinomial responses approach was applied to estimate the transition probabilities of the sewer system. The developed model intends to establish the relationship between a response variable (performance score) and a set of explanatory variables (age, diameter, length, slope, material, etc.). The structure of the ordered logit model also known as Proportional Odds Model for a specific sewer segment denoted i can be expressed as a linear function shown in Equation 6-9 as;

$$\mathbf{y}^* = \mathbf{x_i}\boldsymbol{\beta} + \boldsymbol{\varepsilon}_\mathbf{i} \qquad \text{(Equation 6-9)}$$

Where; y_i^* = continuous and unobservable dependent variable,

β = vector of regression coefficients to be estimated,

x_i = row vector of independent variables, and

ε_i = random disturbance term, which here has a logistic distribution.

The model is interpreted regarding of the latent variable y_i^* (performance score). The infrastructure deterioration process is assumed to be continuous. Therefore, the underlying continuous random variable can be used to express such deterioration. Ordered Probit and Ordered Logit models are specifically designed to account for the latent nature of the deterioration process.

Given that y_i^* is unobservable, Equation 6-9 cannot be directly determined; hence the need for a measurement equation that maps the latent variable y_i^* to y. This equation (6-10), expressed as;

$$\mathbf{y_i} = \sum_{\mathbf{k=1}}^{\mathbf{k}} \boldsymbol{\beta}_\mathbf{k}\mathbf{X_{ki}} = \mathbf{F}(\mathbf{y_i^*}) \qquad \text{(Equation 6-10)}$$

y_i is therefore linked to y_i^* by providing categories responses as expressed by equation 6-11 as follows:

$y_i = 1$ → Excellent if $y_i^* \leq \theta_1$

$y_i = 2$ → Very Good if $\theta_1 < y_i^* \leq \theta_2$

$y_i = 3$ → Good if $\theta_2 < y_i^* \leq \theta_3$

$y_i = 4$ → Satisfactory if $\theta_3 < y_i^* \leq \theta_4$

$y_i = 5$ → Fair if $\theta_4 < y_i^* \leq \theta_5$

$y_i = 6$ → Bad if $\theta_5 < y_i^* \leq \theta_6$

$y_i = 7$ → Poor if $\theta_6 < y_i^* \leq \theta_7$

$y_i = 8$ → Very Poor if $\theta_7 < y_i^* \leq \theta_8$

$y_i = 9$ → Failure if $\theta_8 < y_i^* \leq \theta_9$

$y_i = 10$ → Failed if $\boldsymbol{\theta_9} < \boldsymbol{y_i^*}$ (Equation 6-11)

Where: θ_n= threshold to be estimated.

The probability of observing value n in y for given values of x can be computed as shown by equation 6-12 as follows:

$$\mathbf{P(y_i = n|x_i) = P(\theta_n - x_i\beta \leq \varepsilon_i < \theta_{n+1} - x_i\beta|x_i} \quad \text{(Equation 6-12)}$$

The probability to see ε_i falling between two values is the difference between the cumulative distribution function (CDF) considered at these values (Equation 8-13).

$$\mathrm{P(y_i = n|x_i) = P(\varepsilon_i < \theta_{n+1} - x_i\beta|x_i) - P(\varepsilon_i < \theta_n - x_i\beta|x_i) = F(\theta_{n+1} - x_i\beta) - F(\theta_n - x_i\beta)}$$

(Equation 6-13)

The maximum likelihood procedure is used to estimate the value of the parameter vector β and thresholds θ_n simultaneously. The log-likelihood function is given in the form;

$$\boldsymbol{Ln\ L(\beta, \theta|y, x) = \sum_{i=0}^{n} \sum_{y_{i=0}} \ln[F(\theta_{n+1} - x_i\beta) - F(\theta_n - x_i\beta)} \quad \text{(Equation 6-14)}$$

Based on the parameters obtained through Equation 8-14, the transition probabilities for each conduit segment can be calculated. Computation is performed for nine incremental degradation models. Condition state 1 requires nine increments: 1→1; 1→2; 1→3; 1→4; 1→5; 1→6; 1→7;

1→8; 1→9; 1→10; assuming that the deterioration is irreversible and nothing is done to improve the overall conduit conditions. The probabilities are obtained as follows (Equation 6-15):

$$P(Y_{ik} = 1|X_{ki}) = F(\theta_{i1} - \beta x)$$
$$P(Y_{ik} = 2|X_{ki}) = F(\theta_{i2} - \beta x) - F(\theta_{i1} - \beta x)$$
$$P(Y_{ik} = 3|X_{ki}) = F(\theta_{i3} - \beta x) - F(\theta_{i2} - \beta x)$$
$$P(Y_{ik} = 4|X_{ki}) = F(\theta_{i4} - \beta x) - F(\theta_{i3} - \beta x)$$
$$P(Y_{ik} = 5|X_{ki}) = F(\theta_{i5} - \beta x) - F(\theta_{i4} - \beta x)$$
$$P(Y_{ik} = 6|X_{ki}) = F(\theta_{i6} - \beta x) - F(\theta_{i5} - \beta x)$$
$$P(Y_{ik} = 7|X_{ki}) = F(\theta_{i7} - \beta x) - F(\theta_{i6} - \beta x)$$
$$P(Y_{ik} = 8|X_{ki}) = F(\theta_{i8} - \beta x) - F(\theta_{i7} - \beta x)$$
$$P(Y_{ik} = 9|X_{ki}) = F(\theta_{i9} - \beta x) - F(\theta_{i8} - \beta x)$$
$$\boldsymbol{P(Y_{ik} = 10|X_{ki}) = 1 - F(\theta_{i9} - \beta x)} \qquad \text{(Equation 6-15)}$$

Where $P(Y_{ik} = i|X_{ki})$ is the transition probability from condition state s_i to state s_j for a given conduit. Working principle of the ordinal logit model is summarized in figure 6-7.

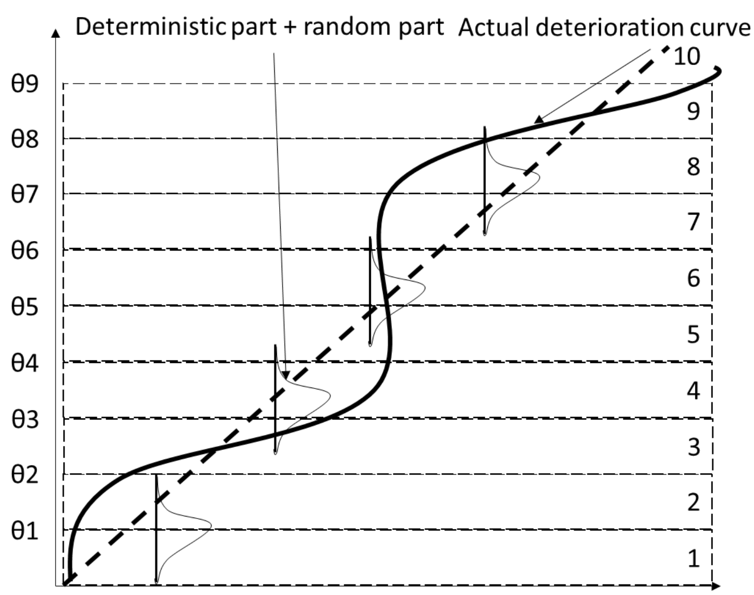


Figure 6-7. Illustration of the Ordered Logit Model

Different estimation models are created for each performance module. Example equation for integrity module is shown in Equation 6-16.

$$Y^*(\text{Integrity Score}) = \alpha_o + \beta_1 \text{ x Location} + \beta_2 \text{ x Soil Type} + \beta_3 \text{ x Pipe Depth} + \beta_4 \text{ x Groundwater Table} + \beta_5 \text{ x Bedding Condition} + \beta_6 \text{ x Ground Cover} + \beta_7 \text{ x Age} + \beta_8 \text{ x Pipe Surcharging} + \beta_9 \text{ x Soild Disturbance} + \beta_{10} \text{ x Flooding} + \beta_{11} \text{ x Frost Penetration} + \beta_{12} \text{ x Bedding Type} + \beta_{13} \text{ x Backfill Type} + \beta_{14} \text{ x Backfill Compaction} + \beta_{15} \text{ x pH of Lining} + \beta_{16} \text{ x Bedding Height} + \beta_{17} \text{ x Concrete Encasement}$$

(Equation 6-16)

These equations can therefore be drawn upon to generate the transition probabilities matrices. The cumulative predicted probabilities from the logistic model are first obtained through Equation 6-17 for each case.

$$\boldsymbol{P(y_i = n|x_i) = \frac{1}{1+\{\exp[-y^*)]\}}} \quad \text{(Equation 6-17)}$$

Table 6-1 represents the regression coefficients for the deterioration curve developed with the ordered logit method for a participation utility from EPA Region #3, Sewershed #1, PVC pipes. Figure 6-8 represents the deterioration curve develop with this model. This example represents the effects of variation in depth of the PVC pipe. As model suggests, the shallower PVC pipes deteriorate faster than the deeper buried pipes.

Table 6-1. Regression Coefficients for Participating Utility Sewer Shed #1 PVC Pipes.

Input Factors	Estimate (Maximum Likelihood Method)
θ1	1.01
θ2	1.69
θ3	1.73
θ4	1.94
θ5	2.07
θ6	2.12
θ7	2.22
θ8	2.33
θ9	2.39
β1 (Age)	-0.02
β2 (Depth)	0.02

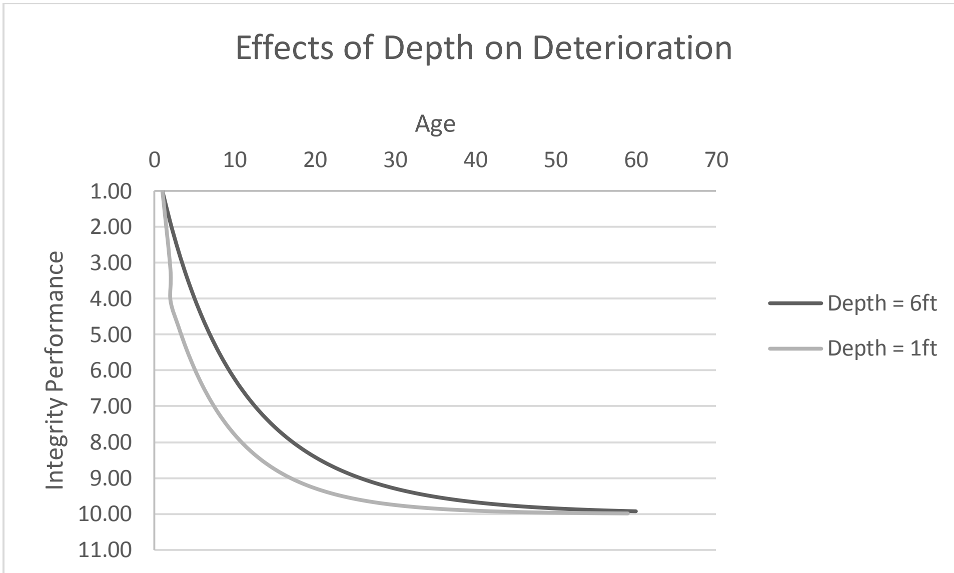


Figure 6-8. Example State Dependent Deterioration Curve with Ordered Logistic Regression.

6.6.3 <u>Parameter Inference Techniques for Ordered Logit Regression</u>

There are numerous techniques which can be applied to estimate the regression coefficients (θ and β). The previous section investigated the use of the maximum likelihood estimation technique to estimate these coefficients.

A set of probability distribution parameters (θ), which are from the dataset (D) are determined with the help of the Bayes' Rule as follows:

$$\boldsymbol{p(\theta|D) = p(D|\theta) * p(\theta) p(D)}$$

$$\textbf{posterior} = \frac{\textbf{likelihood} * \textbf{prior}}{\textbf{evidence}} \qquad \text{(Equation 6-18)}$$

Maximum Likelihood Estimate

Maximum likelihood estimation (MLE) is a probability model for data. It is used for optimizing the joint likelihood function of the observed data over one or more parameters. This method seeks a point value for θ which maximizes the likelihood, p(D|θ), shown in the equation 6-18. The MLE value can be noted as $\hat{\theta}$. In MLE, $\hat{\theta}$ is a point estimate, and not a random variable.

Bayesian Estimate

Bayesian estimation, fully calculates (or at times approximates) the posterior distribution p(θ|D). Bayesian inference treats θ as a random variable. In Bayesian estimation, it is possible to put in probability density functions and get out probability density functions, rather than a single point as in MLE.

Bayesian Ordinal Logistic Regression

Although the density can be used in constructing a maximum likelihood for parameter inference, difficulties arise when simple non- informative priors are chosen for the covariance parameters when this method has been followed. Bayesian approaches can also be used in parameter inference to overcome this problem (O’Brien and Dunson 2004).

Gibbs sampling or a Gibbs sampler is a MCMC algorithm for obtaining a sequence of observations which are approximated from a specified multivariate probability distribution (i.e. from the joint probability distribution of two or more random variables), when direct sampling is difficult. This sequence can be used to approximate the joint distribution (e.g., to generate a histogram of the distribution); to approximate the marginal distribution of one of the variables, or some subset of the variables (for example, the unknown parameters or latent variables); or to compute an integral (such as the expected value of one of the variables). Typically, some of the variables correspond to observations whose values are known, and hence do not need to be sampled.

Gibbs sampling is a regular method used for Bayesian parameter inference for logistic regression models. This approach has been generalized for multivariate probit analysis (Chib and Greenberg 1998), for random effects modeling of binary data (Chib 2000), and for analysis of correlated ordinal (Chen and Dey 2000), discrete-time survival (Albert and Chib 2001), and mixed discrete and continuous analysis (Dunson 2000; Dunson et al. 2003, O'Brien and Dunson 2004).

6.6.4 Comparison of MLE and Bayesian Estimation Methods

A preliminary comparison of the MLE and Bayesian Estimation methods were conducted to establish which method gives a better fit for the data used to develop the ordinal logistic regression. Akaike information criterion (AIC) was used to compare the models developed. AIC offers a relative estimate of the information lost when a given model is used to represent the process that generates the data. When evaluating the models which fit the evaluated data best, the preferred model is the one with the minimum AIC value. AIC value of the model can be calculated by equation 6-19.

$$\mathbf{AIC} = \frac{\mathbf{2k-2}}{\mathbf{in(L)}} \qquad \text{(Equation 6-19)}$$

Where; L = Maximum value of likelihood function of the model.
k = Number of estimated parameters.

Ordinal logistic regression models using MLE estimation method was well as Bayesian estimation methods using Gibbs sampler with MCMC is developed with the participating utility from EPA Region #3, sewer shed #1, PVC pipes. Table 6-2 summarizes the outputs for these models as well as the AIC numbers for the determination of the best model.

Table 6-2. Ordinal Logistic Model Estimation Method Comparisons

Function Name	**mnrfit**	**polr**	**lrm**	**VGAM**	**Zelig**	**MCMC**
Estimation Type	MLE	MLE	MLE	MLE	**MCMC**	MCMC
Reference		(Venables and Ripley 2002)	(Harrell 2015)	(Yee 2015)	**(Choirat et al 2015)**	(Geyer and Thompson 2015)
Modeling Platform	MATLAB	R	R	R	**R**	R
Parameter Coefficients						
Pipe Age	0.051	0.725	0.051	0.051	**0.053**	0.028
Pipe Depth	0.007	0.013	0.007	0.007	**0.009**	0.018
Pipe Diameter	0.367	0.219	0.367	0.367	**0.357**	0.216
Pipe Length	0.004	0.002	0.004	0.004	**0.008**	0.003
Pipe Location	-0.065	0.152	-0.065	-0.065	**-0.071**	-0.045
Pipe Slope	-0.097	-0.058	-0.097	-0.097	**-0.086**	-0.069
Intercepts						
y>=2	5.661	5.043	5.661	5.661	**5.68**	0.516
y>=3	6.478	5.845	6.478	6.478	**6.451**	0.573
y>=4	6.525	5.892	6.525	6.525	**6.85**	0.734
y>=5	6.777	6.038	6.777	6.777	**6.777**	0.844
y>=6	6.95	6.135	6.95	6.95	**6.95**	0.899
y>=7	7.01	6.39	7.01	7.01	**7.01**	0.976
y>=8	7.129	6.959	7.129	7.129	**7.129**	1.072
y>=9	7.25	7.457	7.25	7.25	**7.25**	1.135
y>=10	7.316	9.082	7.316	7.316	**7.316**	1.358
AIC	381.73	398.373	381.73	381.73	**335.47**	395.568

As summarized in Table 6-2, the R package Zelig, which uses a Bayesian estimation method for ordinal logistic regression analysis gives the results with the lowest AIC value making this model the preferred model. Moreover, since this algorithm uses the Bayesian estimation method, it allows the expert elicitations for the missing data to be incorporated as conjugate priors for the model.

6.7 Develop Time Dependent Models

Time-dependent models determine the probability of a transition event of the performance state (one unit). Historical data was used to develop the time-dependent model. However, historical data has certain limitations caused by the gaps which affect the accuracy of the time-dependent model. Table 6-3 summarizes the constraints in the time-dependent data observed. The research team developed several time-dependent prediction models to evaluate the better fitting model among them for the data from participating utilities.

Table 6-3. Uncensored, left censored, right censored, and interval censored datasets.

Condition State							
TE (2,3)			**TE (3,4)**				
i	j	k	i	j	k	Time in State Tj	Data Type
PS1	PS2	PS3	PS2	PS3	PS4	(Tij+Tjk)/2	Uncensored
PS2	PS2	PS2	PS2	PS3	PS3	(Tij/2)+Tijk	Right Censored
PS2	PS2	PS3	PS3	PS3	PS4	Tij+(Tjk/2)	Left Censored
PS2	PS2	PS2	PS3	PS3	PS3	Tij+Tjk	Internal Censored

6.7.1 <u>Time Dependent Model #1</u>

Kaplan-Maier estimator (K-M) method is used for time-dependent model #1. K-M is a non-parametric statistic method used to estimate the survival function from lifetime data. In medical research, it is often used to measure the fraction of patients living for a certain amount of time after treatment. In infrastructure asset management, Life data analysis of multiply censored data is performed using this method to estimate the non-parametric survival and hazard functions of infrastructure. The survival function S(t), sometimes called reliability function, represents the probability that a bridge deck remains in its condition state over the period [0-t]. This function can be expressed as follows:

$$\mathbf{S(t) = 1 - F(t) = 1 - \int_0^t f(t)dt} \qquad \text{(Equation 6-20)}$$

At the above equation, t is the random variable that represents the transition time, f(t) is the probability density function of the transition time (t), and F(t) is the cumulative distribution function. The hazard function h(t) represents the probability that the pipes will change its condition state to the next lower condition state at time t, which is related to f(t) and S(t) as follows:

$$\mathbf{h(t)} = \frac{\mathbf{f(t)}}{\mathbf{S(t)}} \quad \text{(Equation 6-21)}$$

Figure 6-9 gives an example of time dependent data and model for participating utility from USEPA region #3, sewer shed #1, PVC pipe class #3 (collection, less than 18” diameter, construction era 1998 to present).

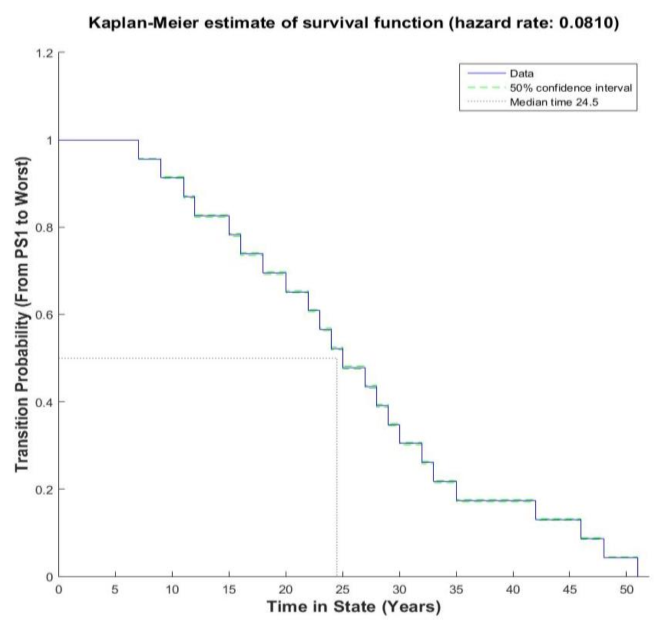


Figure 6-9. Time Dependent Model Example.

6.7.2 Time Dependent Model #2

An evaluation of time-dependent models from literature with data from a participating utility from USEPA Region #2 was conducted. Similar to the state dependent model, the AIC process was used to select the better fitting mathematical technique for the time-dependent model. As summarized in Table 6-3, the best fitting method was established as the exponential regression.

Table 6-4. Best Fitting Mathematical Technique for Time Dependent Model.

Distribution	AIC
Weibull	389.54
Exponential	302.89
Lognormal	325.74
Gamma	389.48
Log logistic	458.25

Exponential regression method has been used in order to develop the time dependent model #2 which can be expressed as;

$$y = \alpha e^{\beta x} \quad \text{(Equation 6-22)}$$

Figure 6-10 represents operational level time dependent data and model for participating utility from EPA region #3, sewer shed #2, Vitrified Clay pipe class #1 (collection, less than 24” diameter, construction era 1955 to 1975).

us_node_id	ds_node_id	Install Date	Length	material	pacp_overall_index_rating	Integrity Index	date_completed	joined_pipe_type	Age at Inspection
01A-3657.0	01A-3652.0	1/2/1960	152.0445	VCP	1.14	2.28	6/14/2012	COLLECTOR	52.4865
01A-3657.0	01A-3652.0	1/2/1960	152.0445	VCP	1	2	10/5/2010	COLLECTOR	50.79355

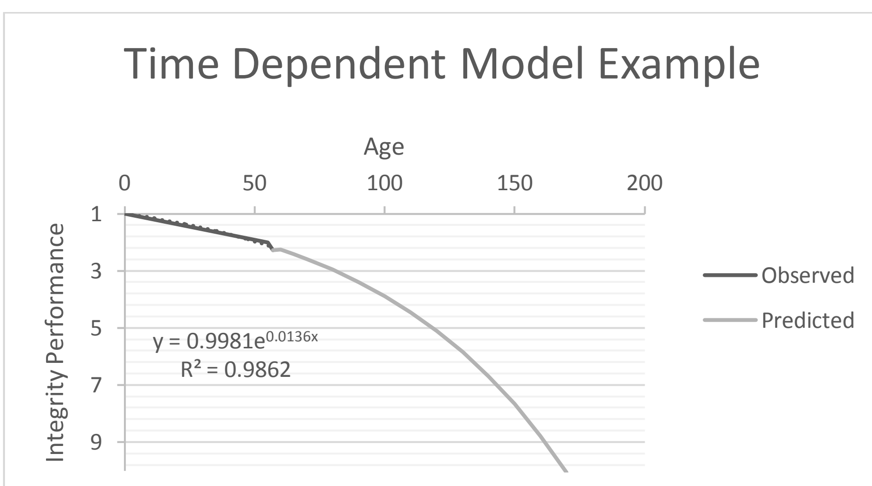


Figure 6-10. Example Time Dependent Model

6.8 Piloting Prediction Model

6.8.1 Goodness of Fit Tests (χ^2)

Prediction model verification by was conducted by using Goodness-of-fit test using Chi-squared test statistics (χ^2). This method was used for verification by various performance prediction models in literature for pipes, bridges, and pavements (Micevski et al. 2002; Tran 2007; Salman and Salem 2011, Ranjith et al. 2013, Karunarathna et al. 2013). Chi-squared test statistics (χ^2) in this study will be calculated according to equation 9-1.

$$\chi^2 = \sum_{\mathbf{i=1}}^{\mathbf{10}} \frac{(\mathbf{O_i} - \mathbf{P_i})^{\mathbf{2}}}{\mathbf{P_i}} \qquad \text{(Equation 6-22)}$$

Where, O_i is observed number of pipes in condition i, P_i is predicted number of pipes in condition i.

The verification was conducted only with the calibration dataset which is used to develop the prediction models. The calibration data set takes 85% of the entire data set, and the test data set takes only 15%. The test dataset will be used for validation. Table 6-4 summarizes χ2 values for participating utility datasets for the state-dependent model. The utility datasets containing CCTV inspection data are highlighted with asterisks. The results indicate that there is a significant improvement in the correlation between the predictions and observations when the utility dataset contains inspection results.

Table 6-5. χ^2 Values for the Participating Utility Datasets for State Dependent Model.

Utility	χ2 Value
City of Boston*	1.09
Ocean County*	1
Alexandria Renew	0.34
Arlington County	0.38
Baltimore County*	0.66

County of Pulaski	0.37
Fairfax County	0.53
Pittsburg	0.36
Prince William County	0.39
WSSC*	0.97
WVWA*	0.89
Blacksburg	0.49
City of Atlanta*	0.97
Gwinnett County*	0.82
City of Springfield, MO	0.33
Johnson County*	0.93
Orange County	0.27
Seattle Public Utilities*	0.78
Anchorage Water and Wastewater	0.48
Cobb County	0.2

6.8.2 Fitting Tests and Accuracy Tests

A prediction model was further verified with fitting and accuracy tests conducted with the historical data. Confusion between the developed deterioration curves generated by the 85% of the data (fitting test) and the 15% of the data (accuracy test) was conducted. These tests were done by the confusion matrix. The use of confusion matrices for performance prediction models for stormwater pipes is documented in Tran (2007). An example confusion matrix is provided in Table 6-5, and the precision of the validated algorithm is calculated by equation 6-23.

Table 6-6. Example Confusion Matrix

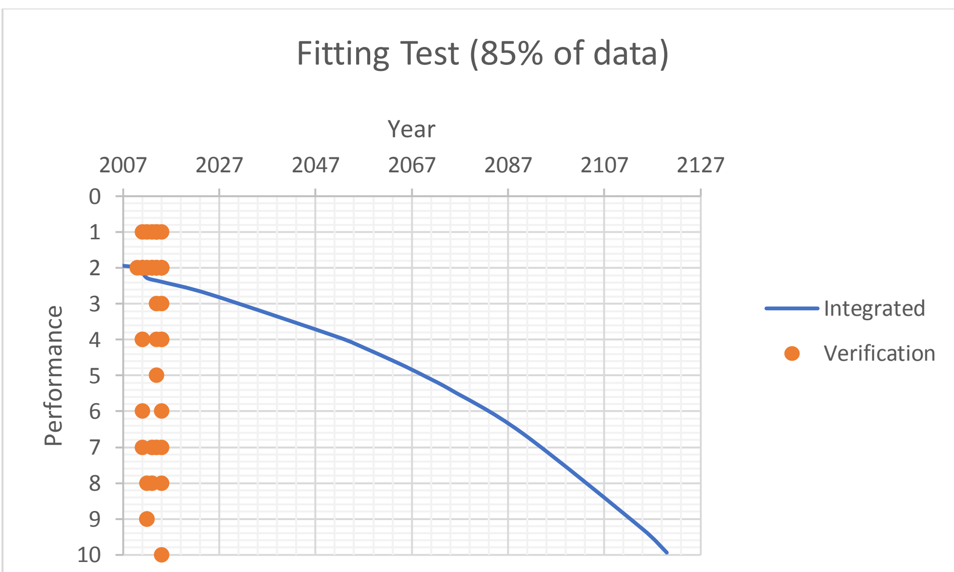
		Predicted Condition										Total
		1	2	3	4	5	6	7	8	9	10	
Observed Condition	1	AP	UP	UP	UP	UP	UP	UP	UP	UP	UP	O1
	2	UP	AP	UP	UP	UP	UP	UP	UP	UP	UP	O2
	3	UP	UP	AP	UP	UP	UP	UP	UP	UP	UP	O3
	4	UP	UP	UP	AP	UP	UP	UP	UP	UP	UP	O4
	5	UP	UP	UP	UP	AP	UP	UP	UP	UP	UP	O5
	6	UP	UP	UP	UP	UP	AP	UP	UP	UP	UP	O6
	7	UP	UP	UP	UP	UP	UP	AP	UP	UP	UP	O7
	8	UP	UP	UP	UP	UP	UP	UP	AP	UP	UP	O8

	9	UP	UP	UP	UP	UP	UP	UP	UP	AP	UP	O9
	10	UP	UP	UP	UP	UP	UP	UP	UP	UP	AP	O10
Total		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	

$$\textbf{Accuracy} = \frac{\textbf{Acceptable Predicions}}{\textbf{Acceptable Predictions+Unacceptable Predictions}} \quad \text{(Equation 6-23)}$$

6.8.2.1 Piloting of the Deterioration Model for Gravity Pipes

Figures 6-11 and 6-12 represent the fitting tests (85% of the dataset) and accuracy test (15% of the dataset) conducted for a participating utility in USEPA Region #3. Please note that these models are developed for Vitrified clay pipes in one sewer shed, which are less than 24" diameter and construction era 1955 to 1975. The deterioration model is developed by integrating state and time-dependent models. The results of prediction by this model are 61.29% for verification, and 72.72% for validation.



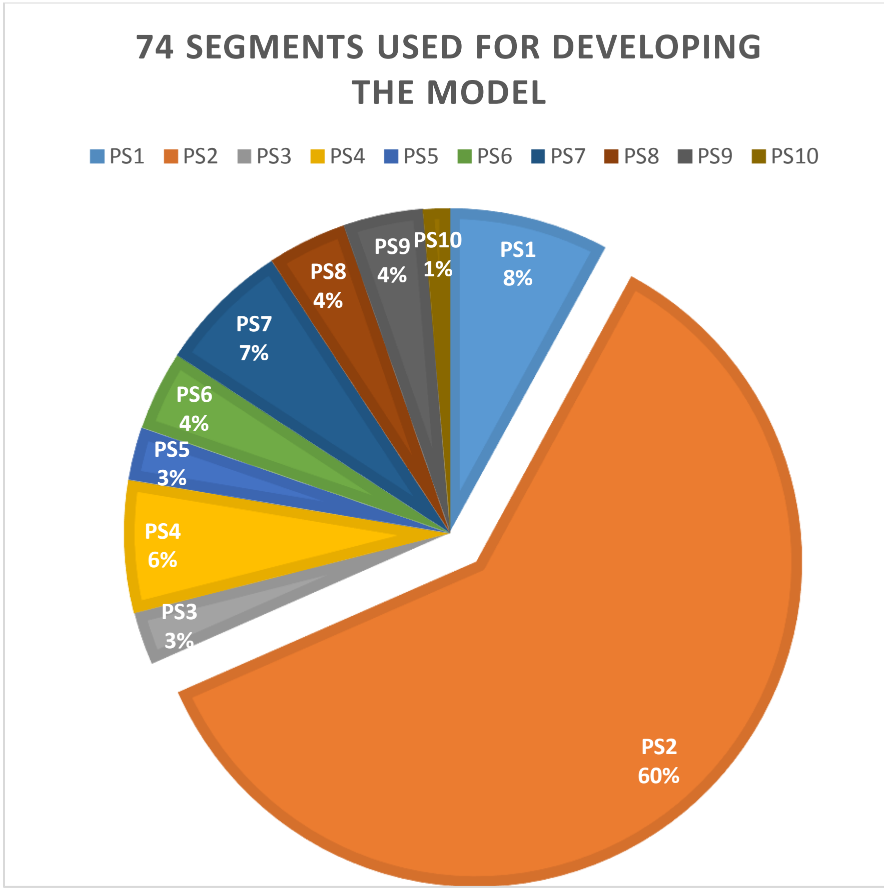
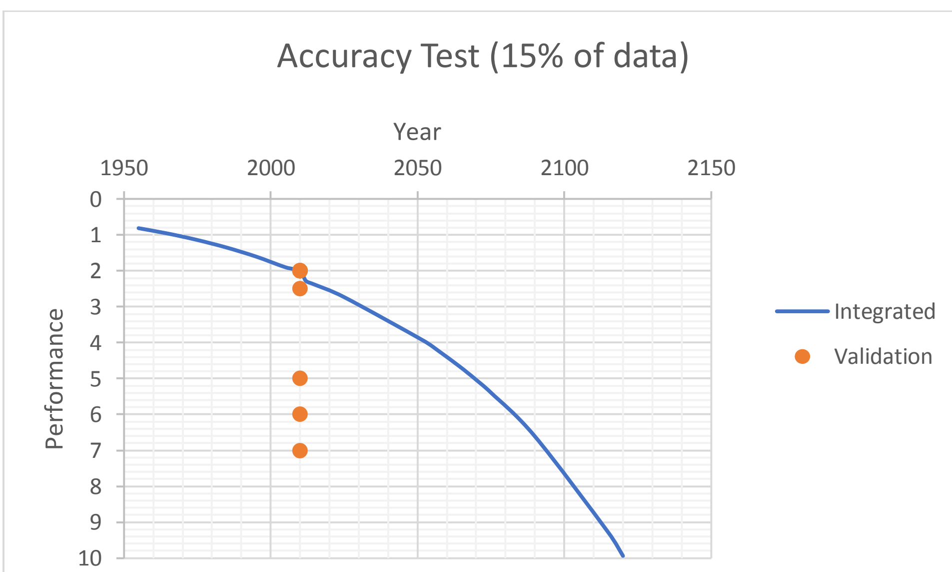


Figure 6-11. Integrated Performance Prediction Model Fitting Test (61.29%)



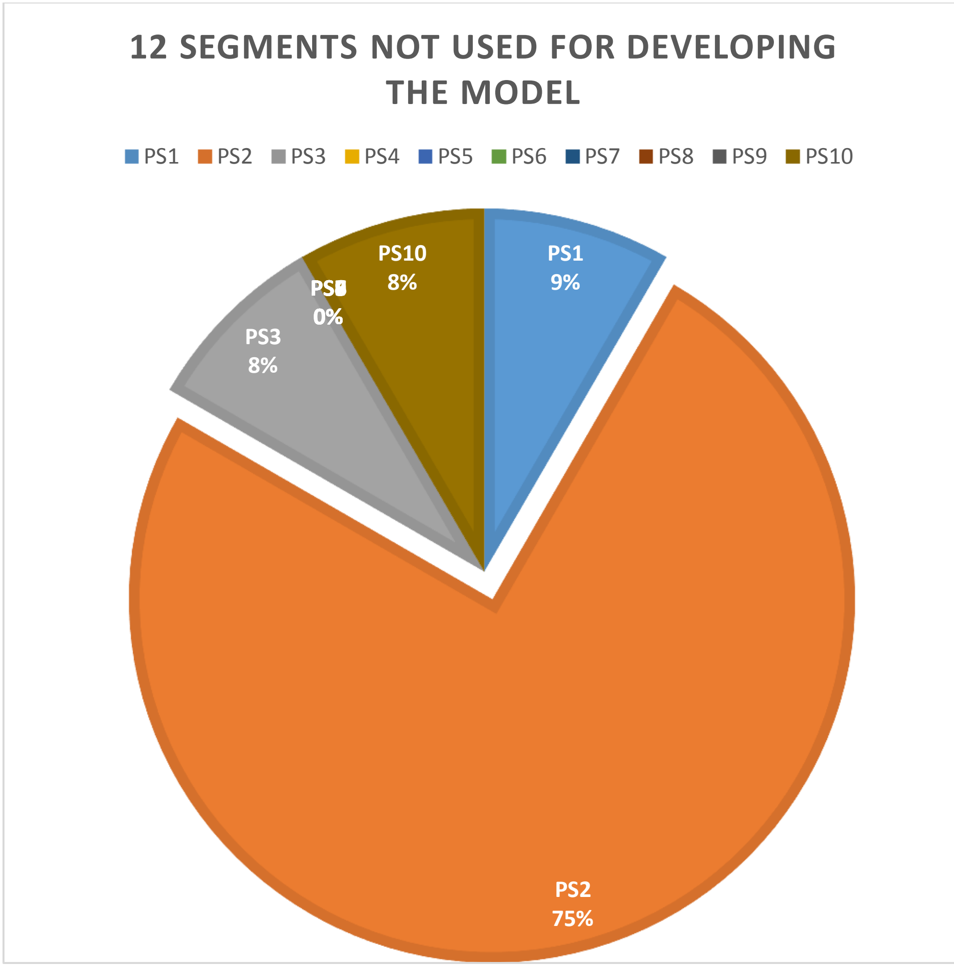


Figure 6-12. Integrated Performance Prediction Model Accuracy Test (72.72%)

6.8.2.2 Piloting of the Deterioration Model for Force Main Pipes

Figures 6-13 represents the accuracy test conducted for a participating utility in USEPA Region #3 with force main pipe data. Please note that these models are developed for asbestos cement pipes in one sewer shed, and construction era 1955 to 1975. The deterioration model is developed by integrating state and time-dependent models. 739 pipe segments were found in the dataset fitting the criteria. When the prediction model and the performance index results are compared, 537 were acceptable predictions, and 199 were unacceptable predictions. The results indicate that accuracy of prediction of this model is at 72.69%.

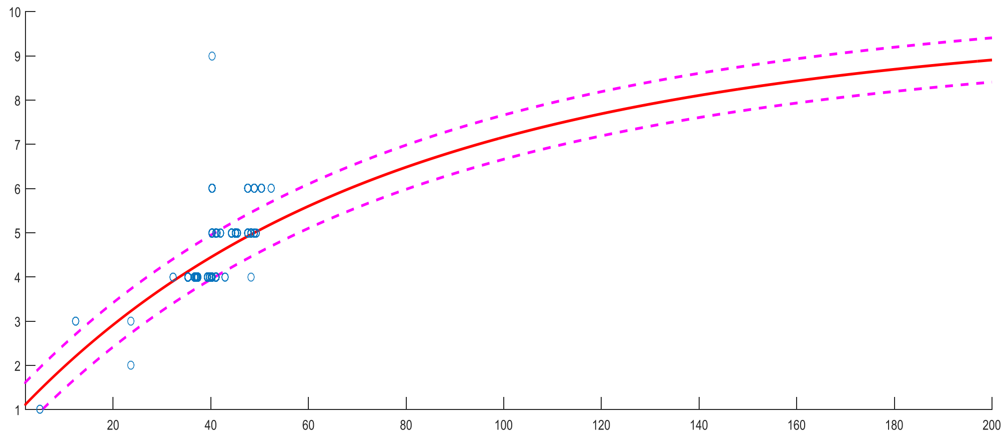


Figure 6-13. Force Main Performance Prediction Model Accuracy Test (72.69%)

6.9 Conclusions from Phase 3

The overall objective of this research is to develop the prediction models for determining the remaining life of wastewater pipes. To develop deterioration models, the Markov chain is one of the modeling methods most utilized in predicting infrastructure deterioration. Two techniques used to calibrate the Markov Chain models; state dependent and time dependent. Due to the limitation of the historical data, a records selection process was developed to select data from participating utilities to run the time-dependent or state-dependent models according to the availability. Additionally, a pipe selection process was designed to classify pipes regarding;

- Sewer Shed – Varies by utility
- Sewer Type – Gravity, Force Main
- Pipe Type – Lateral, Main, Trunk, Interceptor, Outfall
- Pipe Material – Various (19 Classes total)
- Construction Era – Varies by material

- Size – Varies by material
- Shape – Varies by material

Various state dependent and time dependent models were developed in order to evaluate the best fitting modeling technique. Eventually, ordinal logit regression with MCMC calibration technique was selected for the state dependent model. These techniques gave the best fit according to the AIC testing. Similarly, AIC tests indicated that the best fitting mathematical technique for the time dependent model was the exponential regression technique.

7. Conclusions and Recommendations

7.1 Conclusions

Performance prediction modeling is a crucial step in assessing the remaining service life of pipelines. Sound infrastructure deterioration models are essential for accurately predicting future performance that, in turn, are critical tools for efficient maintenance, repair and rehabilitation decision making. The objective of this research is to develop a gravity and force main pipe performance deterioration model for predicting the remaining economic life of wastewater pipe for infrastructure asset management. For condition assessment of gravity pipes, the defect indices currently in practice use CCTV inspection and a defect coding scale to assess the internal condition of the wastewater pipes. Unfortunately, in practice, the distress indices are unable to capture all the deterioration mechanisms and distresses on pipes to provide a comprehensive and accurate evaluation of the pipe performance. Force main pipes present a particular challenge in performance prediction modeling. Consequences of failure are higher for the force mains about the gravity pipes which increases the risk associated with these assets. However, unlike gravity pipes, there are no industry standards for inspection and condition assessment for force mains. Furthermore, accessibility issues for inspections add to this challenge.

The mere generation of models that are piloted within a limited number of participating utilities and limited data will always be incapable of achieving a significant and lasting change in utility asset management practices. Truly effective asset management, which leads to the promised cost-savings, improved service levels, and overall performance requires tactical and operational decisions to be driven by field- level data. This research has addressed these shortcomings in the practice. A three-phase research methodology was followed to develop the prediction models to conduct remaining life analysis for the wastewater pipes.

For phase 1, the previously developed data standards for gravity pipes have been updated with the input from participating utilities. Specific parameters for the pipe elements such as the laterals, corrosion mitigation methodologies (cathodic protection), linings, and coatings were added. A new data standard of 98 parameters was developed to capture the physical, structural, operational, functional, environmental, financial, and other parameters pertaining the performance of force main pipes were developed. A secure data collection and conflation strategy was developed to collect data from participating utilities.

For phase 2, the previously established gravity performance index was updated to incorporate failure modes and mechanisms which were not included in the previous research. Specifically, joint and lining performance modules were developed to capture these performances. A new performance index utilizing the fuzzy logic interference methodology was developed to determine the performance of the force main pipes. Specifically, modules to determine the integrity, internal corrosion, external corrosion, surface wear, joint performance, lining performance, blockage, and capacity were developed. Moreover, the application of a new 10-grade scale was adopted improving the 5-point scale which is the current industry standard. The 10-point scale gives more granularities of the performance data especially in the middle sections of the performance level.

For Phase 3, which is the primary focus of this research, the data standards and performance indices developed by the previous phases were leveraged. Due to limitations in historical performance data, an integrated method for probabilistic performance modeling to construct workable transition probabilities for predicting long-term performance has been developed. A selection process within this method chooses a suitable prediction model for a given situation in terms of available historical data. Prediction models using time and state-dependent data has been developed for this integrated method for reliable long-term performance prediction.

Piloting has been conducted with the help of participating utilities nationwide. Although the piloting for the performance indices and prediction models were developed and conducted, the available data for the piloting process was limited.

This research provides utility managers with a practical and accurate technique for the predicting wastewater pipeline performance and estimating end of the remaining life deterioration curve for decision-making. A comprehensive understanding of the pipe deterioration parameters and process is presented regarding the performance index which captures the coupled effects of performance parameters. In turn, this better understanding reflects in high accuracies of future predictions (up to 70% accuracy) with the performance prediction models which leverage these performance indices. 70% accuracy results depend on many different factors and is not a full reflection of the real accuracy of the model. All the data which were identified at the data standards was not collected by the participating utilities. Moreover, the data provided by the participating utilities come with many reliability levels as summarized in the following figure.

Figure 7-1. Data Reliability Levels

Unknown: The parameter is unknown

Educated guess: A guess based on knowledge and experience.

Derived: Data element derived from other data elements using a mathematical, logical, or another type of transformation

External Data Source: Data collected by another entity obtained to perform the analysis.

Direct Measurement: Data collected the model user or developer for performance analysis.

As more parameters and higher reliability data collected by the utilities, the accuracy of the model is expected to improve.

The site selection for the validation was made without the research teams knowledge or influence. The site selection process was done by the participating utility without any pre-notions of the model outputs. The site selection was purely made by the utility in terms of feasibility and sites accessible during the piloting time. The piloting can be extended as more data collected from participating utilities through the PIPEiD database.

The indices and prediction models created for this research can operate at the strategic and tactical level. It can only provide decision support at these levels. It is a tool to identify regions of interests or problematic areas for further investigations, which is a useful tool for the practitioners. For more detailed decision support (i.e. operational level) models and tools with more focused data (such as the FE models) can be used.

7.2 Recommendations for Future Work

Although there are significant contributions to the practice and literature by the conducted research, some areas of improvement still exist which can be addressed by future research;

1) Although there are 118 parameters were defined for gravity and 98 parameters defined for the force mains, the availability of the parameters from participating

utilities were limited. Utilities need to be informed to collect additional parameters which are essential for the performance evaluation and prediction. The utility datasets for this research was missing the essential soil parameters such as the soil Corrosivity. These parameters can be acquired from external dataset such as the USGS datasets. However, the accuracy and reliability of these datasets are lacking in order to provide sound analysis.

2) Although there is no statistical difference between the 5-scale and 10-scale performance indices. The 10-scale index is theoretically providing better granulation at the middle of the scale range. Different dataset can be investigated to further strengthen this theory.

3) Utilities should be encouraged to collect uncensored time dependent data. This kind of data will form the basis of the adaptation of the time dependent models which are proven to be more accurate compared to the state depended analysis. Certain hot spots or regions of interest in the pipe system can be chosen to collect time dependent data in a cost effective manner.

4) Although AIC analysis was conducted to assess the best fitting mathematical methods for the state and time dependent models, this analysis is only valid for the dataset evaluated. If more data will be collected from participating utilities, the AIC analysis can indicate a different mathematical method to be better fitting. Thus further analysis should be conducted with datasets containing variabilities to determine the best fitting mathematical techniques.

5) Additional techniques such as the expert elicitation and artificial intelligence methods should be evaluated to run with the state and time dependent modes in order to fill the gaps in the data collected from the participating utilities.

A new protocol to collect and analyze filed samples to create ground truths for the models and tools should be developed. Additionally, artificial data creation methods such as the Monte Carlo simulations should be considered to develop validation datasets. Scheidegger et al. (2011) investigated a method to artificially created validation datasets utilizing Monte Carlo simulation. This method can be utilized the data collected for this study to develop a validation dataset for similar models.

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Appendix A -Wastewater Gravity Pipe Performance Essential Parameters

Key: Number. **Parameter Name**-*Parameter explanation.*

- Description: (unit of parameter)

Physical/Structural

1. **Node Identification Number**-Identification of each pipes segments (Manhole-Manhole)

- Section ID: (Node)

1. Pipe Material-. *Different pipe materials deteriorate at different rates*

- Pipe material can be classified as following: (Type)

a) Asbestos Cement
b) Brick
c) Cast Iron
d) Corrugated Metal Pipe
e) Concrete Pipe (Non-reinforcement)
f) Concrete Segments (bolted)
g) Concrete Segments (unbolted)
h) Clay Tile (not vitrified clay)
i) Ductile Iron
j) Fiberglass reinforced pipe
k) Glass reinforced cement
l) Pitch fiber (Orangeburg)
m) Polyethylene
n) Polypropylene
o) Plastic / steel composite
p) Polyvinyl Chloride
q) Prestressed Concrete Cylinder Pipe
r) Reinforced concrete pipe
s) Reinforced plastic matrix (truss pipe)
t) Steel pipe
u) Transite
v) Vitrified clay pipe
w) Wood
x) Not know
y) Others:______________________________

2. Pipe Diameter-*Different pipe sizes may fail in different failure modes.*

- Diameter of pipe: (Inch)

3. Installation Year: *Older pipes may deteriorate faster than newer pipes.*

- Installation Year: (Year)

4. Pipe Depth-*Pipe depth affects pipe loading and deteriorating rate.*

- Distance from ground level to the crown of the pipe: (Feet)

5. Pipe Wall Thickness-*Wall thickness affects rupture resistance and corrosion penetration rate.*

- Original thickness of pipe wall: (Inch)

6. Pipe Location-*Geographical location may affect the performance of pipe.*

- Geographical Location: (Area)

a. Urban
b. Sub-urban
c. Rural
d. Coastal
e. Industrial
f. Agricultural

7. Pipe Shape-*Different pipe shapes may result in different failure modes and deteriorations.*

- Shape of pipe: (Type)

a. Arched with flat bottom (A)
b. Barrel (B)
c. Circular (C)
d. Egg Shaped (E)
e. Horseshoe (H)
f. Oval or Elliptical (O)
g. Rectangle (R)
h. Square (S)
i. Trapezoidal (T)
j. U shaped with flat bottom (U)
k. Other – Please State

8.Pipe Joint Type-*Some types of joints may undergo premature failure.*

- Type of pipe joint: (Type)

a. Lead Yarn Joints
b. Flanged Joints
c. Mechanical Joints

d. Welded Joints
e. Others

9. Pipe Bedding-*Inadequate bedding may cause premature pipe failure.*

- Special bedding and soil type If used special bedding, also provide the type: (Yes/No-Type)

a. No Bedding
b. Clay
c. Granular
d. Variable Soils
e. Concrete
f. Other Known material
g. Unknown material

10. Trench Backfill-*Some backfill materials are more corrosive or frost susceptible.*

- Trench backfill soil: (Type)

a. Clay
b. Granular
c. Variable Soils
d. Other Known Soil
e. Unknown Soil

11. Pipe Slope-*Slope affects the velocity of gravity flow and may result in different pipe deterioration rates.*

- Slope: (Gradient)

12. Design Life of Pipe-*Original design life of each pipe.*

- Life: (Year)

13. Design Strength of Pipe-*Original design strength of each pipe.*

- Strength: (psi)

a. Longitudinal Strength
b. Ring Strength

14. Node Length – *Length of Node (manhole-manhole)*

- Node length: (Feet)

15. **Pipe Lining** -*Lined pipes have higher resistance to corrosion and reduce infiltration.*

- Lining of pipe: (Type)

a. Factory Installed
b. Field Installed
c. Cured in place (CIP)
d. Fold and Form or Deform/Reform (FF)
e. Spiral Wound (SW)
f. Segmented panel (SN)
g. Segmented pipe (SP)
h. Others (ZZZ)
i. Unknown

16. **Pipe Lining pH**– *he pH of lining can be used as an indicator for the deterioration.*

- Lining pH: (pH)

Operational/Functional

17. **Pipe Hydraulics**- *Pipe Hydraulics may affect deteriorated rate*

- Capacity of the sewage gravity conveying pipe: (Gallon/Min)

18. **Pipe Surcharging**-*Surcharging in gravity sewers in dry & wet weather should be considered.*

- Surcharging: (Yes/No)

19. **Operational & Maintenance Practice**-*Poor Practices can compromise structural integrity and water quality.*

- Operation and Maintenance Practice: (Type)

Cleaning

a. Rodding
b. Bucket Machine
c. Balling
d. Flushing
e. Jetting
f. Scooter
g. Kites, Bags, and Poly pigs
h. Silt Traps
i. Grease traps and sand/oil interceptors
j. Chemical
k. Others

Maintenance

a. Pipe Cleaning
b. Pipe Corrosion Control
c. Pipe Grouting

Repairs

a. Joint and Leak Seals
b. Point Repairs

20. Pipe Renewal Record-*All records of pipe repair/rehab /replace including method use*

- Renewal Record: (Type)
  a) Cured-In-Place Pipe (CIPP) Liners
  b) Pipe Coatings
  c) Fold and Form Pipe Liners
  d) Grout-In-Place Pipe (GIPP) Liners
  e) Modified Slip lining
  f) Spray-In-Place Pipe (SIPP) Liners
  g) Slip lining
  h) Spiral Wound - Ungrouped

21. Pipe Defect Type-*All records of pipe failures including failure modes.*

- Defect record: (Record)
- Type Defects: (Types)

Structural

a. Crack
   i. Longitudinal
   ii. Circumferential
   iii. Multiple
   iv. Spiral
   v. Hinge
b. Fracture
   i. Longitudinal
   ii. Circumferential
   iii. Multiple
   iv. Spiral
   v. Hinge
c. Broken
   i. Soil Visible
   ii. Void Visible
d. Hole
   i. Soil Visible
   ii. Void Visible
e. Deformed
   i. Vertically

ii. Horizontally

f. Collapsed
    i. Pipe Collapse
    ii. Brick Collapse
g. Joint
    i. Offset (Displaced)
    ii. Separation (Open)
    iii. Angular
h. Surface Damage
    i. Roughness Increased(Mechanical or Chemical)
    ii. Aggregate Visible (Mechanical or Chemical)
    iii. Aggregate Projecting (Mechanical or Chemical)
    iv. Aggregate Missing (Mechanical or Chemical)
    v. Reinforcement Visible (Mechanical or Chemical)
    vi. Reinforcement Projecting (Mechanical or Chemical)
    vii. Missing Wall (Mechanical or Chemical)
    viii. Surface Spalling (Mechanical or Chemical)
    ix. Other
    x. Corrosion (Graphitization, Pitting, Crazing)
i. Buckling
    i. Wall
    ii. Dimpling
    iii. Inverse Curvature
j. Lining Features
    i. Detached Lining
    ii. Defective End
    iii. Blistered Lining
    iv. Service Cut Shifted
    v. Abandoned
    vi. Overcut Service
    vii. Undercut Service
    viii. Buckled Lining
    ix. Wrinkled Lining
    x. Annular Space
    xi. Bulges
    xii. Discoloration
    xiii. Delamination
    xiv. Resin Slug
    xv. Pinholes
    xvi. Other
k. Weld Failure
    i. Longitudinal
    ii. Circumferential
    iii. Multiple
    iv. Spiral
    v. Unidentified

l. Point Repair
    i. Pipe Replaced
    ii. Patch Repair
    iii. Localized Pipe Liner
    iv. Other
m. Brickwork
    i. Displaced
    ii. Missing
    iii. Dropped Invert
    iv. Missing Mortar (Small, Medium, Large)

Operational and Maintenance

a. Deposits
    i. Attached (Encrustation, Grease, Ragging, Other)
    ii. Settled (Fine, Gravel, Hard/Compacted, Other)
    iii. Ingress (Fine, Gravel, Other)
b. Roots
    i. Fine (Barrel, Lateral, Connection, Joint)
    ii. Tap (Barrel, Lateral, Connection, Joint)
    iii. Medium (Barrel, Lateral, Connection, Joint)
    iv. Ball (Barrel, Lateral, Connection, Joint)
    v. Infiltration
    vi. Stain
    vii. Weeper
    viii. Dripper
    ix. Runner
    x. Gusher
c. Obstacles/Obstructions
    i. Brick or Masonry
    ii. Pipe Material in Invert
    iii. Object protruding through wall
    iv. Object wedged in joint
    v. Object through connection/junction
    vi. External pipe cable
    vii. Build into structure
    viii. Construction Debris
    ix. Rocks
    x. Others
d. Vermin
    i. Rat
    ii. Cockroach
    iii. Other
e. Grout Test and Seal
    i. Grout test passed
    ii. Grout test failed

Construction Features

6.1 Tap
6.1.1 Factory Made (Intruding, Active, Capped, Capped, Abandoned, Defective)
6.1.2 Break in/Hammer (Intruding, Active, Capped, Capped, Abandoned, Defective)
6.1.3 Saddle (Intruding, Active, Capped, Capped, Abandoned, Defective)
6.1.4 Rehabilitated (Intruding, Active, Capped, Capped, Abandoned, Defective)
6.2 Intruding Sealing material
6.2.1 Sealing ring (Hanging, Broken, Loose)
6.2.2 Grout
6.2.3 Other
6.3 Line
6.4 Access Point
6.4.1 Manhole
6.4.2 Wastewater Access
6.4.3 Discharge Point
6.4.4 Tee Connection
6.4.5 Other Special Chamber
6.4.6 Meter
6.4.7 Wet Well
6.4.8 Junction Box
6.4.9 Mainline
6.4.10 Properly
6.4.11 Catch Basin
6.4.12 End of Pipe

22.Pipe Defect Level – The extend of the defects

- Level of Defects;
  - a)1- Excellent: Minor Defect Present
  - b)2- Good: Defects that have not begun to deteriorate
  - c)3- Fair: Moderate defects that will continue to deteriorate
  - d)4- Poor: Severe defects that will become Grade 5 in the foreseeable future
  - e)5- Fail: Pipe no longer functional due to extend of defects.

23.Location of Defects – Location of the defects observed (*More detailed information on how to record Defects can be found in NASSCO's PACP manual)*

- Defects location
  - a)Internal, external, or mid-wall
  - b)angular location (i.e., 12, 3, 6, 9 O'clock)

24.Infiltration/Inflow-*Infiltration may cause soil erosion, and increasing flow volume.*

- Level of infiltration/inflow, if available, also provide in Gal/Min: (Level-Gallon/Minute)
  - a)Low
  - b)Medium
  - c)High

25.Exfiltration- *Exfiltration may cause soil erosion, and change soil loading on pipe.*

- Level of Exfiltration: (Level)

a) Low
b) Medium
c) High

26.Blockage/Stoppage-*Blockage/stoppage make the pipeline network inoperative, sewer pipe is no longer functional.*

- Blockage/Stoppage: (Yes/No- Type)

27.Sediments-*Sediments per unit length.*

- Amount of Sediment per feet: (Ton/feet)

28.Inspection Record-*Record of inspection i.e. by CCTV, Smoke test, Dye test*

- Method Use: (Type)

a) Visual Inspection
b) Camera Inspection
c) Closed Circuit Television (CCTV)
d) Lamping Inspection

29.Flow Velocity-*Flow velocity may affect internal corrosion of unlined/coated pipes.*

- Velocity: (Feet/Second)

<u>Environmental</u>

30.Soil Type-*Some soils are corrosive, expansive, and compressible. Some soils contain hydrocarbons and solvents that may cause pipe deterioration.*

- Type of soil: (Type)

a) Clay
b) Granular
c) Mucks
d) Mud
e) Organic Soil
f) Variable Soils
g) Other Known Soil
h) Unknown Soil

31.Soil Corrosivity-*Soil present may be corrosive and may affect pipe environment.*

- Corrosivity level of soil: (Level)

a) Low
b) Medium
c) High

32.Soil Moisture Content-*Moisture present in the soil may affect loading and pipe deterioration rate.*

- Moisture Content of the Soil: (Percent)

33.Stray Currents-*Stray electrical currents may cause electrolytic corrosion.*

- Electrical currents present near pipe: (Yes/No)

34.Groundwater Table-*Groundwater affects soil loading on the pipe and pipe deterioration rate.*

- Depth of water table: (Feet)

35.Ground Cover-*Paved ground or vegetation covers result in different deterioration mode and rate.*

- Land Cover: (Type)

  a) Grass
  b) Asphalt
  c) Concrete
  d) Trees
  e) Bare Ground
  f) Water
  g) Other Known Type
  h) Unknown Type

36.Loading Condition (Dead Load) -*loading depends on depth of pipe and infrastructure loading.*

- Death Load i.e. soil, structure, or stockpile above pipe: (Lbs/Sq.ft.)

37.Loading Condition (Live Load) - *Live load can be determined from average daily traffic volume and railway loading etc.*

- Live Load i.e. Traffic, Railway, Aircraft: (Average daily traffic volume (ADT) or Level)

  a) High Traffic
  b) Medium Traffic
  c) Low Traffic

38.Rainfall/Precipitation-*Rainfall in the areas should be monitored.*

- Rate of rainfall per year: (Inch/Year)

39.Climate-Temperature-Frost action in cold *regions may accelerate pipe deterioration.*

- Region temperature: (°F)

  a) Average
  b) High
  c) Low

40. H_2S - *Concentration of Hydrogen Sulfide can increase pipe internal deterioration rate.*

- Hydrogen Sulfide concentration inside the pipe.: (ppm)

41. Frost Penetration-*Pipe dwindling or defects may result from frozen soil.*

- Soil frozen near or around pipe, depth of penetration in feet: (Yes/No-Ft.)

42. Proximity to Trees-*Root intrusion may cause pipe distress and accelerate pipe deterioration.*

- Average distance between sewer and trees: (Feet)

43. Tidal Influences-*Coastal areas with tidal influences may affect pipe bedding.*

- Tidal influences present: (Yes/No)

Financial

44. Annual Capital Cost – *Utility annual capital cost*

Other

- Annual Capital Cost: (Dollar/Year)

45. FOG-*Fats, Oils, and Grease entering the sewer system.*

- FOG released to the system: (Yes/No)

Appendix B - Wastewater Gravity Pipe Performance Preferable Parameters

Key: Number. **Parameter Name**-*Parameter explanation.*

- Description: (unit of parameter)

Physical/Structural

1. **Pipe Section Length** - *Length of pipe section (Joint - joint)*

- Pipe Section length: (Feet)

2. **Dissimilar Materials -** If dissimilar materials exists.

- Dissimilar Materials: (yes/no)

3. **Pipe External Coating** - *external coating prevents corrosion of the pipe.*

- Pipe External Coating: (Type)

a) No Coating
b) Factory Installed
c) Field Installed
   - Asphaltic
   - Epoxy
   - Polyethylene
   - Bio-Enhanced Polyethylene
   - Other: _
d) Unknown

4. **Cathodic Protection** - *Technique used to control the corrosion of a metal surface.*

- Cathodic Protection (yes/no/unknown)

5. **Pipe Vintage –** *Pipes made at a different time and place may deteriorate differently.*

- When the pipe was made: (Year)

a) After 1995
b) 1985 - 1994 (inclusive)
c) 1975 - 1984 (inclusive)
d) 1950 - 1974 (inclusive)
e) 1925 - 1949 (inclusive)
f) Before 1925
g) Unknown age

6.Pipe Manufacturer Name - *Name of the manufacturer who manufactured the pipe sample.*

- Name of manufacturer: (Name)

7.Pipe Manufacture Class - *Name of the manufacturer who manufactured the pipe sample.*

- Pipe class (e.g., AWWA 301, etc.): (Class)

8.Pipe Manufacture Date- *Manufacture date determines some deterioration characteristics*

- Manufacture date: (Year)

9.Pipe Trench Width - *Trench width may affect soil loading on the pipes and deterioration rate*.

- Trench Width: (Feet)

10.Cathodic Protection Installation Year – *Year cathodic protection installed.*

- Cathodic Protection Installation Year: (Year)

11.Cathodic Protection Present Potential - *As pipes age the cathodic protection potential decreases suggesting wall thickness loss*

- Cathodic Protection Present Potential: (%)

12.Pipe Thrust Restrain - *Inadequate restraint may increase longitudinal pipe stresses.*

- Restraint present, holding or cradling the pipe, if yes, provide type: (Yes/No-Type)

  a) Thrust Block
  b) Restraint Joint
  c) Others

13.Type of Dissimilar Materials – *Different types of dissimilar materials effect the corrosion rates*

- Type of dissimilar materials can be classified as following: (Type)

  a) Stainless Steel
  b) Monel Metal
  c) Bronze
  d) Copper

e) Brass
f) Nickel
g) Lead
h) Aluminum
i) Cadmium
j) Zinc
k) Magnesium
l) Other: _

14. **Height of Bedding:** *Height of bedding is an important factor for deterioration.*

- Height of Bedding: (inches)

15. **Lateral Connections**-*Condition of laterals and other related information.*

- Condition and other information: (Record)

16. **Lateral Connections Type** - *Type of Lateral connection can be a determining factor for deterioration rates.*

- Lateral Connections Type: (Type)

17. **Lateral Connections Location**- *Location of Lateral Connections influences the blockage and capacity*.

- Lateral Connections Location: (Location)

18. **Lateral Connections Height**- *The height of the lateral connection effects the deterioration*

- Lateral Connections Height: (Feet/10)

19. **Lateral Connections Flow Rate**- *The flow rate for the lateral connections effects the blockage and capacity performance*

- Lateral Connections Flow Rate: (Gal/Min)

20. **Lateral Connection Size** - *The size of the lateral connections effects the performance by increasing the amount of water conveyed.*

- Lateral Connection Size: (Inches)

21. **Lateral Connection Slope** - *The slope of the lateral connections effects the surface wear and corrosion rates.*

- Lateral Connection Slope: (%Grade)

22. **Distance to WWTP** - *The distance the Wastewater treatment plant indicates*

how much time the conveyed water spends in the system.

- Distance to WWTP: (Miles/10)

23. Wastewater TSS - *The total suspended solids can increase the Corrosivity of the conveyed water.*

- Wastewater TSS: (ppm)

24. Concrete Encasement - *The presence of concrete encasement can protect the pipe against external corrosion*

- Concrete Encasement: (Yes/No)

Operational/Functional

25. Sewer Flooding-*Flooding may change property of surrounding soil and loading on pipe.*

- Flooding : (Yes/No)

26. Flow Depth/Diameter - *Pipes with different flow depth over diameter ratios deteriorate different.*

- Flow Depth/Diameter: (Ratio)

27. Maintenance Frequency – *Frequent maintenance performed will increase the life of the pipe.*

- Maintenance Frequency: (Level)

28. Type of Cleaning – *Type of cleaning performed previously*

- Type of Cleaning: (Type)
    a) Jetting
    b) Rutting
    c) Bucketing

29. Cleaning Frequency – *The cleaning frequency can determine the defects such as the blockage and surface defects.*

- Cleaning Frequency: (Frequency)

30. Sewer Odors - *Solids build-ups, poor system hydraulics, flat grade, etc.*

- Odors reported: (Yes/No)

31.Sewer Overflow (SSO/CSO)-*Overflow may inundate surrounding soil and change loading on pipe.*

- Overflow: (Yes/No)

32.Backup Flooding-*Number of properties affected by flooding in Dry & Wet weather.*

- Number of Properties: (Number)

33.Dry Weather Flow - *The high dry weather flow rates indicate capacity problems.*

- Dry Weather Flow: (Gal/Min)

Environmental

34.Extreme Events-*Events may threaten pipe sustainability.*

- Events: (Type)

  a) No extreme events
  b) Hurricanes
  c) Floods
  d) Tornadoes
  e) Tsunami
  f) Earthquakes
  g) Other Known Event
  h) Unknown Event

35.Soil Disturbance-*Disturbance of soil near the pipe may cause pipe damage or change soil support or loading.*

- Any reason for soil disturbance around the pipe i.e. new construction: (Yes/No)

36.Soil Chloride-*Mortar coating usually creates a pH environment of >12.4. Low chloride levels in high pH (>11.5) environments can lead to serious corrosion.*

- Chloride: (Percent)

37.Soil Sulfate-Accounts for microbial induced corrosion (MIC) and possible food source for sulfate reducing bacteria in anaerobic conditions under loose coatings.

- Sulfate: (Percent)

38.Soil Redox Potential- *Low Redox potentials are more favorable for sulfate* *reducing bacteria leading to corrosion.*

- Redox Potential: (Level, mV)

39. Soil Resistivity- *Soils with low electrical resistivity are more likely to have high corrosion rates.*

- Soil Resistivity: (Level, mV)

40. Wastewater pH - *Low pH (<4) means conveyed water is acidic and likely to promote corrosion; high alkaline conditions (pH>8) can also lead to high corrosion.*

- Wastewater pH: (pH)

41. Wastewater Sulfate - *Higher concentrations contribute to oxidization.*

- Wastewater Sulfate: (mg/l)

42. Wastewater Dissolved Oxygen - *Higher concentrations contribute to oxidization.*

- Wastewater Dissolved Oxygen: (mg/l)

43. Wastewater Temperature – *Average Temperature of Wastewater.*

- Wastewater Temperature: (F°)

44. Foreign Anode Bay Distance - *Distance of the foreign anode bay causing stray current is proportional to external corrosion.*

- Foreign Anode Bay Distance: *(Feet)*

45. Runoff Rate-*Excess water flow which can be caused by rainfall, evaporation, snow melting, etc.*

- Peak Runoff Rate: (Cubic feet/Second)

46. Non-Uniform Soil-*Non-uniform soil support in longitudinal axis may increase shear and bending stresses.*

- Non-Uniform Soil: (Yes/No)

47. Non-Uniform Slope-*Non-uniform slope may reduce operating performance.*

- Non- uniform Slope: (Yes/No)

48. Unstable Slope-*Pipes in unstable slope may be subjected to down* *slope creep displacement.*

•Slope of land above pipe unstable: (Yes/No)

49.Soil pH-low or high *soil pH may accelerate the rate of deterioration.*

•Soil pH: (pH)

50.Soil Sulfide - *Sulfate reducing bacteria giving off sulfides which are excellent electrolytes.*

•Soil Sulfide: (%)

Financial

51. Annual Maintenance Cost- *Cost of Maintenance like Routine Cleaning etc.*

•Cost: (Dollar/Year)

52. Annual Renewal Cost- *Cost of Preservation and Improvement like grouting, lining, etc.*

•Cost: (Dollar/Year)

53. Installation and Replacement Cost-*Original cost of installation and replacement cost.*

•Cost: ($)

54.Annual Operational Cost- C*ost spent each year for operating and functioning sewer system*

•Cost: (Dollar/Year)

55.Depreciated Value-*Depreciated value, method of calculation, and year analysis started.*

Other

•Depreciated value: (%)

56. Density of Connections-*Number of properties connected to the sewer per mile.*

•properties: (Number/mile)

57. Third Party Damage-*Damages to pipe or bedding may be due to third parties.*

•Damages due to third party: (Yes/No)

58. Other Information –*Other related information that may affect pipe deterioration.*

CCTV Inspection Data (For detailed information please refer to the NASSCO's PACP Manual)

CCTV Inspection Form Headers

59. Survey Date - *Date which the CCTV inspection was conducted.*
- Survey Date (Date)

60. Upstream manhole ID - *Reference number for the upstream manhole*
- Upstream manhole ID: (ID)

61. Upstream rim to invert - *Distance between rim level of manhole and invert level of pipe*
- Upstream rim to invert: (Feet and 1/10)

62. Upstream grade to invert - *Depth between the grade (ground) and the invert*
- Upstream grade to invert: (Feet and 1/10)

63. Upstream rim to grade – *Depth between the rim of the manhole and grade (ground)*
- Upstream rim to grade: (Feet and 1/10)

64. Downstream manhole ID - *Reference number for the upstream manhole*
- Downstream manhole ID: (ID)

65. Downstream rim to invert - *Distance between rim level of manhole and invert level of pipe*
- Downstream rim to invert: (Feet and 1/10)

66. Downstream grade to invert - *Depth between the grade (ground) and the invert*
- Downstream grade to invert : (Feet and 1/10)

67. Downstream rim to grade - *Depth between the rim of the manhole and grade (ground)*
- Downstream rim to grade: (Feet and 1/10)

68. Direction of Survey - *Indicate the direction of the survey*
- Direction of Survey : (Upstream/Downstream)

69. Flow Control - *Indicate how the flow has been controlled during the survey*
- Flow Control: (Type)
  - a) Plugged (P)
  - b) Lift Station (L)
  - c) Bypassed (B)
  - d) Not Controlled (N)

e) De-watered using jetter (D)

70. Size 1 - *pipe diameter if circular, height if not circular*
- Size 1: (inch)
  - a) Pipe diameter (if circular)
  - b) Pipe height (if not circular)

71. Size 2 - *Maximum sewer width*
- Size 2: (inch)

72. Purpose of survey - *Predominant reason survey was conducted*
- Purpose of survey: (Type)
  - a) Maintenance Related (A)
  - b) Infiltration and inflow investigation (B)
  - c) Post rehabilitation (C)
  - d) Pre-rehabilitation (D)
  - e) Pre-acceptance (E)
  - f) Routine Assessment (F)
  - g) Capital Improvement program assessment (G)
  - h) Resurvey for any reason (H)
  - i) Reversal (V)
  - j) Nor Known (Z)

73. Pre-Cleaning - *Type of cleaning conducted for the CCTV Survey*
- Pre-Cleaning: (Type)
  - a) Jetting (J)
  - b) Heavy Cleaning (H)
  - c) No-Pre Cleaning (N)
  - d) Not Known (Z)

74. Date Cleaned - *Date cleaned in year, month, day,*
- Date Cleaned: (Date)

75. Weather - *Weather conditions during survey*
- Weather: (Type)
  - a) Dry (1)
  - b) Heavy Rain (2)
  - c) Light Rain (3)
  - d) Snow (4)

<u>Form Details Section</u>

76. Distance – *Distance of the defect or the observation from the access point or the start of the survey.*
- Distance: (Feet and 1/10)

77. Group/Description - N*ASSCO PACP code to indicate the general description of* *defect Please refer to following tables.*

- Group/Description: (PACP Code) Please refer to following tables

78.Modifier/Severity - *NASSCO PACP code to indicate the general description of defect Please refer to following tables.*

- Modifier/Severity: (PACP Code)

79.Continuous Defect – *If the observation/defect is continuous and type.*

- Continuous Defect: (Type)
  - a)Point defect: Defects which occur at a discrete point in sewer.
  - b)Truly continuous: Defects run along the sewer without any interruption for more than three feet.
  - c)Repeated Continuous: Defect which occur at regular intervals along the sewer. Defects which occur at 75% of joints are also considered to be repeated continuous.

80.Value - *Dimensions of defects. These defects are captured in various dimension types which is summarized at the following table.*

- Value: (Dimensions)
  - a)S/M/L
  - b)Inches
    - 1st Value
    - 2nd Value
  - c)Percentage

81.Joint – *If the observed defect is within 8" of the pipe joint.*

- Joint: (Yes/No)

82.Circumferential Location (At/From) – *Radial or Clock positions of the observations/defects. Depending on the orientation or extend of the observation/defect this value can represent the beginning or position of defect.*

- Circumferential Location (At/From): (Clock position)

83.Circumferential Location (To) – *Radial or clock positions of the end of observations/defects.*

- Circumferential Location (To): Clock Position

Table B-1. Structural Defects

Defect Type	Group	Descriptor	Modifiers	Value Fields
Cracks	(C)	Longitudinal Crack (CL)	Not Used	Not Used
		Circumferential Crack (CC)		
		Multiple Crack (MC)		

		Spiral Cracks (CS)		
Fracture	(F)	Longitudinal Fracture (LF)	Not Used	Not Used
		Circumferential Fracture (FC)		
		Multiple Fractures (FM		
		Spiral Fractures (FS)		
Broken	(B)	Not Used	Soil visible (SV) Void Visible (VV)	Not Used
Hole	(H)	(H)	Soil visible (SV) Void Visible (VV)	Not Used
Deformed	(D)	Vertical Deformation (DV)	Not Used	% deformation
		Horizontal Deformation (DH)		
Collapse	(X)	Pipe Collapse (XP)	Not Used	% (must be more than 40%
		Brick Collapse (XB)		
Joint	(J)	Joint Offset (JO)	Not Used	S/M/L
		Joint Separated (JS)		Medium - 1.0 to1.5 Large - >1.5 of pipe wall
		Joint Angular (JA)		Medium – 5° to 10° Large - > 10°
Surface Damage	(S)	Roughness Increased (SRI)	Mechanical (M) Chemical (C) Not Evident (Z)	Not Used
		Aggregate Visible (SAV)		
		Aggregate Projecting (SAP)		
		Aggregate Missing (SAM)		
		Reinforcement Visible (SRV)		
		Reinforcement Projecting (SRP)		
		Reinforcement Corroded (SRC)		
		Missing Wall (SMW)		
		Surface Spalling (SSS)		
		Other (SZ)		
		Corrosion (SCP)		
		Detached (LFD)		
		Defective End (LFDE)		

Lining Failure	(LF)	Blistered (LFB)	Not Used	Not Used
		Service Cut Shifted (LFAC)		
		Abandoned Connection (LFCS)		
		Overcut Service (LFUC)		
		Undercut Service (LFUC)		
		Buckled (LFBK)		
		Wrinkled (LFR)		
		Other (LFZ		
Weld Failure	(WF)	Longitudinal (WFL)	Not Used	Not Used
		Circumferential (WFC)		
		Multiple (WFM)		
		Spiral (WFS)		
		Other (WFZ)		
Point Repair	(RP)	Pipe Replaced (RPR)	Defective point Repair (D)	Not Used
		Patch Repair (RPP)		
		Localized Pipe liner (RPL)		
		Other (RPZ)		
Brickwork		Displaced (DB)		Not Used
		Missing (MB)		
		Dropped Invert (DI)		Size of Gap (Inch)
		Missing Mortar (MM)		Small - < ½ inch Medium ½ - 2 inch Large - > 3inch

Table B- 2. Operational and Maintenance Defects

Defect Type	Group	Descriptor	Modifiers	Value Fields
		Attached (DA)	Encrustation (DAE)	
			Grease (DAGS)	
			Ragging (DAR)	
			Other (DAZ)	

Deposits	(D)	Settled (DS)	Fine (DSF)	% loss area
			Gravel (DSGV)	
			Hard (DSC)	
			Other (DSZ)	
		Ingress (DN)	Fine (DNF)	
			Gravel (DNGV)	
			Other (DNZ)	
Roots	(R)	Fine (RF)	Barrel (B) Lateral (L) Connection (C)	% loss of cross sectional Area
		Tap (RT)		
		Medium (RM)		
		Ball (RB)		
Infiltration	(I)	Weeper (IW)	Not Used	Estimated loss in Gallons per minute can be used
		Dripper (ID)		Not Used
		Runner (IR)		
		Gusher (IG)		
Obstacles	(OB)	Brick or Masonry (OBB)	Not Used	Quantity of Vermin Observed (Number)
		Pipe Material in Invert (OBM)		
		Object Intruding Through Wall (OBJ)		
		Object Wedged in the Joint (OBJ)		
		Object Through Connection (OBC)		
		External Pipe or Cable (OBP)		
		Build into Structure (OBS)		
		Construction Debris (OBN)		
		Rocks (OBR)		
		Other Obstacles (OBZ)		
Vermin	(V)	Rat (VR)	Not Used	
		Cockroach (VC)		
		Other (VZ)		

Table B-3. Construction Features

Defect Type	Group	Descriptor	Modifiers	Value Fields
Tap	(T)	Factory Made (TF)	Intruding (I) Active (A) Capped (C) Abandoned (B) Defective (D)	Diameter of tap (1st Value) Length of tap intruding (2nd value)
		Break in / Hammer (TB)		
		Saddle Connections (TS)		
Intruding Seal Material	(IS)	Sealing Ring (ISSR)	Hanging (ISSRH) Broken (ISSRB)	% of cross sectional area
		Grout (ISGT)		
		Other (ISZ)		
Line (Direction/Alignment)	(L)	Left (LL)	Not Used	% Deviation
		Left Up (LLU)		
		Left Down (LLD)		
		Right (LR)		
		Right Up (LRU)		
		Right Down (LRD)		
		Up (LU)		
		Down (LD)		
Access Points	(A)	Manhole (AMH)	Mainline (ACOM)	
		Wastewater Access (AWA)	Property (ACOP)	
		Discharge Point (ADP)	House (ACOH)	
		Discharge Point (ADP)		
		Tee Connection (ATC)		
		Other Special Chamber (AOC)		
		Meter (AM)		
		Wet Well (AWW)		
		Junction Box (AJB)		
		Clean Out (ACO)		
		Catch Basin (ACB)		
		End of Pipe (AEP)		

Table B-4 Miscellaneous Features

Defect Type	Group	Descriptor	Modifiers	Value Fields
Miscellaneous Features	(M)	Camera Underwater (MCU)		
		General Observation (MGO)		
		General Photography (MGP)		
		Shape/Size Change (MSC)		Inches, if circular only 1st value for diameter. If not 1st value for vertical, 2nd value for horizontal dimensions.
		Pipe Joint Length Change (MJL)		
		Lining Change (MLC)		
		Material Change (MMC)		
		Survey Abandoned (MSA)		
		Water Level (MWL)	Sag or Slip (MWLS)	% Depth
		Water Mark (MWM)		
		Dye Test (MY)	Visible (MYV) Not Visible (MYN)	% Depth

Appendix C -Wastewater Force Main Pipe Performance Essential Parameters

Detailed Descriptions

Key: Number. **Parameter Name**-*Parameter explanation.*

•Description: (unit of parameter)

<u>**Physical/Structural**</u>

1) **Node Identification Number**-*Identification of each pipes segments (Manhole-Manhole)*
   a)Section ID: (Node)
2) **Pipe Material**-. *Different pipe materials deteriorate at different rates*
   a)Pipe material can be classified as following: (Type)
      i)Asbestos Cement AC
      ii)Brick BR
      iii)Cast Iron CI
      iv)Corrugated Metal Pipe CMP
      v)Concrete Pipe (Non-reinforcement) CP
      vi)Concrete Segments (bolted) CSB
      vii)Concrete Segments (unbolted) CSU
      viii)Clay Tile (not vitrified clay) CT
      ix)Ductile Iron DI
      x)Fiberglass reinforced pipe FRP
      xi)Glass reinforced cement GRC
      xii)Pitch fiber (Orangeburg) OB
      xiii)Polyethylene PE
      xiv)Polypropylene PP
      xv)Plastic / steel composite PSC
      xvi)Polyvinyl Chloride PVC
      xvii)Prestressed Concrete Cylinder Pipe PCCP
      xviii)Reinforced concrete pipe RCP
      xix)Reinforced plastic matrix (truss pipe) RPM
      xx)Steel pipe STL
      xxi)Transite TTE
      xxii)Vitrified clay pipe VCP
      xxiii)Wood WD
      xxiv)Not know XXX

3)**Pipe Diameter**-*Different pipe sizes may fail in different failure modes.*
   a)diameter of pipe: (Inch)

4)**Pipe Installation Year**-*Older pipes may deteriorate faster than newer pipes.*
   a)Pipe installation year: (Year)

5)**Pipe Depth**-*Pipe depth affects pipe loading and deteriorating rate.*
   a)Distance from ground level to the crown of the pipe: (Feet)

6)**Pipe Wall Thickness**-*Wall thickness affects rupture resistance and corrosion penetration rate.*
   a)Original thickness of pipe wall: (Inch)

7)**Pipe Location**-*Geographical location may affect the performance of pipe.*

a)Geographical Location: (Area)
i)Urban
ii)Sub-urban
iii)Rural
iv)Coastal
v)Industrial
vi)Agricultural

8)**Pipe Shape**-*Different pipe shapes may result in different failure modes and deteriorations.*
a)Shape of pipe: (Type)
i)Arched with flat bottom (A)
ii)Barrel (B)
iii)Circular (C)
iv)Egg Shaped (E)
v)Horseshoe (H)
vi)Oval or Elliptical (O)
vii)Rectangle (R)
viii)Square (S)
ix)Trapezoidal (T)
x)U shaped with flat bottom (U)
xi)Other – Please State

9)**Pipe Joint Type**-*Some types of joints may undergo premature failure.*
a)Type of pipe joint: (Type)
i)Lead Yarn Joints
ii)Flanged Joints
iii)Mechanical Joints
iv)Welded Joints
v)Others

10)**Pipe Bedding**-*Inadequate bedding may cause premature pipe failure.*
a)special bedding and soil type If used special bedding, also provide the type: (Yes/No-Type)
i)No Bedding
ii)Clay
iii)Granular
iv)Variable Soils
v)Concrete
vi)Other Known material
vii)Unknown material

11)**Trench Backfill**-*Some backfill materials are more corrosive or frost susceptible.*
a)Trench backfill soil: (Type)
i)Clay
ii)Granular
iii)Variable Soils
iv)Other Known Soil
v)Unknown Soil

12)**Pipe Slope**-*Slope affects the velocity of gravity flow and may result in different pipe deterioration rates.*

a)Slope: (Gradient)

13)**Design Life of Pipe**-*Original design life of each pipe*

a)Life: (Year)

14)**Design Strength of Pipe**-*Original design strength of each pipe.*

a)Strength: (psi)

i)Longitudinal Strength

ii)Ring Strength

15) **Node Length** – *Length of Node (manhole-manhole)*

a)Node length: (Feet)

16) **Pipe Lining** -*Lined pipes have higher resistance to corrosion and reduce infiltration.*

a)Lining of pipe: (Type)

i)Cured in place (CIP)

ii)Fold and Form or Deform/Reform (FF)

iii)Spiral Wound (SW)

iv)Segmented panel (SN)

v)Segmented pipe (SP)

vi)Others (ZZZ)

17) **Pipe Lining pH**– *he pH of lining can be used as an indicator for the deterioration.*

a) Lining pH: (pH)

b)

Operational/Functional

18) **Operational & Maintenance Practice**-*Poor Practices can compromise structural integrity and water quality.*

a)Operation and Maintenance Practice: (Type)

Cleaning

i)Rodding

ii)Bucket Machine

iii)Balling

iv)Flushing

v)Jetting

vi)Scooter

vii)Kites, Bags, and Poly pigs

viii)Silt Traps

ix)Grease traps and sand/oil interceptors

x)Chemical

xi)Others

Maintenance

i)Pipe Cleaning

ii)Pipe Corrosion Control

iii)Pipe Grouting

iv)Repairs

v)Joint and Leak Seals

vi)Point Repairs

19)**Pipe Renewal Record**-*All records of pipe repair/rehab /replace including method use*

a) Renewal Record: (Type)
i)Cured-In-Place Pipe (CIPP) Liners
ii)Pipe Coatings
iii)Fold and Form Pipe Liners
iv)Grout-In-Place Pipe (GIPP) Liner
v)Modified Slip lining
vi)Spray-In-Place Pipe (SIPP) Liners
vii)Sliplining
viii)Spiral Wound – Ungrouped

20)**Pipe Defect Record**-*All records of pipe failures including failure modes.*
a)Defect record: (Record)
b)Type Defects: (Types)

Structural
i)Crack
(1)Longitudinal
(2)Circumferential
(3)Multiple
(4)Spiral
(5)Hinge
ii)Fracture
(1)Longitudinal
(2)Circumferential
(3)Multiple
(4)Spiral
(5)Hinge
iii)Broken
(1)Soil Visible
(2)Void Visible
iv)Hole
(1)Soil Visible
(2)Void Visible
v)Deformed
(1)Vertically
(2)Horizontally
vi)Collapsed
(1)Pipe Collapse
(2)Brick Collapse
vii)Joint
(1)Offset (Displaced)
(2)Separation (Open)
(3)Angular
viii)Surface Damage
(1)Roughness Increased (Mechanical or Chemical)
(2)Aggregate Visible (Mechanical or Chemical)
(3)Aggregate Projecting (Mechanical or Chemical)
(a)Aggregate Missing (Mechanical or Chemical)

(b)Reinforcement Visible (Mechanical or Chemical)
(c)Reinforcement Projecting (Mechanical or Chemical)
(d)Missing Wall (Mechanical or Chemical)
(e)Surface Spalling (Mechanical or Chemical)
(f)Other
(g)Corrosion (Graphitization, Pitting, Crazing)

ii)Buckling
(1)Wall
(2)Dimpling
(3)Inverse Curvature

ii)Lining Features
(1)Detached Lining
(2)Defective End
(3)Blistered Lining
(4)Service Cut Shifted
(5)Abandoned
(6)Overcut Service
(7)Undercut Service
(8)Buckled Lining
(9)Wrinkled Lining
(10)Annular Space
(11)Bulges
(12)Discoloration
(13)Delamination
(14)Resin Slug
(15)Pinholes
(16)Other

iii)Weld Failure
(1)Longitudinal
(2)Circumferential
(3)Multiple
(4)Spiral
(5)Unidentified

w)Point Repair
- Pipe Replaced
- Patch Repair
- Localized Pipe Liner
- Other

x)Brickwork
- Displaced
- Missing
- Dropped Invert
- Missing Mortar (Small, Medium, Large)

7 **Operational and Maintenance**

g)Deposits

- Attached (Encrustation, Grease, Ragging, Other)
- Settled (Fine, Gravel, Hard/Compacted, Other)
- Ingress (Fine, Gravel, Other)

h) Roots
- Fine (Barrel, Lateral, Connection, Joint)
- Tap (Barrel, Lateral, Connection, Joint)
- Medium (Barrel, Lateral, Connection, Joint)
- Ball (Barrel, Lateral, Connection, Joint)

i) Infiltration
- Stain
- Weeper
- Dripper
- Runner
- Gusher

j) Obstacles/Obstructions
- Brick or Masonry
- Pipe Material in Invert
- Object protruding through wall
- Object wedged in joint
- Object through connection/junction
- External pipe cable
- Build into structure
- Construction Debris
- Rocks
- Others

k) Vermin
- Rat
- Cockroach
- Other

l) Grout Test and Seal
- Grout test passed
- Grout test failed

8 **<u>Construction Features</u>**

e) Tap
- Factory Made (Intruding, Active, Capped, Capped, Abandoned, Defective)
- Break in/Hammer (Intruding, Active, Capped, Capped, Abandoned, Defective) Saddle
- (Intruding, Active, Capped, Capped, Abandoned, Defective) Rehabilitated (Intruding,
- Active, Capped, Capped, Abandoned, Defective)

f) Intruding Sealing material
- Sealing ring (Hanging, Broken, Loose)
- Grout
- Other

g) Line

h) Access Point
- Manhole
- Wastewater Access
- Discharge Point

- Tee Connection
- Other Special Chamber
- Meter
- Wet Well
- Junction Box
- Mainline
- Properly
- Catch Basin
- End of Pipe

2)**Pipe Defect Leve**l – The extend of the defects

- Level of Defects;
  - f)1- Excellent: Minor Defect Present
  - g)2- Good: Defects that have not begun to deteriorate
  - h)3- Fair: Moderate defects that will continue to deteriorate
  - i)4- Poor: Severe defects that will become Grade 5 in the foreseeable future
  - j)5- Fail: Pipe no longer functional due to extend of defects.

3)**Location of Defect**s – Location of the defects observed

- Defects location
  - c)Internal, external, or mid-wall angular location (i.e., 12, 3, 6, 9 O'clock)

4)**Blockage/Stoppage**-*Blockage/stoppage make the pipeline network inoperative, sewer pipe is no longer functional.*

- Blockage/Stoppage: (Yes/No- Type)

5)**Sediments**-*Sediments per unit length.*

- Amount of Sediment per feet: (Ton/feet)

6)**Inspection Record**-*Record of inspection i.e. by CCTV, Smoke test, Dye test*

- Method Use: (Type)
  - e)Visual Inspection
  - f)Camera Inspection
  - g)Closed Circuit Television (CCTV)
  - h)Lamping Inspection

7)**Water Corrosivity –** *Corrosivity of the conveyed water*

- Water Corrositivy: (Level)

8)**Hazen Williams C Factor –** *Hazen Williams C factor is used to determine the head loss* *in flow*

- C Factor: (Number)

9) **Operational Pressure** – *Operational pressure pipe is designed for.*

- Operational Pressure: (psi)

10) **Pipe Break** – *The historical break records can be used to assess the probability of failure*

Pipe Break: (Number)

11) **Pipe Break<5 Years** – *The current pipe breaks indicate an ongoing problem with the pipe.*

Pipe Break<5 Years: (Yes/No)

12) **Leak** – *The presence of leak indicates exfiltration*

Leak: (Gal/Min)

13) **Tuberculation** – The presence of tuberculation indicates a surface wear/internal corrosion problem

Tuberculation: (Yes/No)

14) **Pressure Exceeded** – *Pipes operating on higher pressure is prone to structural failures*

Pressure Exceeded: (Yes/No)

15) **Pressure Surges** – *Pipes operating on higher pressure is prone to structural failures*

Pressure Surges: (Yes/No)

16) **Distance to WWTP** – *Pipes operating on higher pressure is prone to structural failures*

Distance to WWTP: (Miles)

17) **Surcharging** – *The presence of surcharging indicates capacity and blockage problems.*

Surcharging: (Yes/No)

18) **Number of Gas Pockets**– *Number of gas pockets indicate gas accumulation and internal corrosion problems*

Number of Gas Pockets: (Yes/No)

*19)***Length of Gas Pockets** – *Length of gas pockets indicate gas accumulation and internal corrosion problems*

Length of Gas Pockets: (Feet)

*20)***Factor of Safety** – *The factor of safety left at the pipe ins an indicator for deterioration.*

Factor of Safety: (Ratio)

Environmental

21)**Soil Type**-*Some soils are corrosive, expansive, and compressible. Some soils contain hydrocarbons and solvents that may cause pipe deterioration.*

- Type of soil: (Type)

  i)Clay
  j)Granular
  k)Mucks
  l)Mud Organic Soil
  m)Variable Soils
  n)Other Known Soil
  o)Unknown Soil

22)**Soil Corrosivity**-*Soil present may be corrosive and may affect pipe environment.*

- Corrosivity level of soil: (Level)

  d)Low
  e)Medium
  f)High

23)**Soil Moisture Content**-*Moisture present in the soil may affect loading and pipe deterioration rate.*

- Moisture Content of the Soil: (Percent)

24)**Stray Currents**-*Stray electrical currents may cause electrolytic corrosion.*

- Electrical currents present near pipe: (Yes/No)

25)**Groundwater Table**-*Groundwater affects soil loading on the pipe and pipe deterioration rate.*

• Depth of water table: (Feet)

26) **Ground Cover**-*Paved ground or vegetation covers result in different deterioration mode and rate.*

• Land Cover: (Type)

i) Grass
j) Asphalt
k) Concrete
l) Trees
m) Bare Ground
n) Water
o) Other Known Type
p) Unknown Type

27) **Loading Condition (Dead Load)** -*loading depends on depth of pipe and infrastructure loading.*

• Death Load i.e. soil, structure, or stockpile above pipe: (Lbs/Sq.ft.)

28) **Loading Condition (Live Load)** - *Live load can be determined from average daily traffic volume and railway loading etc.*

• Live Load i.e. Traffic, Railway, Aircraft: (Average daily traffic volume (ADT) or Level)

d) High Traffic
e) Medium Traffic
f) Low Traffic

29) **Rainfall/Precipitation**-*Rainfall in the areas should be monitored.*

• Rate of rainfall per year: (Inch/Year)

30) **Climate-Temperature**-Frost action in cold *regions may accelerate pipe deterioration.*

a) Region temperature: (°F)

d) Average
e) High
f) Low

31) **H2 S -** *Concentration of Hydrogen Sulfide can increase pipe internal deterioration rate.*

a) Hydrogen Sulfide concentration inside the pipe.: (ppm)

32)**Frost Penetration**-*Pipe dwindling or defects may result from frozen soil.*

a)Soil frozen near or around pipe, depth of penetration in feet: (Yes/No-Ft.)

33)**Tidal Influences**-*Coastal areas with tidal influences may affect pipe bedding.*

a)Tidal influences present: (Yes/No)

Financial

34) **Annual Capital Cost –** *Utility annual capital cost*
a) Annual Capital Cost: (Dollar/Year)

35) **FOG**-*Fats, Oils, and Grease entering the sewer system.*

- FOG released to the system: (Yes/No)

Appendix D -Wastewater Force Main Pipe Preferable Performance Parameters

Key: Number. **Parameter Name**-*Parameter explanation.*
- Description: (unit of parameter)

Physical/Structural

1. **Pipe Section Length** - *Length of pipe section (Joint - joint)*
   - Pipe Section length: (Feet)
2. **Dissimilar Materials -** If dissimilar materials exists.
   - Dissimilar Materials: (yes/no)
3. **Pipe External Coating** - *external coating prevents corrosion of the pipe.*
   - Pipe External Coating: (Type)

     a) No Coating
     b) Factory installed
     c) Field Installed
        - Asphaltic
        - Epoxy
        - Polyethylene
        - Bio-Enhanced Polyethylene
        - Other: _

     d) Unknown
4. **Cathodic Protection** - *Technique used to control the corrosion of a metal surface.*
   - Effective methods used to prevent stress corrosion cracking: (yes/no)
5. **Pipe Vintage –** *Pipes made at a different time and place may deteriorate differently.*
   - When the pipe was made: (Year)

     h) After 1995
     i) 1985 - 1994 (inclusive)
     j) 1975 - 1984 (inclusive)
     k) 1950 - 1974 (inclusive)
     l) 1925 - 1949 (inclusive)

m) Before 1925
n) Unknown age

6. **Pipe Manufacturer Name** - *Name of the manufacturer who manufactured the pipe sample.*

- Name of manufacturer: (Name)

7. **Pipe Manufacture Class** - *Name of the manufacturer who manufactured the pipe sample.*

- Pipe class (e.g., AWWA 301, etc.): (Class)

8. **Pipe Manufacture Date**- *Manufacture date determines some deterioration characteristics*

- Manufacture date: (Year)

9. **Pipe Trench Width** - *Trench width may affect soil loading on the pipes and deterioration rate.*

- Trench Width: (Feet)

10. **Cathodic Protection Design Potential -** *The cathodic protection design potential*

- Cathodic Protection Design Potential: (mV)

11. **Cathodic Protection Present Potential -** *As pipes age the cathodic protection potential decreases suggesting wall thickness loss*

- Cathodic Protection Present Potential: (%)

12. **Pipe Thrust Restrain** - *Inadequate restraint may increase longitudinal pipe stresses.*

- Restraint present, holding or cradling the pipe, if yes, provide type: (Yes/No-Type)

d) Thrust Block
e) Restraint Joint
f) Others

13. **Type of Dissimilar Materials –** *Different types of dissimilar materials effect the corrosion rates*

- Type of dissimilar materials can be classified as following: (Type)

m) Stainless Steel
n) Monel Metal
o) Bronze

p) Copper
q) Brass
r) Nickel
s) Lead
t) Aluminum
u) Cadmium
v) Zinc
w) Magnesium
x) Other: _

14. **Height of Bedding:** *Height of bedding is an important factor for deterioration.*

- Height of Bedding: (inches)

15. **Lateral Connections**-*Condition of laterals and other related information.*

- Condition and other information: (Record)

Operational/Functional

16. **Sewer Flooding**-*Flooding may change property of surrounding soil and loading on pipe.*

- Flooding: (Yes/No)

17. **Maintenance Frequency –** *Frequent maintenance performed will increase the life of the pipe.*

- Maintenance Frequency: (Level)

18. **Type of Cleaning** – *Type of cleaning performed previously*

- Type of Cleaning: (Type)
  d) Jetting
  e) Rutting
  f) Bucketing

19. **Sewer Odors** - *Solids build-ups, poor system hydraulics, flat grade, etc.*

- Odors reported: (Yes/No)

20. **Sewer Overflow (SSO/CSO)**-*Overflow may inundate surrounding soil and change loading on pipe.*

- Overflow: (Yes/No)

21.**Backup Flooding**-*Number of properties affected by flooding in Dry & Wet weather.*

- Number of Properties: (Number)

22.**Name of Treatment Plant** - *Name of treatment plan indicate the location and sewer shed of the pipes.*

- Name of Treatment Plant: (Name)

Environmental

23.**Soil Disturbance**-*Disturbance of soil near the pipe may cause pipe damage or change soil support or loading.*

- Any reason for soil disturbance around the pipe i.e. new construction: (Yes/No)

24.**Soil Chloride**-*Mortar coating usually creates a pH environment of >12.4. Low chloride levels in high pH (>11.5) environments can lead to serious corrosion.*

- Chloride: (Percent)

25.**Soil Sulfate**-Accounts for microbial induced corrosion (MIC) and possible food source for sulfate reducing bacteria in anaerobic conditions under loose coatings.

- Sulfate: (Percent)

26.**Soil Redox Potential**- *Low Redox potentials are more favorable for sulfate reducing bacteria leading to corrosion.*

- Redox Potential: (Level, mV)

27.**Soil Resistivity**- *Soils with low electrical resistivity are more likely to have high corrosion rates.*

- Soil Resistivity: (Level, mV)

28.**Wastewater pH** - *Low pH (<4) means conveyed water is acidic and likely to promote corrosion; high alkaline conditions (pH>8) can also lead to high corrosion.*

- Wastewater pH: (pH)

29.**Wastewater Sulfate** - *Higher concentrations contribute to oxidization.*

- Wastewater Sulfate: (mg/l)

30.**Wastewater Dissolved Oxygen** - *Higher concentrations contribute to oxidization.*

- Wastewater Dissolved Oxygen: (mg/l)

31. **Wastewater Temperature** – *Average Temperature of Wastewater.*

- Wastewater Temperature: (F°)

32. **Foreign Anode Bay Distance** - *Distance of the foreign anode bay causing stray current is proportional to external corrosion.*

- Foreign Anode Bay Distance: *(Feet)*

33. **Runoff Rate**-*Excess water flow which can be caused by rainfall, evaporation, snow melting, etc.*

- Peak Runoff Rate: (Cubic feet/Second)

34. **Non-Uniform Soil**-*Non-uniform soil support in longitudinal axis may increase shear and bending stresses.*

- Non-Uniform Soil: (Yes/No)

35. **Non-Uniform Slope**-*Non-uniform slope may reduce operating performance.*

- Non- uniform Slope: (Yes/No)

36. **Unstable Slope**-*Pipes in unstable slope may be subjected to down slope creep displacement.*

- Slope of land above pipe unstable: (Yes/No)

37. **Soil pH**-low or high *soil pH may accelerate the rate of deterioration.*

- Soil pH: (pH)

38. **Soil Sulfide** - *Sulfate reducing bacteria giving off sulfides which are excellent electrolytes.*

- Soil Sulfide: (%)

Financial

39. **Annual Maintenance Cost**- *Cost of Maintenance like Routine Cleaning etc.*

- Cost: (Dollar/Year)

40. **Annual Renewal Cost**- *Cost of Preservation and Improvement like grouting, lining, etc.*

•Cost: (Dollar/Year)

41.**Installation and Replacement Cost**-*Original cost of installation and replacement cost.*

•Cost: ($)

42.**Annual Operational Cost-** C*ost spent each year for operating and functioning sewer system*

•Cost: (Dollar/Year)

43.**Depreciated Value**-*Depreciated value and method of calculation.*

Other

•Depreciated value: (%)

Appendix E – Gravity Pipe Performance Index Modules

Table E-1. Gravity Integrity Module

Integrity Module				
Parameter	Unit	Range		
		Good	Fair	Poor
Pipe Condition	PACP	0-2.5	0.5-4.5	2.5-5
Location	Year	residence, lawn	national highway	interstate, railroad, airport
Soil Type	Type	coarse sand	fine sand and silt	high plastic clay
Pipe Depth	ft.	0-8	2-18	12-20
Groundwater Table	level	Below Pipe	With Pipe	Above Pipe
Bedding Condition	level	0-2	0.5-4.5	3-5
Pipe Age	Year	0-30	20-60	40-100
Pipe Surcharging	level	0-2	0.5-4.5	3-5
Soil Disturbance	yes/no	No		Yes
Flooding	yes/no	No		Yes
Frost Penetration	yes/no	No		Yes
Bedding Type	type	A-2, A-3	A-4	A-6, A-7
Backfill Type	type	A-2,A-3	A-4	A-6, A-7
Backfill Compaction	%	100-90%	90-75%	<75%
pH of Lining	pH	6-9	5.5-6, 9-9.5	<5.5, >9
Bedding Height	Inches	5-20	20-50	>50
Concrete Encasement	Yes/No	Yes		No

Table E-2. Gravity Internal Corrosion Module

Internal Corrosion Module				
Parameter	**Unit**	**Range**		
		Good	Moderate	Poor
Pipe Condition	PACP	0-2.5	0.5-4.5	2.5-5
Pipe Age	Year	0-30	20-60	40-100
Pipe Slope	%	0-2	1.5-4.5	4-5
Flow Velocity	ft./s	2-3.5	2.5-8	7-10
H2S	ppm	0-50	0-150	100-500
Flow Depth/Diameter	ratio	0-0.3	0.2-0.8	0.7-1
Wastewater pH	pH	6-9	5.5-6, 9-9.5	<5.5, >9
Wastewater Sulfate	mg/l	0-49	50-100	>100
Maintenance Frequency	level	0-2	1-4	3-5
Wastewater Alkalinity	ppm	0-100	100-200	>200
Wastewater Hardness (Carbonate)	gpg	0.5-4	3.5-7	>6.5
Lining Present	yes/no	Yes		No
Lining pH	pH	6-9	5.5-6, 9-9.5	<5.5, >9
Lining Age	years	15-30	45-60	>75
Distance to WWTP	miles	>5	1-4.99	0-0.99
Wastewater TSS	mg/l	20-100	100-150	>150

Table E-3. Gravity External Corrosion Module

External Corrosion Module				
Parameter	**Unit**	**Range**		
		Good	Fair	Poor
Pipe Age	Year	0-30	20-60	40-100
Wall Thickness	% loss	0-10	6-24	20-30
Groundwater Table	level	0-1	0.5-4.5	3-5
Soil Resistivity	ohm cm	0-999	1000-1999	>2000
Soil pH	pH	0-6.5	6-9.5	9-14
Soil Sulfate	ppm	0-999	1000-1999	>2000
Soil Chloride	ppm	200-350		300-400
Soil Redox Potential	mV	-100—60	-80—20	-50-0
Stray Currents	yes/no	No		Yes
Coating Presence	yes/no	Yes		no
Cathodic Protection	yes/no	Yes		no
Cathodic Protection Design Pot.	mv	-900 - -650	-500 - -100	
Cathodic Protection Present Pot.	%	80%-90%	60%-50%	<40%
Dissimilar Materials	yes/no	No		Yes
Foreign Anode Bay Distance	ft.	>10	1-10	0-1

Table E-4. Gravity Surface Wear Module

Surface Wear Module				
Parameter	**Unit**	**Range**		
		Good	Fair	Poor
Pipe Condition	PACP	0-2.5	0.5-4.5	2.5-5
Pipe Age	Year	0-30	20-60	40-100
Pipe Slope	%	0-2	1.5-4.5	4-5
Flow Velocity	ft./s	2-3.5	2.5-8	7-10
Type of Cleaning	Type	Jetting	Rodding	Bucketing
H2S	ppm	0-50	0-150	100-500
Flow Depth/Diameter	ratio	0-0.3	0.2-0.8	0.7-1
Lining Present	yes/no	Yes		No

Table E-5. Gravity Joint Module

Joint Module				
Parameter	**Unit**	**Range**		
		Good	Fair	Poor
Pipe Condition	PACP	0-2.5	0.5-4.5	2.5-5
Joint Type	type	Restrained	Bell on Spigot	Tongue and Groove
Joint Material	type	Steel	Rubber, lead, oakum	Leadite
Pipe Age	Age	0-15	45-60	>75
Backfill Type	type	A-2, A-3	A-4, A-5	A-6, A-7
Groundwater Table	level	0-1	0.5-4.5	3-5

Table E-6. Gravity Lining Module

Lining Module				
Parameter	**Unit**	**Range**		
		Good	Fair	Poor
Lining Present	yes/no	Yes		No
Pipe Condition	PACP	0-2.5	0.5-4.5	2.5-5
Lining Type	type	Structural	semi-structural	non-structural
Lining Material	Type	Fiberglass, Carbon fiber, felt	Vinyl, polyester	epoxy
Lining Age	years	20-60	40-100	>75

Table E-7. Gravity Blockage Module

Blockage Module				
Parameter	**Unit**	**Range**		
		Good	Fair	Poor
Pipe Condition	PACP	0-2.5	0.5-4.5	2.5-5
Pipe Age	Year	0-30	20-60	40-100
Pipe Length	ft.	0-200	100-400	300-500
Pipe Diameter	inch	0-24	12-60	36-72
Pipe Slope	%	4-5	1.5-4.5	2-0
Flow Velocity	ft./s	0-3.5	0.5-8	7-10
Flow Depth/Diameter	ratio	0-0.3	0.2-0.8	0.7-1
Density of Connections	level	0-0.3	0.2-0.8	0.7-1
Lateral Connection Height	Inch	5-4	3-2	<1

of Drop				
Lateral Connection Slope	%	4-5	1.5-4.5	2-0

Table E-8. Gravity I & I Filtration Module

I & I Filtration Module				
Parameter	**Unit**	**Range**		
		Good	Fair	Poor
Pipe Condition	PACP	0-2.5	0.5-4.5	2.5-5
Pipe Age	Year	0-30	20-60	40-100
Pipe Surcharging	level	0-2	0.5-4.5	3-5
Groundwater Table	level	0-1	0.5-4.5	3-5
Soil Type	Type	0-2	0.5-4.5	3-5
Soil Moisture	%	0-15	10-20	20-40
Flooding	yes/no	No		Yes
Tidal Influence	yes/no	No		Yes

Table E-9. Gravity Root Intrusion Module

Root Intrusion Module				
Parameter	**Unit**	**Range**		
		Good	Fair	Poor
Pipe Condition	PACP	0-2.5	0.5-4.5	2.5-5
Pipe Age	Year	0-30	20-60	40-100
Pipe Diameter	inch	0-24	12-60	36-72

Proximity to Trees	ft.	0-10	2-18	10-20
Maintenance Frequency	level	0-2	1-4	3-5
Concrete Encasement	Yes/no	Yes		No

Table E-10. Gravity Capacity Module

Capacity Module				
Parameter	**Unit**	**Range**		
		Good	Fair	Poor
Pipe Condition	PACP	0-2.5	0.5-4.5	2.5-5
Pipe Slope	%	0-2	1.5-4.5	4-5
Flow Depth/Diameter	ratio	0-0.3	0.2-0.8	0.7-1
Flow Velocity	ft./s	2-3.5	2.5-8	7-10
Pipe Surcharging	level	0-2	0.5-4.5	3-5
Maintenance Frequency	level	0-2	1-4	3-5
Flooding	yes/no	No		Yes
Tidal Influence	yes/no	No		Yes
Lateral Connection Size	Inch	36-60	18-24	<8

Appendix F – Force Main Pipe Performance Index Modules

Table F-1. Force Main Integrity Module

Integrity Module				
Parameter	**Unit**	**Range**		
		Good	Fair	Poor
Pipe Age	Year	0-30	20-60	40-100
Location	Year	residence, lawn	national highway	interstate, railroad, airport
Design Life	Year	101-130	100-50	50-0
Vintage	Year	1945-2016	1800-1921	1921-1945
Lining Present	Yes/No	Yes		No
C Factor (1 to 4 Inch)	Factor	90-140	89-70	69-0
C Factor (5 to 8 Inch)	type	95-140	94-75	74-0
C Factor (9 to 12 Inch)	Year	100-140	99-80	79-0
C Factor (13 to 72 Inch)	level	105-140	104-85	84-0
Remaining Wall Thickness	%	100-95	94-70	69-0
Tuberculation	%	0-5	6-55	56-100
Leak	Yes/No	No		Yes
Pipe Break	Frequency	0-1	1-5	>5
Break<5 Years	Yes/No	No		Yes
Defect Type	Type	No	Hole, Joint	Crack, Fracture
Renewal Type	Type	Segment	Section	None
Cathodic Protection	Yes/No	Yes		No
Pressure Class Exceeded	%	0	1-33	>33

Pressure Surges	Frequency	0	1	>1

Table F-2. Force Main Internal Corrosion Module

Internal Corrosion Module				
Parameter	**Unit**	**Range**		
		Good	Fair	Poor
Pipe Age	Year	0-30	20-60	40-100
Wastewater Sulfate	mg/l	0-49	50-100	>100
Wastewater pH	pH	6-9	5.5-6, 9-9.5	<5.5, >9
Distance to WWTP	Miles	>5	1-4.99	0-0.99
H2S	ppm	0-50	0-150	100-500
Lining Present	Yes/No	Yes		No
Lining pH	type	0-6.5	6-9.5	9-14
Flow Velocity	ft./s	>5	4.99 - 3	<2.99
Gas Pockets	Frequency	<1	1-5	>5

Table F-3. Force Main External Corrosion Module

External Corrosion Module				
Parameter	**Unit**	**Range**		
		Good	Fair	Poor
Pipe Age	Year	0-30	20-60	40-100
Coating Present	Yes/No	Yes		No
Soil Resistivity	Ohm-cm	0-999	1000-1999	>2000

Soil pH	pH	0-6.5	6-9.5	9-14
Soil Sulfate	ppm	0-999	1000-1999	>2000
Soil Chloride	ppm	0-99	100-300	>300
Redox Potential	mV	0-19	20-40	>40
Groundwater Table	Level	Below Pipe	With Pipe	Above Pipe
Stray Currents	Yes/No	No		Yes
Dissimilar Materials	Yes/No	No		Yes

Table F-4. Force Main Surface Wear Module

Surface Wear Module				
Parameter	**Unit**	**Range**		
		Good	Fair	Poor
Pipe Age	Year	0-30	20-60	40-100
Wastewater Sulfate	ppm	0-999	1000-1999	>2000
Wastewater pH	pH	0-6.5	6-9.5	9-14
Distance to WWTP	Miles	>5	1-4.99	0-0.99
H2S	ppm	0-49	50-100	>100
Lining Present	Yes/No	Yes		No
Lining pH	type	0-6.5	6-9.5	9-14
Flow Velocity	ft./s	>5	4.99 - 3	<2.99

Table F-5. Force Main Capacity Module

Capacity Module				
Parameter	**Unit**	**Range**		
		Good	Fair	Poor
Pipe Age	Year	0-30	20-60	40-100
Flow Velocity	ft./s	<2.99	5 - 3	>5
Pipe Diameter	Inches	>36	12-36	0-11
Maintenance Frequency	Frequency	>3	3-1	>1
Tidal Influence	Yes/No	No		Yes
Tuberculation	%	0-5	6-55	56-100

Table F-6. Force Main Joint Performance Module

Joint Performance Module				
Parameter	**Unit**	**Range**		
		Good	Fair	Poor
Joint Type	type	Restrained	Bell on Spigot	Tongue and Groove
Joint Material	type	Steel	Rubber, lead, oakum	Leadite
Pipe Age	Age	0-15	45-60	>75
Backfill Type	type	A-2, A-3	A-4, A-5	A-6, A-7
Groundwater Table	level	0-1	0.5-4.5	3-5

Table F-7. Force Main Lining Performance Module

Lining Performance Module				
Parameter	**Unit**	**Range**		
		Good	Fair	Poor
Lining Present	yes/no	Yes		No
Lining Type	type	Structural	semi-structural	non-structural
Lining Material	Type	Fiberglass, Carbon fiber, felt	Vinyl, polyester	epoxy
Lining Age	years	20-60	40-100	>75

Table F-8. Force Main Blockage Module

Blockage Module				
Parameter	**Unit**	**Range**		
		Good	Fair	Poor
Pipe Age	Year	0-30	20-60	40-100
Pipe Length	ft.	0-100	100-300	>300
Pipe Diameter	Inches	>36	12-36	0-11
Maintenance Frequency	Frequency	>3	3-1	>1
Wastewater TSS	mg/l	20-100	100-150	>150
Number of Valves	Number	0-1	1-3	>3

Appendix G – Piloting Results

Appendix G1 – Utility #1 Piloting Results

Overview

Research team has received data from participating utility #1 in the form of;

- CCTV inspection records
- Maps of Trunk sewer locations
- Capacity, Management, Operations, and Maintenance (CMOM) report from 2013.

Due to limitations of the data received, piloting can only be conducted with data obtained from the trunk sewer #1. Trunk Sewer #1 is owned and operated by utility #1 and was originally constructed in 1954. The sewer is approximately 6.4 miles and varies in diameter from 30 to 72 inches. Three segments in this trunk sewer were inspected and data extracted for these five investigated segments to pilot the performance index and prediction model. Of these 30 segments, 26 were selected to develop the prediction model, and four were chosen to assess the accuracy of the developed deterioration model. Extracted data from utility records are summarized in Table G1-1.

Table G1-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe Age	CMOM
Pipe Condition	CCTV Inspection Data
Pipe Depth	CCTV Inspection Data
Pipe Diameter	CCTV Inspection Data
Pipe Length	CCTV Inspection Data
Pipe Location	Map
Pipe Material	CCTV Inspection Data
Pipe Slope	CCTV Inspection Data
Lining Presence	CCTV Inspection Data
Lining Type	CCTV Inspection Data

Flow Depth/Diameter	CCTV Inspection Data
Density of Connections	CCTV Inspection Data
Type of Cleaning	
Renewal Date	

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset are summarized at Table G1-2.

Table G1-2. Focused Calibration Dataset.

Parameter	Lower Range	Higher Range
Pipe Age	61	NA
Pipe Depth	9.5	15
Pipe Diameter	30	36
Pipe Length	16	347
Pipe Location	No Load	Under Highway
Pipe Slope	41.45-82.8	0.03-0.09
Flow Depth/Diameter	0.05	0.05
Pipe Material	RCP	NA

After the model run with the dataset, the results of the PACP coding and the model outputs are compared. It is important to note that the PACP coding results are normalized by multiplying by 2 to have a comparable scale with the index outputs. The results differences between the PACP defect coding and performance index output range between 0-2. Table G1-3 summarizes the overall performance for the focused dataset. Following section discuss the reason for the differences.

Table G1-3 Final Piloting Results

Total Number of Segments	Segments with 0 difference	Segments with 1 difference	Segments with 2 Difference
26	12	6	8
100%	46.15%	23.08%	30.77%

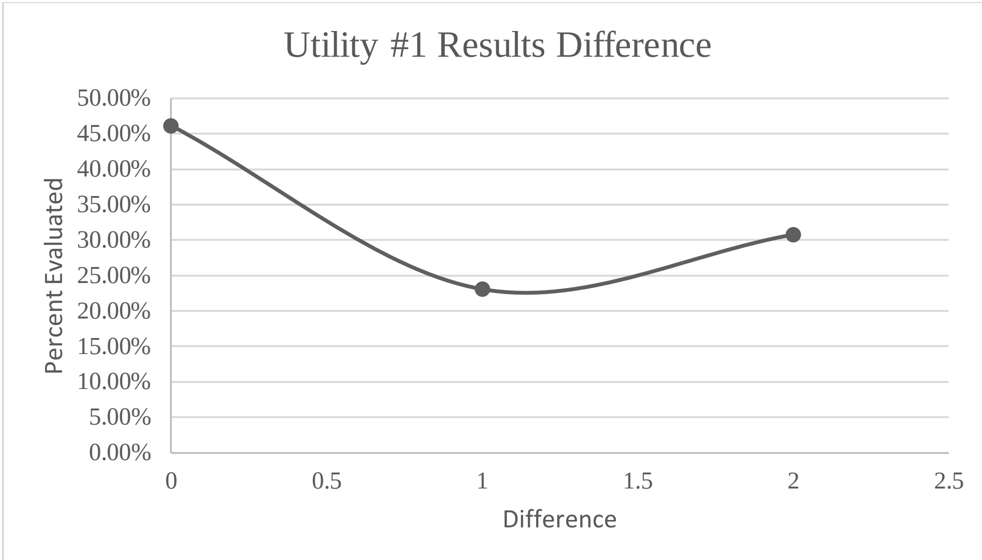

Figure G1-1. Utility #1 Results Difference

Results with 0 Difference

Pipes with PACP grade of 5 (failed) tend to give the same result for the index. Table G1-4 summarizes already failed pipes in the sample population.

Table G1-4. Segments with 0 Difference

PIPEiD	Model	PACP (Normalized)	Difference
1-2	4	4	0
4-5	4	4	0
5-6	4	4	0
6-7	4	4	0
7-7A	4	4	0
7A-8	4	4	0
8-9	4	4	0
13-14	7	7	0
21-22	4	4	0
22-23	4	4	0
24-25	4	4	0
27-28	4	4	0

Results with 2 Difference

Pipe segments where results are two difference between the normalized PACP grade and the index output is summarized in Table G1-5. Results summarized indicate the pipes with the desirable parameters (low range) are not penalized for the performance. Results also suggest that although there are undesirable parameters for some of the pipe segments, the effects of these parameters are not significant for the pipe performance due to various other parameters.

Table G1-5. Segments with 2 Differences

PIPEiD	Model	PACP Normalized	Difference
2-3	2	0	2
3-4	2	0	2
10-11	4	2	2
11A-12	4	2	2
17-18	8	6	2
20-21	8	6	2

Results with 4 Difference

Pipe segments where results are four difference between the normalized PACP grade and the index output is summarized in Table G1-6. Results summarized indicate that although for some segments have undesirable parameters and the performance of these segments are calculated by considering these parameters. Some significant pipe segments with the high difference between the index and the PACP grades are further investigated in the following case studies.

Table G1-6. Pipe segments where results are 4 difference between the normalized PACP grades.

PIPEiD	Model	PACP (Norm.)	Diff.	Diff. Module
11-11A	4	0	4	Integrity
12-13	4	0	4	Integrity

14-15	4	0	4	Integrity
15-16	4	0	4	Integrity
16-17	4	0	4	Integrity
19-20	4	0	4	Integrity
23-24	4	0	4	Integrity
26-26A	4	0	4	Integrity

Case Studies

Table G1-7. Pipe Segment 11-11A

Parameter	Value
Pipe Age	61
Pipe Depth	9.5
Pipe Diameter	30
Pipe Length	16
Pipe Location	Highway
Pipe Slope	3.12
Flow Depth/Diameter	0.05
Pipe Material	RCP

PACP vs. index output: 0 vs. 4

Module with maximum result: Integrity

Reason: Aged pipe under highway

Discussion: Although there is no defect noted by the CCTV inspection, the pipe is located on a major highway and has a high age. These parameters indicate that there is the high amount of dynamic loading on the pipe which makes it prone to integrity issues.

Prediction Model Piloting and Discussion

Time Dependent Analysis

The data received from participating utility was used to illustrate the implementation of the performance prediction model and present preliminary results. The initial results for Gravity concrete pipes inspected at the participating utility suggest that the expected remaining lives of these pipes are 103 years. Results of the state dependent performance prediction are summarized in figure G1-2. Validation dataset was also plotted to summarize the validation results in this figure.

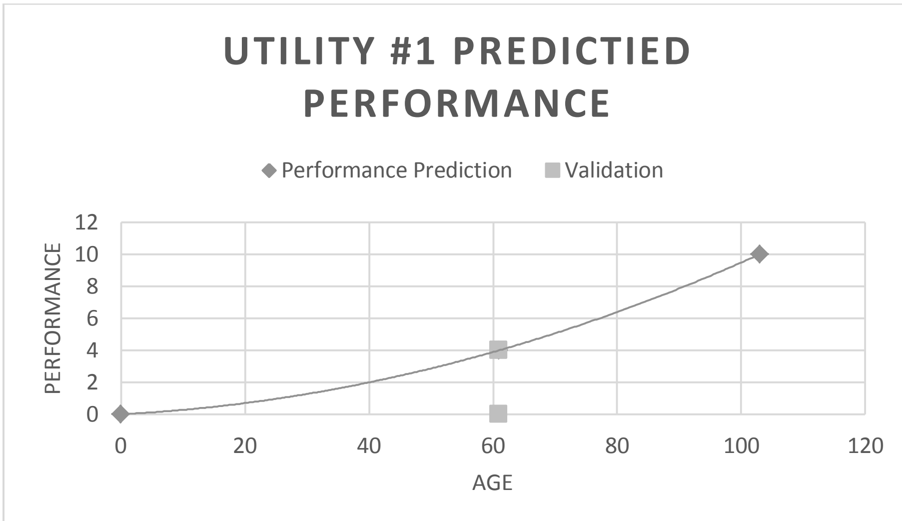

Figure G1-2. Preliminary State Dependent Performance Prediction Results

Four segments (13.3%) was used as the testing dataset, the accuracy of the predictions is measured with the confusion matrix using this dataset. The accuracy of the predictions with the dataset used is 75%. Table G1-8 summarizes the selected segments, only one segment (26A-27) does not agree with the predictions.

Table G1-8. Validation Dataset

PIPEiD	Model	PACP (Norm.)	Diff.
9-10	4	4	4
18-19	4	4	4
25-26	4	4	4
26A-27	4	0	4

State Dependent Analysis

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The initial results for gravity pipes suggest that the expected remaining lives of these pipes are 98 years. Results of the time-dependent performance prediction are summarized in figures G1-3 and G1-4.

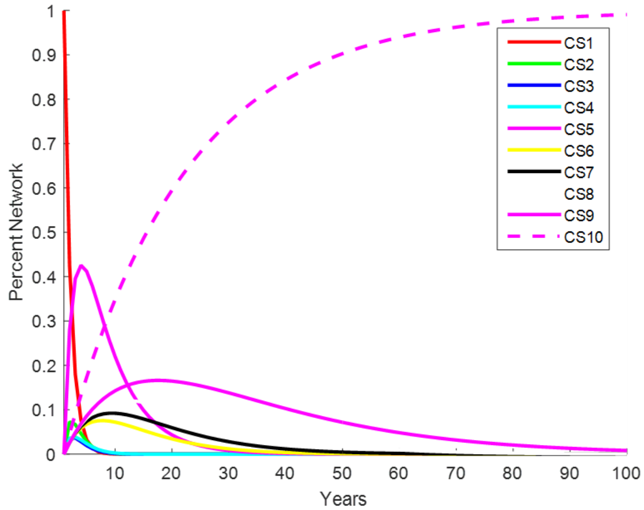

Figure G1-3. Preliminary State Dependent Performance Prediction Results

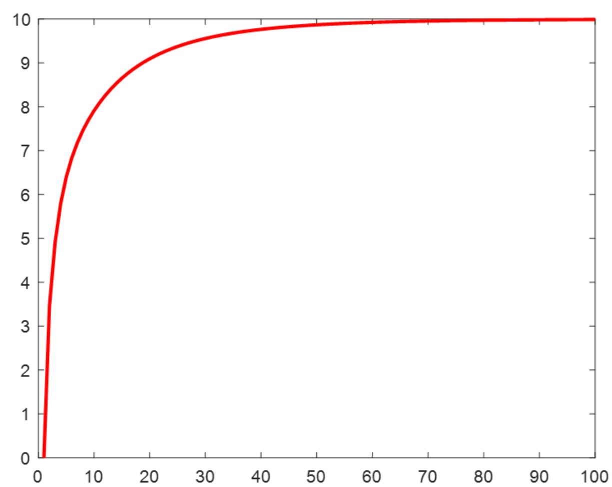

Figure G1-4. Preliminary State Dependent Performance Prediction Results

Appendix G2 – Utility #2 Piloting Results

Overview

The research team has received data from participating utility #2 in the form of GIS geo-database. This GIS geodatabase contains records for 15644 pipe segments totaling in 493.23 miles in length. 88 segments were randomly selected for the piloting the performance index. Data is extracted for these 88 segments to pilot the performance index. Extracted data from utility records are summarized in Table G2-1.

Table G2-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe ID	Geodatabase
Pipe Age	Geodatabase
Pipe Diameter	Geodatabase
Pipe Length	Geodatabase
Pipe Slope	Geodatabase
Pipe Material	Geodatabase
Pipe Shape	Geodatabase

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset are summarized at Table G2-2.

Table G2-2. Focused Calibration Dataset.

Parameter	Lower Range	Higher Range
Pipe Age	14.26	84.41
Pipe Diameter	8	36
Pipe Length	8	400
Pipe Slope	0.04	32.1
Pipe Material	RCP, DI	
Pipe Shape	Circular	

The index was run with the dataset and the performance index output ranges between 1-10. Table G2-3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G2-3 Final Piloting Results

Total Number of Segments	Segments in Condition (1)	Segments in Condition (2)	Segments in Condition (3)	Segments in Condition (4)	Segments in Condition (5)	Segments in Condition (6)	Segments in Condition (7)	Segments in Condition (8)	Segments in Condition (9)	Segments in Condition (10)
88	5	53	9	4	3	2	2	2	2	2
100%	5.68%	60.23 %	10.23 %	4.55%	3.41%	2.27%	2.27%	2.27%	2.27%	2.27%

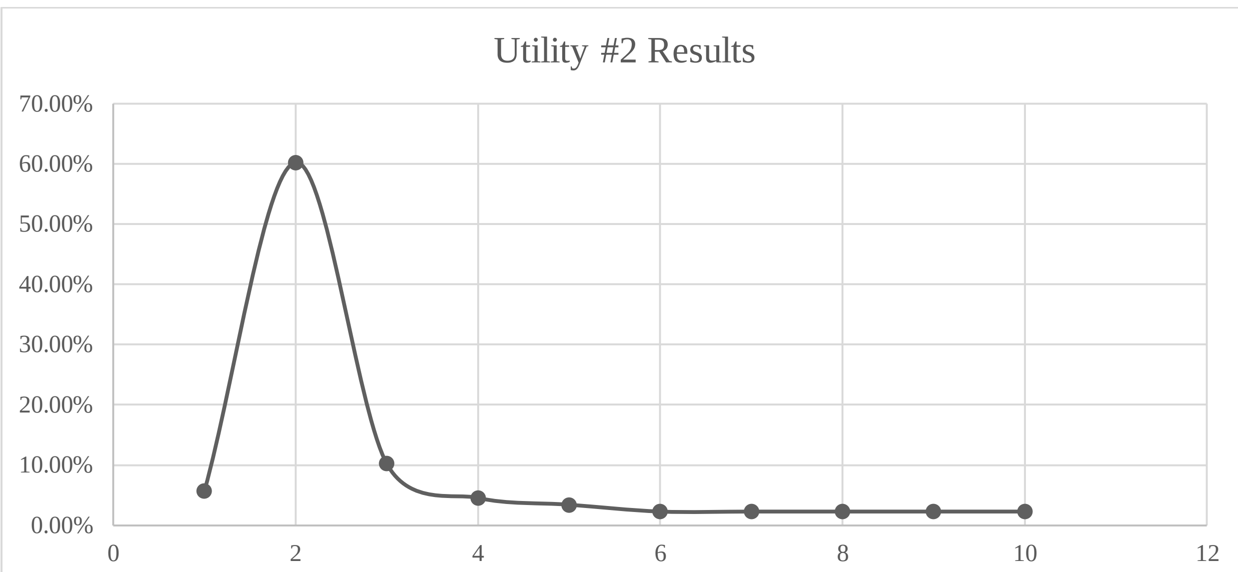

Figure G2-1. Utility #2 Results

Results with 1 (excellent) and 2 (very good) performance grade

Table G2-4 discuss summarize pipes with 1 (excellent) and 2 (very good) performance grade.

Table G2-4. Segments with 1 (excellent) and 2 (very good) performance

PIPEiD	Model
1	2
2	2
4	2
5	1
7	2
8	2
9	2
12	2
14	2
16	2
17	2
18	2
19	2
20	2
21	2
22	2
23	1
24	2
25	2
27	2
28	2
29	2
30	2
32	2
33	2
34	2
36	2
37	2
38	1
39	2
42	2
44	2
46	2
47	2
48	2
49	2
53	2
55	2
57	2

58	2
60	2
65	1
67	2
68	2
69	2
71	2
72	2
74	2
75	1
76	2
77	1
78	2
80	2
81	2
82	2
83	2
84	2

Results with 3 (good) and 4 (satisfactory) performance grade.

Pipe segments with 3 (good) and 4 (Satisfactory) performance grade are summarized in Table G2-5.

Table G2-5. Segments with 3 (good) and 4 (Satisfactory) performance grade.

PIPEiD	Model
10	3
11	3
15	4
26	4
40	4
50	4
51	3
52	3
59	3
61	3
62	3
63	3
64	3

Results with 5 (fair) and 6 (poor) performance grade.

Pipe segments with 5 (fair) and 6 (poor) performance grade are summarized in Table G2-6.

Table G2-6. Segments with 5 (fair) and 6 (poor) performance grade.

PIPEiD	Model
3	6
6	6
56	5
79	5

Results with 7 (serious) and 8 (critical) performance grades.

Pipe segments with 7 (serious) and 8 (critical) performance grades are summarized in table G2-7.

Table G2-7. Segments with 7 (serious) and 8 (critical) performance grades.

PIPEiD	Model
31	7
35	7
45	8
54	8

Results with 9 (failure) and 10 (failed) performance grade.

Pipe segments with 9 (failure) and 10 (failed) performance grade are summarized in Table G2-8.

Table G2-8. Segments with 9 (failure) and 10 (failed) performance grade.

PIPEiD	Model
13	10
41	10
66	9
73	9
85	10

Case Studies

Table G2-8. Pipe Segment 1487

Parameter	Value
Pipe ID	85
Pipe Age	84.5
Pipe Diameter	8
Pipe Length	298
Pipe Slope	12.41
Pipe Material	Cast Iron
Pipe Shape	Circular

Index output: 10 (Critical)

Module with maximum result: Integrity

Reason: High age, cast iron pipe

Discussion: This high aged (84.5) cast iron pipe is prone to integrity issues.

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The initial results for gravity pipes suggest that the expected remaining lives of these pipes are 92 years. Results of the time-dependent performance prediction are summarized in Figures G2-2 and G2-3.

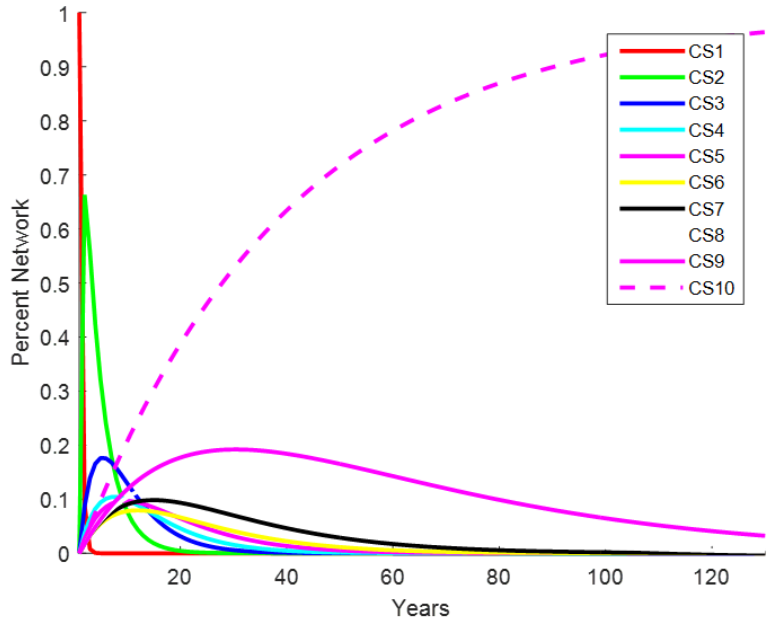

Figure G2-2. Preliminary Time Dependent Performance Prediction Results

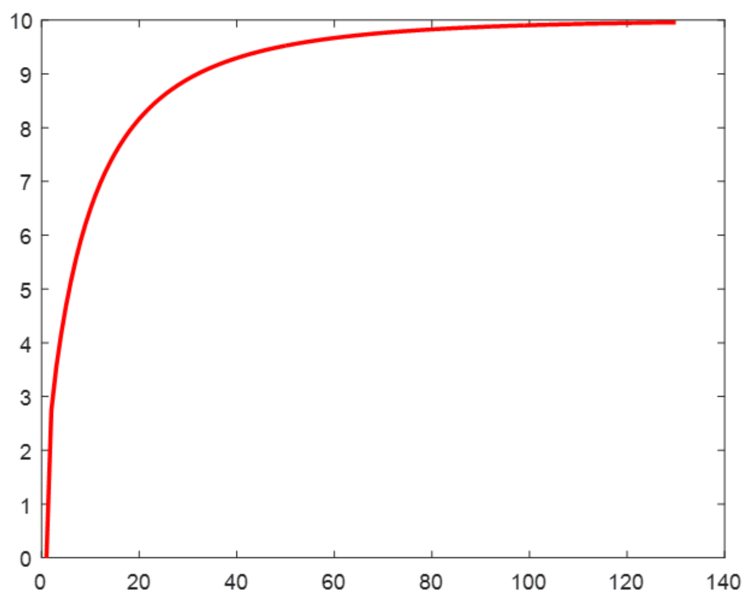

Figure G2-3. Preliminary Time Dependent Performance Prediction Results

Appendix G3 – Utility #3 Piloting Results

Overview

The research team has received data from participating utility #3 in the form of GIS geo-database. This GIS geodatabase contains records for 19251 pipe segments totaling in 728.08 miles in length.

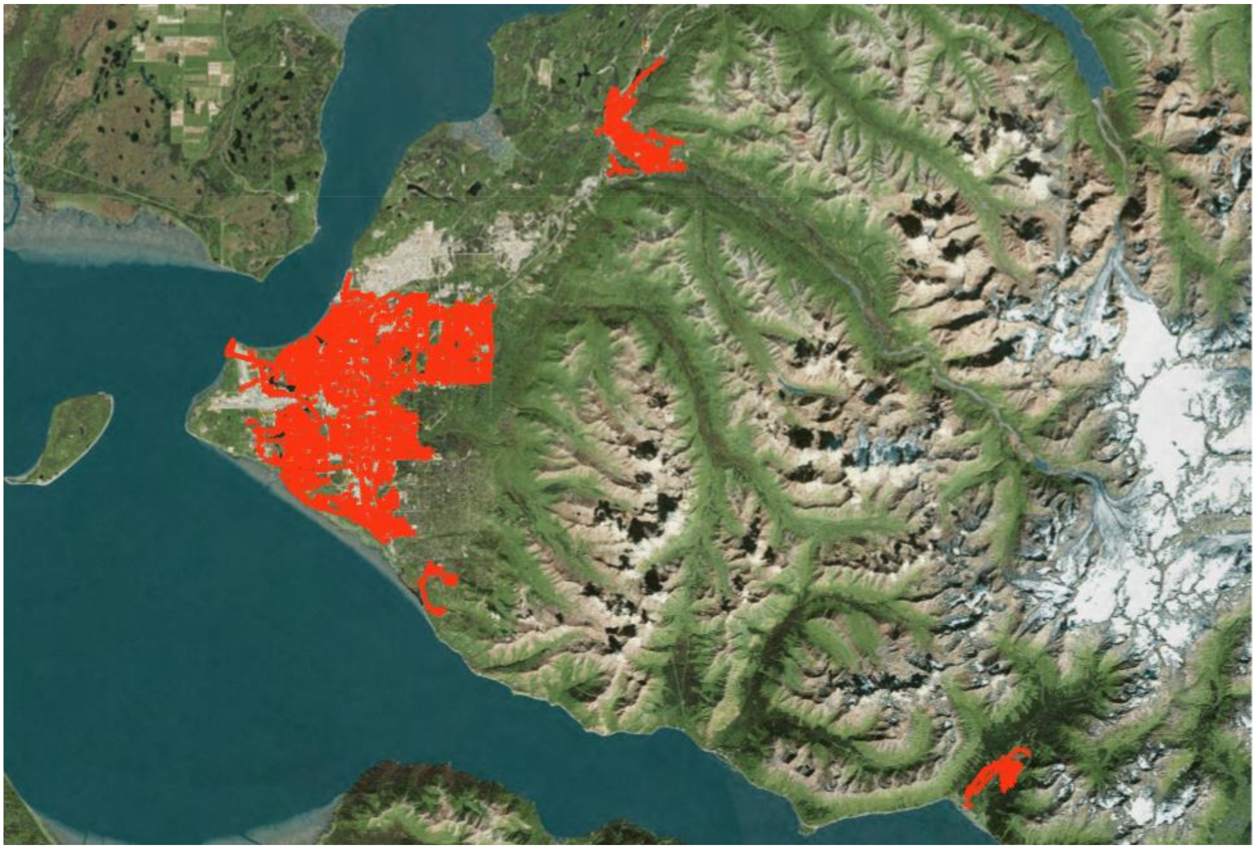

Figure G3-1. Participating Utility Sewer System

265 segments were randomly selected for the piloting the performance index. Data is extracted for these 265 segments to pilot the performance index. Extracted data from utility records are summarized in Table G3-1.

Table G3-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe ID	Geodatabase

Pipe Age	Geodatabase
Pipe Diameter	Geodatabase
Pipe Length	Geodatabase
Pipe Slope	Geodatabase
Pipe Material	Geodatabase
Shape	Geodatabase

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset are summarized at Table G3-2.

Table G3-2. Focused Calibration Dataset.

Parameter	Unit	Lower Range	Higher Range
Pipe Age	Years	8.33	69.54
Pipe Diameter	Inch	8	48
Pipe Length	Feet	19.55	506.58
Pipe Slope	%	0.33	8.5
Pipe Material	Type	AC, CL, CI, CV, DI, HDPE, RC, WC	
Pipe Shape	Type	Circular	

The index was run with the dataset and the performance index output ranges between 1-10. Table G3-3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G3-3 Final Piloting Results

Total Number of Segments	Segments in Condition (1)	Segments in Condition (2)	Segments in Condition (3)	Segments in Condition (4)	Segments in Condition (5)	Segments in Condition (6)	Segments in Condition (7)	Segments in Condition (8)	Segments in Condition (9)	Segments in Condition (10)
262	65	27	45	53	36	4	4	20	5	3
100%	24.81 %	10.31 %	17.18 %	20.23 %	13.74 %	1.53%	1.53%	7.63%	1.91%	1.15%

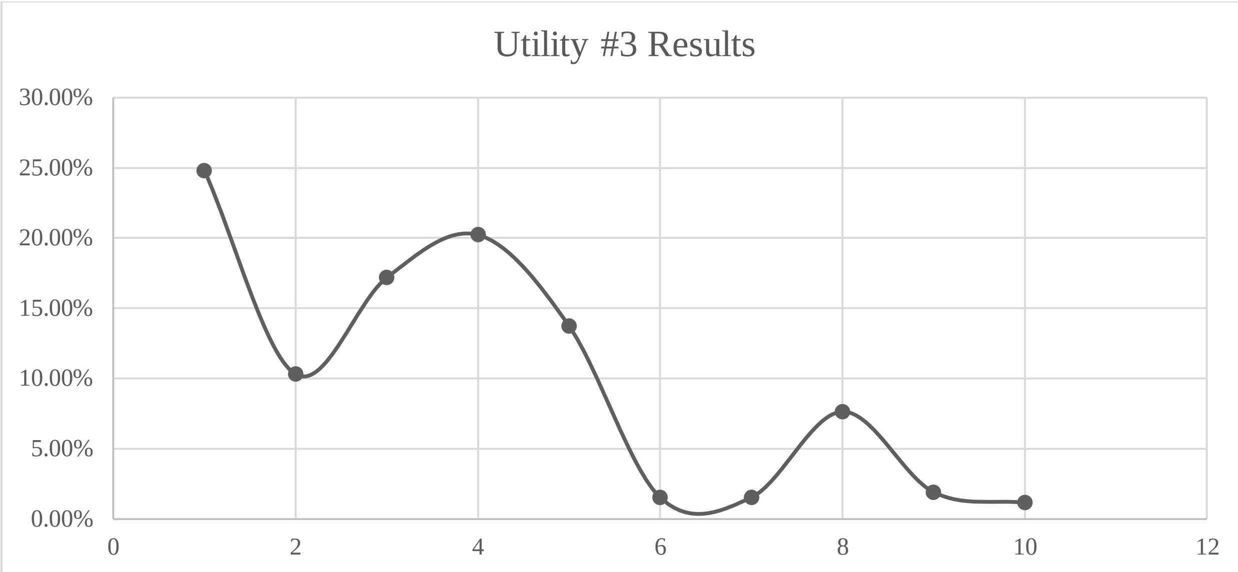

Figure G3-2. Utility #3 Results

Results with 1 (excellent) performance grade

Table G3-4 discuss summarize pipes with 1 (excellent) and 2 (very good) performance grades.

Table G3-4. Segments with 1 (excellent) and 2 (very good) Performances.

PIPEiD	Model
3	1
7	1
9	1
12	1
16	1
17	1
19	1
20	1
34	1
36	1
37	1
40	1
41	1
46	1
47	1
50	1
58	1

60	1
62	1
66	1
70	1
88	1
89	1
90	1
95	1
100	1
101	1
103	1
105	1
109	1
114	1
130	1
149	1
157	1
161	1
162	1
165	1
166	1
167	1
170	1
171	1
172	1
175	1
179	1
180	1
181	1
183	1
192	1
194	1
196	1
200	1
206	1
214	1
215	1
216	1
218	1
219	1
222	1
229	1

242	1
250	1
251	1
255	1
256	1
260	1
169	2
124	2
131	2
136	2
137	2
4	2
5	2
6	2
8	2
10	2
11	2
13	2
14	2
21	2
22	2
32	2
38	2
39	2
42	2
44	2
45	2
51	2
52	2
53	2
54	2
56	2
57	2

Results with 3 (good) and 4 (satisfactory) performance grade.

Pipe segments with 3 (good) and 4 (Satisfactory) performance grade are summarized in table G3-5.

Table G3-5. Segments with 3 (good) and 4 (Satisfactory) performance grade.

PIPEiD	Model
59	3
61	3
64	3
67	3
69	3
74	3
80	3
87	3
93	3
98	3
102	3
111	3
133	3
141	3
147	3
150	3
151	3
153	3
154	3
158	3
159	3
173	3
184	3
185	3
187	3
190	3
191	3
201	3
203	3
205	3
209	3
210	3
223	3
227	3
231	3
232	3
234	3
237	3
240	3

241	3
243	3
244	3
246	3
252	3
259	3
120	4
220	4
63	4
55	4
104	4
1	4
18	4
24	4
26	4
28	4
30	4
65	4
73	4
75	4
76	4
81	4
82	4
85	4
96	4
107	4
108	4
110	4
112	4
113	4
115	4
116	4
121	4
123	4
127	4
129	4
134	4
138	4
142	4
143	4
145	4
148	4

155	4
168	4
182	4
189	4
195	4
197	4
198	4
217	4
224	4
233	4
236	4
245	4
247	4
248	4
249	4
253	4
254	4

Results with 5 (fair) and 6 (poor) performance grade.

Pipe segments with 5 (fair) and 6 (poor) performance grade are summarized in table G3-6.

Table G3-6. Segments with 5 (fair) and 6 (poor) performance grade.

PIPEiD	Model
213	5
31	5
199	5
68	5
188	5
91	5
2	5
94	5
23	5
160	5
152	5
27	5
35	5
71	5
77	5
79	5
83	5

86	5
92	5
97	5
99	5
106	5
125	5
126	5
132	5
135	5
163	5
177	5
186	5
204	5
225	5
228	5
230	5
238	5
239	5
257	5
235	6
193	6
211	6
48	6

Results with 7 (serious) and 8 (critical) performance grades.

Pipe segments with 7 (serious) and 8 (critical) performance grades are summarized in table G3-7.

Table G3-7. Segments with 7 (serious) and 8 (critical) performance grades.

PIPEiD	Model
128	7
29	7
202	7
221	7
15	8
25	8
43	8
49	8
72	8
78	8
84	8

118	8
119	8
122	8
139	8
144	8
146	8
156	8
174	8
176	8
178	8
207	8
208	8
261	8

Results with 9 (failure) and 10 (failed) performance grade.

Pipe segments with 9 (failure) and 10 (failed) performance grade are summarized in table G3-8.

Table G3-8. Segments with 9 (failure) and 10 (failed) performance grade.

PIPEiD	Model	Module
140	9	Blockage
117	9	Blockage
258	9	Blockage
212	9	Surface Wear
164	9	Blockage
33	10	Blockage
262	10	Blockage
226	10	Blockage

Case Studies

Table G3-9. Pipe Segment 212

Parameter	Value
PIPEiD	212
Pipe Age	69.54

Pipe Diameter	16
Pipe Length	279.34
Pipe Slope	0.24
Pipe Material	AC
Pipe Shape	Circular

Index output: 9 (Failing)

Module with maximum result: Surface Wear

Reason: High age, low slope

Discussion: This high aged (69.51) asbestos cement pipe is prone to surface wear issues due to its low slope (0.24%).

Table G3-10. Pipe Segment 226

Parameter	Value
Pipe ID	226
Pipe Age	42.52
Pipe Diameter	42
Pipe Length	501.125
Pipe Slope	0.04
Pipe Material	DI
Pipe Shape	Circular

Index output: 10 (Failed)

Module with maximum result: Blockage

Reason: High length, low slope

Discussion: This ductile iron pipe is prone to blockage issues due to its high length (501 ft.) and low slope (0.04%)

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The initial results for gravity pipes suggest that the expected remaining lives of these pipes are 126 years. Results of the time-dependent performance prediction are summarized in Figures G3-3 and G3-4.

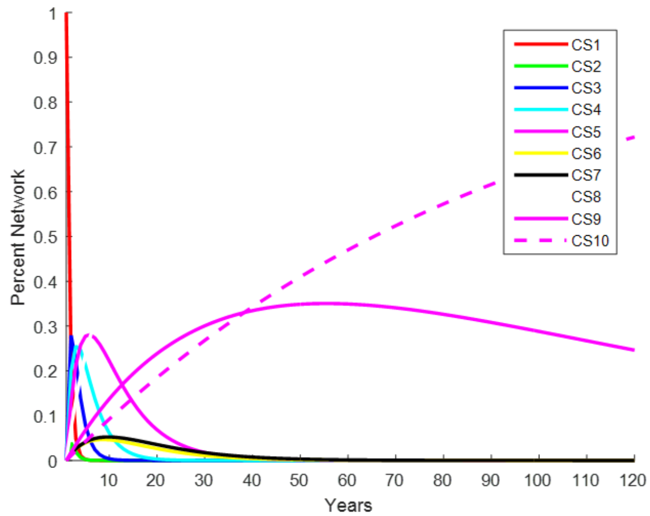

Figure G3-3. Preliminary State Dependent Performance Prediction Results

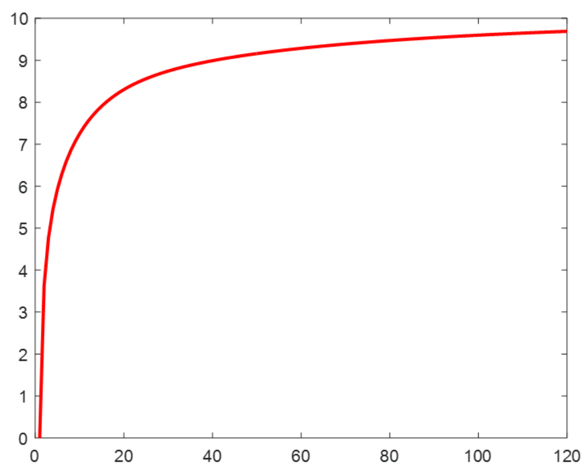

Figure G3-4. Preliminary State Dependent Performance Prediction Results

Appendix G4 – Utility #4 Piloting Results

Overview

The research team has received data from participating utility #4 in the form of GIS Geodatabase files. This database contains records for 53657 pipe segments totaling in 1868 miles in length. Utility sewer system is summarized in figure G4-1.

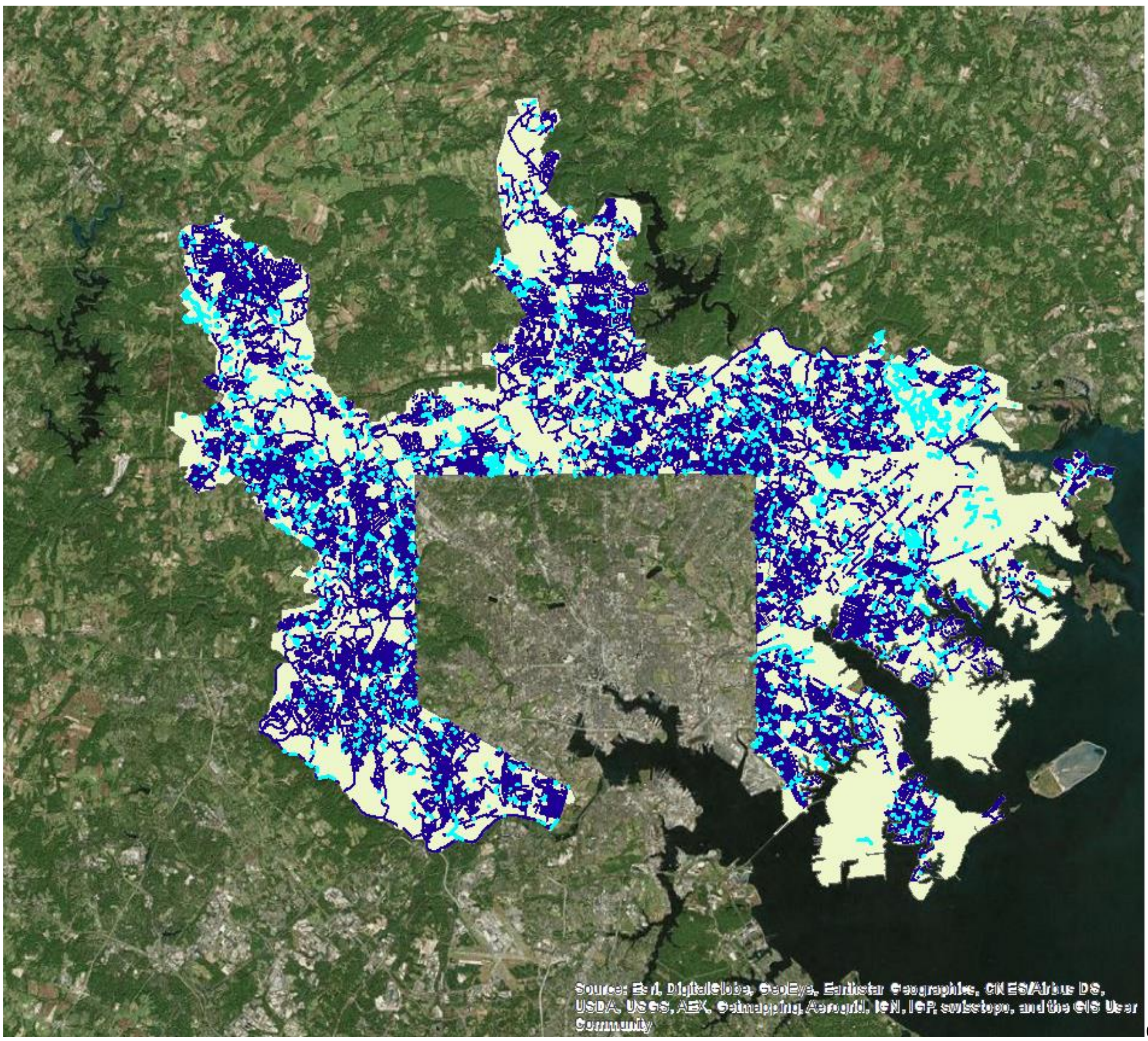

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Figure G4-1. Utility #4 Sewer System

159 segments were randomly selected for the piloting the performance index. Data is extracted for these 154 segments to pilot the performance index. Extracted data from utility records are summarized in Table G4-1.

Table G4-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe ID	Geo-database
Pipe Age	Geo-database
Pipe Size	Geo-database
Pipe Length	Geo-database
Pipe Lining	Geo-database
Lining Type	Geo-database
Slope	Geo-database
Pipe Material	Geo-database
Pipe Shape	Geo-database

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset are summarized at Table G4-2.

Table G4-2. Focused Calibration Dataset.

Parameter	Unit	Lower Range	Higher Range
Pipe Age	Year	7	84
Pipe Size	Inches	8	33
Pipe Length	Feet	4.4	610.4
Pipe Lining	Yes/No	No	Yes
Lining Type	Type	CIPP, Fold and Form	
Slope	% Grade	0.21	16
Pipe Material	Type	AC, CI, CP, DI, PVC, TC	
Pipe Shape	Type	Circular	

The index run with the dataset and the performance index output range between 1-10. Tables 3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G4-3. Final Piloting Results

Total Number of Segments	Segments in Condition (1)	Segments in Condition (2)	Segments in Condition (3)	Segments in Condition (4)	Segments in Condition (5)	Segments in Condition (6)	Segments in Condition (7)	Segments in Condition (8)	Segments in Condition (9)	Segments in Condition (10)
158	34	23	16	27	23	12	10	9	3	1
100%	21.52 %	14.56 %	10.13 %	17.09 %	14.56 %	7.59%	6.33%	5.70%	1.90%	0.63%

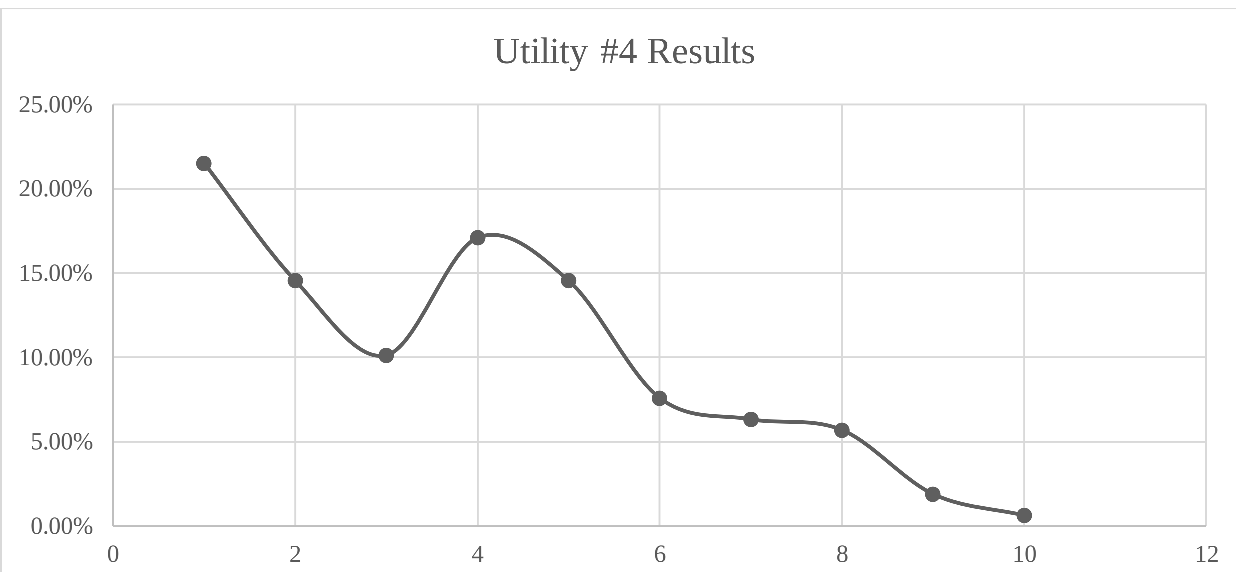

Figure G4-1. Utility #4 Results

Results with 1 (excellent) performance grade

Table G4-4 discuss summarize pipes with 1 (excellent) and 2 (very good) performance grade.

Table G4-4. Segments with 1 (excellent) and 2 (very good) performance

PIPEiD	Model
58271	1
66498	1
92960	1
107111	1
114854	1
118035	1
123818	1
126739	1
128027	1
128350	1
132483	1
139233	1
144644	1
144656	1
146886	1
163586	1
191192	1
306279	1
325478	1
332201	1
371581	1
471817	1
481103	1
485580	1
485985	1
487187	1
489125	1
489760	1
490723	1
491991	1
503830	1
540645	1
574570	1
585453	1
58577	2
64076	2
75577	2
77448	2
102188	2
61754	2
76226	2

102431	2
58222	2
58481	2
58675	2
58789	2
61569	2
66869	2
71621	2
73311	2
75473	2
75941	2
76233	2
76297	2
76299	2
77580	2
84445	2

Results with 3 (good) and 4 (satisfactory) performance grade.

Pipe segments with 3 (good) and 4 (Satisfactory) performance grade are summarized in Table G4-5.

Table G4-5. Segments with 3 (good) and 4 (Satisfactory) performance grade.

PIPEiD	Model
85107	3
85189	3
88992	3
93721	3
96631	3
100666	3
183177	3
186372	3
195393	3
216587	3
226166	3
232274	3
234174	3
262130	3
308844	3
445581	3

57615	4
64140	4
64507	4
238692	4
79123	4
79330	4
81526	4
85943	4
100580	4
88231	4
57164	4
57385	4
60753	4
62899	4
65002	4
65192	4
66063	4
66148	4
66989	4
78972	4
90344	4
92744	4
97228	4
97555	4
97791	4
200510	4
200511	4

Results with 5 (fair) and 6 (poor) performance grade.

Pipe segments with 5 (fair) and 6 (poor) performance grade are summarized in table G4-6.

Table G4-6. Segments with 5 (fair) and 6 (poor) performance grade.

PIPEiD	Model
63892	5
69349	5
70753	5
70961	5
86656	5
89356	5
268527	5

79829	5
57524	5
75507	5
82253	5
86133	5
100520	5
221115	5
57154	5
63802	5
103146	5
105257	5
235153	5
399466	5
59594	5
60176	5
85224	5
80971	6
104192	6
104461	6
199616	6
63947	6
57651	6
63030	6
305975	6
59016	6
65390	6
69794	6
77675	6

Results with 7 (serious) and 8 (critical) performance grades.

Pipe segments with 7 (serious) and 8 (critical) performance grades are summarized in table G4-7.

Table G4-7. Segments with 7 (serious) and 8 (critical) performance grade.

PIPEiD	Model
99963	7
218895	7
271724	7
72268	7
95993	7
100480	7

87923	7
278145	7
71924	7
96338	7
98746	8
98793	8
87009	8
71900	8
71902	8
90283	8
101258	8
386353	8
511834	8

Results with 9 (failure) and 10 (failed) performance grades.

Pipe segments with 9 (failure) and 10 (failed) performance grade are summarized in table G4-8.

Table G4-8. Segments with 9 (failure) and 10 (failed) performance grades.

PIPEiD	Model	Module
96388	9	Surface Wear
101127	9	Surface Wear
101632	9	Surface Wear
87481	10	Surface Wear

Case Studies

Table G4-9. Pipe Segment 87481

Parameter	Unit	Value
Pipe Age	Year	84.049
Pipe Size	Inches	8
Pipe Length	Feet	213.13
Pipe Lining	Yes/No	No
Lining Type	Type	N/A
Slope	% Grade	2.2
Pipe Material	Type	Terra Cota
Pipe Shape	Type	Circular

Index output: 10 (failed)

Module with maximum result: Surface Wear

Reason: High age, low slope

Discussion: This terracotta pipe is prone to surface wear issues due to its high age and low slope.

Prediction Model Piloting and Discussion

The data received from the utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The initial results for gravity pipes suggest that the expected remaining life of these pipes is 154 years. Results of the time-dependent performance prediction are summarized in Figures G4-2 and G4-3.

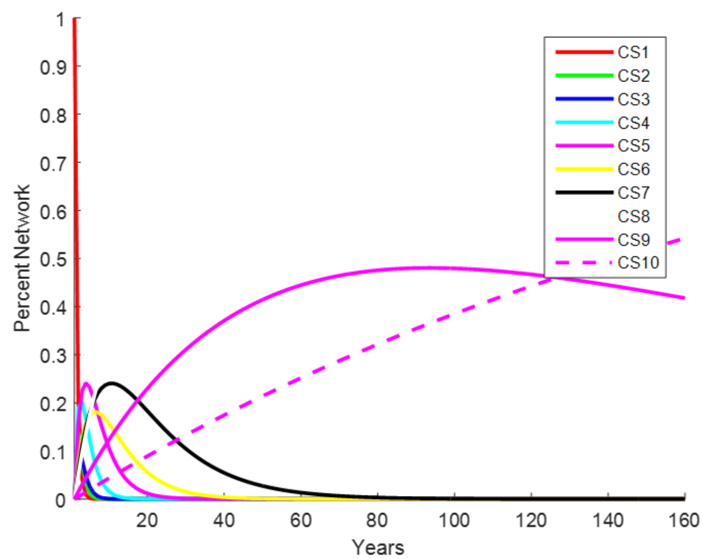

Figure G4-2. Preliminary State Dependent Performance Prediction Results

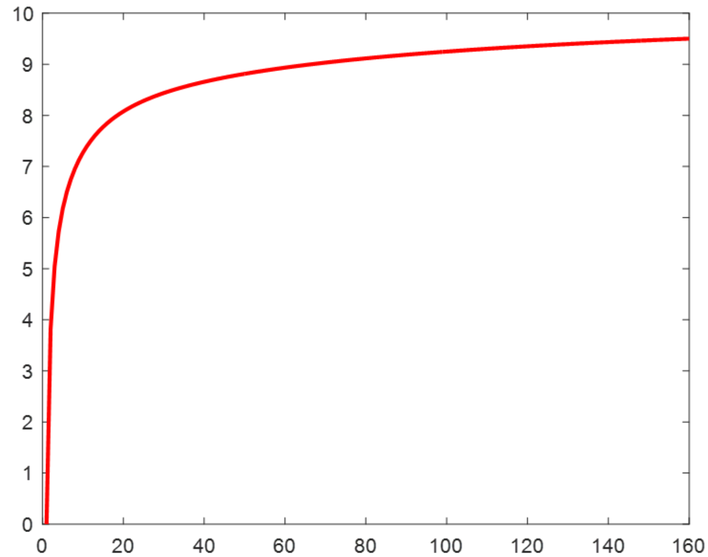

Figure G4-3. Preliminary State Dependent Performance Prediction Results

Appendix G5– Utility #5 Piloting Results

The research team has been piloting the developed performance index with the GIS, defect, and failure data received from participating utility #5. These records contain data for 154,675 pipe segments. 112 of these segments was randomly selected to be evaluated. Figure 1 represents the inspected pipes at the utility. Extracted data from utility records are summarized in Table G5-1.

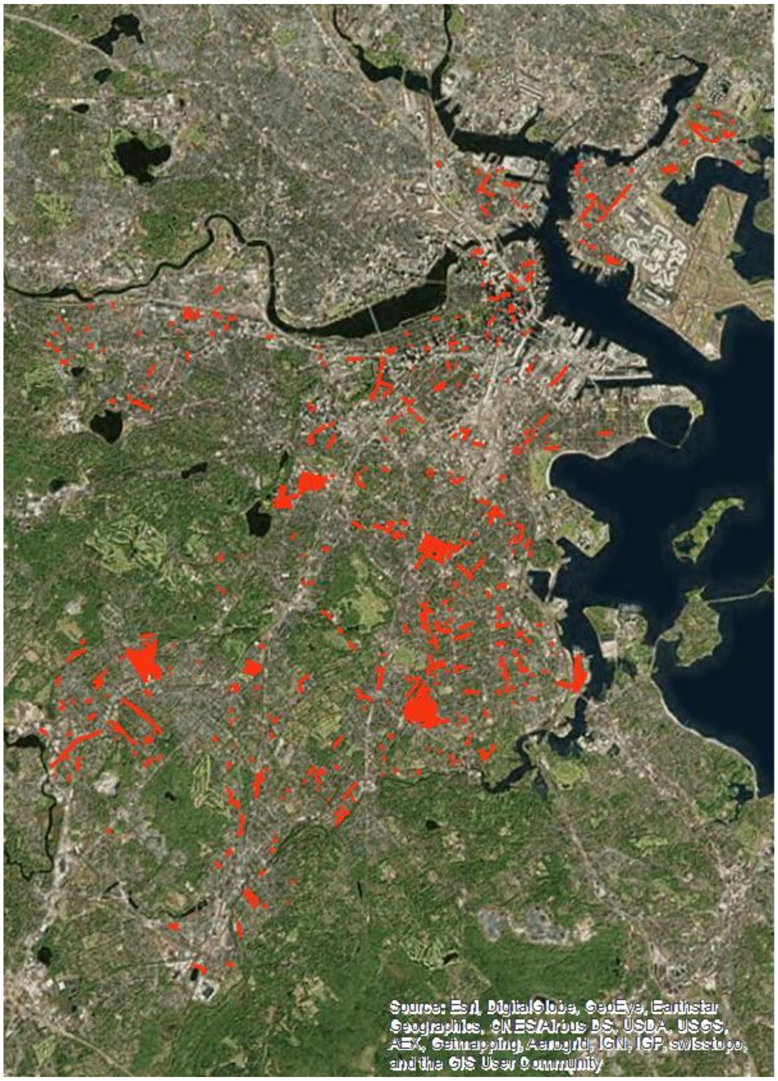

Figure G5-1. Utility #5 Sewer System Overview

Table G5-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe Age	Geodatabase
Pipe Condition	CCTV Inspection Data
Pipe Depth	CCTV Inspection Data
Pipe Diameter	CCTV Inspection Data
Pipe Length	CCTV Inspection Data
Pipe Location	Geodatabase
Pipe Slope	CCTV Inspection Data
Pipe Surcharging	Failure Reports
Lining Presence	CCTV Inspection Data
Lining Type	CCTV Inspection Data
Flow Depth/Diameter	CCTV Inspection Data
Density of Connections	CCTV Inspection Data
Flow Velocity	Geodatabase

2. Performance Index Piloting Results Discussion

A focused dataset of 108 pipes was selected to calibrate the index further. This dataset includes the pipe samples with the highest and lowest ranges of the parameters and the pipe segments with the greatest results differences from the previous pass. The ranges and the number of pipe segment selected for the focused calibration dataset are summarized at Table G5-2.

Table G5-2. Focused Calibration Dataset.

Parameter	Lower Range	Number of Segments	Higher Range	Number of Segments
Pipe Age	6	5	86-84	10
Pipe Depth	0.3-1.4	9	4.5-8.3	5
Pipe Diameter	4-6	4	60-66	4
Pipe Length	1	5	758.2-568.9	5
Pipe Location	No Load	3	Under Highway	12
Pipe Slope	41.45-82.8	6	0.03-0.09	5
Pipe Surcharging	High frequency (3-4 per 10 year)	4	No Surcharging issues	0
Flow Depth/Diameter	0.05	3	1-0.9	7
Density of	0	2	23-26	8

Connections				
Flow Velocity	0.007-0.014	5	68.60-88.5	6

After the model run with the dataset, the results of the PACP coding and the model outputs are compared. It is important to note that the PACP coding results are normalized by multiplying by 2 to have a comparable scale with the index outputs. The results differences between the PACP defect coding and performance index output range between 0-7. Table G5-3 summarize the overall performance for the focused dataset. Following section discuss the reason for the differences.

Table G5-3 Final Piloting Results

Total Number of Segments	Segments with 0 difference	Segments with 1 difference	Segments with 2 Difference	Segments with 3 Difference	Segments with 4 Difference	Segments with 5 Difference	Segments with 6 Difference	Segments with 7 Difference
108	11	32	29	25	6	1	2	2
100%	10.19%	29.63%	26.85%	23.15%	5.56%	0.93%	1.85%	1.85%

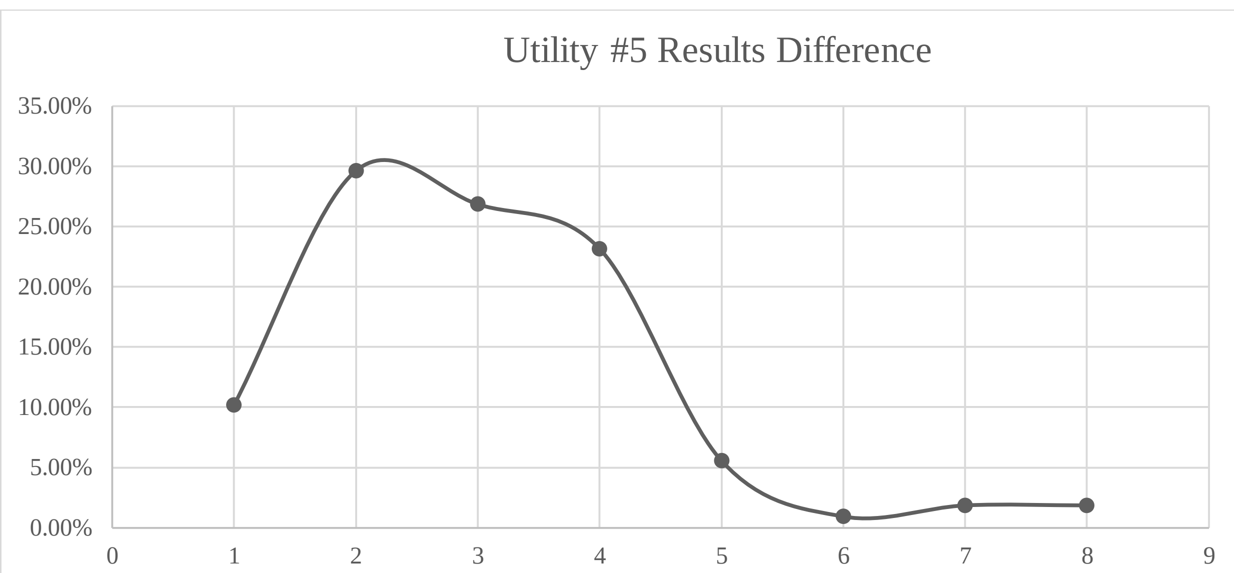

Figure G5-2. Utility #5 Results Difference

Results with 0 Differences

Pipes with PACP grade of 5 (failed) tend to give the same result for the index. The algorithm cannot further penalize the already failed pipe segments. Table G5-4 discusses already failed pipes in the sample population.

Table G5-4. Segments with 0 Differences – Failed Pipes

Significant Parameter	PIPEiD	Model	PACP (Normalized)	Difference
Pipes with high density connections	1002	10	10	0
Short pipes	1144	10	10	0
Pipes with high density connections	1267	10	10	0
High velocity pipe	1359	10	10	0
High velocity pipe	1366	10	10	0
Shallow pipes under highway	1423	10	10	0
Pipes operating in high capacity	4528	10	10	0
Pipes operating in high capacity	6884	10	10	0
Deep pipes	8571	10	10	0
Old pipes	9274	10	10	0
Long length pipe	9889	10	10	0

Results with 1 Difference

Pipe segments where results are 1 difference between the normalized PACP grade and the index output is summarized in table G5-5. Results summarized indicate the pipes with the desirable parameters (low range) are not penalized for the performance. Results also indicate that although there are undesirable parameters for some of the pipe segments, the effects of these parameters are not significant for the pipe performance due to various other parameters.

Table G5-5. Segments with 1 Difference

Significant Parameter	PIPEiD	Model	PACP Normalized	Difference
Under Highway	1	3	2	1
Metallic pipe with moderate flow depth and low flow velocity	12	9	8	1

Low Capacity	39	9	8	1
No Load	68	7	6	1
Shallow Pipe under light/heavy traffic	83	7	6	1
No Load	226	1	0	1
No Load	301	9	8	1
small diameter	484	7	6	1
Shallow Pipes	1231	9	8	1
Large Diameter	1389	5	4	1
High Velocity Pipe	1702	1	0	1
Pipes with High Slopes	2398	3	2	1
Shallow Pipe under light/heavy traffic	2703	9	8	1
Shallow Pipe under light/heavy traffic	2741	7	6	1
small diameter	2822	1	0	1
small diameter	2831	1	0	1
Newer Pipes	2833	7	6	1
Newer Pipes	2834	7	6	1
Low Velocity Pipe	5676	7	6	1
Newer Pipes	5895	1	0	1
Short Pipes	6786	1	0	1
Low Velocity Pipe	6862	9	8	1
Pipes with High Slopes	6893	3	2	1
Short Pipes	7150	1	0	1
Short Pipes	7644	7	6	1
Deep Pipes	7742	9	8	1
Pipes with High Slopes	8161	3	2	1
Low Velocity Pipe	9090	1	0	1
Old Pipes	9268	9	8	1
Large Diameter	9378	5	4	1
Pipes operating in high capacity	9573	9	8	1
Long Length Pipe	9900	9	8	1

Results with 2 or 3 Difference

Pipe segments where results are 2 or 3 difference between the normalized PACP grade and the index output is summarized in Table G5-7. Results summarized indicate that although for some segments have undesirable parameters and the performance of these segments are calculated by considering these parameters. Some significant pipe segments with a high difference between the index and the PACP grades are further investigated in the following case studies.

Table G5-1. Pipe segments where results are 2 or 3 difference between the normalized PACP grades.

Explanations	PIPEiD	Model	PACP (Norm.)	Diff.	Diff. Module
Under highway, moderate depth	2	2	0	2	Integrity
High slope, high velocity, and moderate flow depth/diameter	65	6	4	2	Integrity
Under highway, moderate depth, high velocity and moderate flow depth/diameter	67	2	0	2	Integrity
Under highway, moderate depth	82	3	0	3	Integrity
Under highway, moderate depth	84	2	0	2	Integrity
Shallow Pipe under light/heavy traffic	85	6	4	2	Integrity
Moderate diameter, high density connections	485	6	4	2	Blockage
Long pipe with high density of connections	540	3	0	3	Blockage
Moderate diameter, high density connections	733	8	6	2	Blockage
Moderate diameter, high density connections	736	8	6	2	Blockage
Long Pipe, Very low flow depth/diameter and low flow velocity	861	3	0	3	Blockage
High slope, high velocity, and moderate flow depth/diameter	1133	6	4	2	Integrity
Very high pipe age	1142	7	4	3	Integrity
Long pipe, Very low flow depth/diameter and low flow velocity	1170	3	0	3	Blockage
Very high Velocity, moderate flow depth/diameter	1230	2	0	2	Surface Wear
Metallic pipe with moderate flow depth and low flow velocity	1232	2	0	2	Internal Corrosio
Metallic pipe with moderate flow depth and low flow velocity	1233	2	0	2	Internal Corrosio
Under highway, moderate depth	1307	2	0	2	Integrity
Moderate age, shallow pipe under light highway	1390	3	0	3	Integrity

High Velocity Pipe, moderate flow depth/diameter	1424	2	0	2	Integrity
Under highway, moderate depth	2165	6	4	2	Integrity
High age, low flow velocity	2535	3	0	3	Surface Wear
Metallic pipe with moderate flow depth and low flow velocity	2584	6	4	2	Internal Corrosio
Under highway, moderate depth	2704	6	4	2	Integrity
Long pipe, low flow velocity	2835	6	4	2	Blockag e
High surcharging	3023	7	4	3	IandE
Large diameter, moderate age	3241	6	4	2	Root Intrusio
Pipe surcharging issues	3574	8	6	2	IandE
High density of connections, long pipe, low flow velocity	4355	3	0	3	Blockag e
High density of connections, long pipe, low flow velocity	4630	3	0	3	Blockag e
Small diameter, high pipe surcharging, moderate flow depth/diameter	4652	7	4	3	Capacity
Long pipe, low flow velocity	4658	3	0	3	Blockag e
Moderate density of connections, long pipe, low flow velocity	5092	3	0	3	Blockag e
Newer Pipes	5896	6	4	2	Integrity
Pipes with low slopes	6250	2	0	2	Blockag e
Low Velocity Pipe	6852	6	4	2	Integrity
Low Velocity Pipe	6861	6	4	2	Integrity
pipes with high density connections	7170	7	4	3	Blockag e
Short Pipes	7871	4	2	2	Capacity
Pipes with low slopes	8222	6	4	2	Integrity
Moderate number of connections	8560	3	0	3	Blockag e

Moderate flow depth/diameter	8570	3	0	3	Capacity
Moderate flow depth/diameter	8579	2	0	2	Capacity
Pipes with high density of connections but large diameter	8945	8	6	2	Blockage
Old, shallow pipe under moderate traffic	9269	5	2	3	Integrity
Old Pipes	9273	7	4	3	Integrity
Old, shallow pipe under moderate traffic	9275	5	2	3	Integrity
Old Pipes	9318	7	4	3	Integrity
Low velocity and moderate flow depth/diameter	9323	3	0	3	Surface Wear
Old pipe with low flow velocity and moderate flow depth/diameter	9339	3	0	3	Surface Wear
Old Pipes	9341	7	4	3	Integrity
Pipes with low slopes	9379	2	0	2	Integrity
Pipes with high density of connections but large diameter	9380	3	0	3	Blockage
Long Length Pipe, moderate number of connections	9890	3	0	3	Blockage

Table G5-8. Pipe Segment #1390

Parameter	Value
PIPEiD	1390
Pipe Age	42
Pipe Condition	0
Pipe Depth	0.338417
Pipe Diameter	8
Pipe Length	264.5
Pipe Location	4
Pipe Slope	0.73913
Pipe Surcharging	0
Pipe Grade	0.73913
Lining Present	-1

Lining Type	0
Flow Depth/Diameter	0.1
Flow Velocity	0.554
Density of Connections	2

PACP vs. index output: 0 vs. 3

Module with maximum result: Integrity

Reason: Shallow pipe under major highway

Discussion: Although there is no defect noted by the CCTV inspection, the pipe is located on a major highway, and pipe depth is shallow. These parameters indicate that there is a high amount of dynamic loading on the pipe which makes it prone to integrity issues.

Table G5-9. Pipe Segment # 2535

Parameter	Value
PIPEiD	2535
Pipe Age	115
Pipe Condition	0
Pipe Depth	2.217583
Pipe Diameter	10
Pipe Length	619.8
Pipe Location	0
Pipe Slope	3.35
Pipe Surcharging	0
Pipe Grade	3.35
Lining Present	-1
Lining Type	0
Flow Depth/Diameter	0.0001
Flow Velocity	2.562
Density of Connections	0

PACP vs. index output: 0 vs. 3

Module with maximum result: Surface Wear

Reason: Aged pipe, low flow velocity, low flow depth/diameter.

Discussion: Although there is no defect noted by the CCTV inspection, the high age, low flow velocity, and low flow depth/diameter means this pipe is prone to surface wear.

Table G5-9. Pipe Segments # 3023

Parameter	Value
PIPEiD	3023
Pipe Age	48
Pipe Condition	2
Pipe Depth	2.091667
Pipe Diameter	6
Pipe Length	106.9
Pipe Location	0
Pipe Slope	4.68
Pipe Surcharging	4
Pipe Grade	4.68
Lining Present	-1
Lining Type	0
Flow Depth/Diameter	0.05
Flow Velocity	0.798
Density of Connections	0

PACP vs. index output: 4 vs. 7

Module with maximum result: Infiltration and Exfiltration

Reason: High surcharging rate, low flow velocity, small diameter.

Discussion: Although the PACP grade for the pipe is 2, this specific segment of pipe (Network id: 02016031S) had three surcharging issues in the last ten years. This is proof that this particular segment is prone to exfiltration problems. Additional parameters contributing to the difference are; small diameter and low flow velocity.

Results with 4 or 5 Difference

There are 7 (15.43%) pipe segments where there is 4 or 5 difference between the PACP grade and the index output. Table G5-10 summarizes these results. Some significant pipe segments with a high difference between the index and the PACP grades are further investigated in the following case studies.

Table G5-10. Pipe segments where results are 4 or 5 difference between the normalized PACP grades.

Significant Parameter	PIPEiD	Model	PACP Norm.	Diff.	Diff. Module
Shallow Pipe under Major highway	1143	6	2	4	Integrity
Very low flow depth/diameter and low flow velocity	1301	4	0	4	Blockage
High density of connections, long pipe, low flow velocity	3151	4	0	4	Blockage
Very high density of connections, long pipe, low flow velocity	3889	6	2	4	Blockage
Long pipe, low flow velocity	5540	4	0	4	Blockage
Very high density of connections, Long pipe, low flow velocity	8193	5	0	5	Blockage
High flow depth/diameter, moderate diameter	9693	8	4	4	Capacity

Case Studies

Table G5-11. Pipe Segment #3151

Parameter	Value	Unit
PIPEiD	3151	ID
Pipe Age	53	Years
Pipe Condition	0	PACP
Pipe Depth	2.186667	Feet
Pipe Diameter	8	Inch
Pipe Length	408.1	Feet
Pipe Location	4	Light Highway
Pipe Slope	4.33	%

Pipe Surcharging	0	Level
Lining Present	-1	Yes/No
Lining Type	0	Type
Flow Depth/Diameter	0.1	Ratio
Flow Velocity	1.631	Gal/Min
Density of Connections	21	Number

PACP vs. index output: 0 vs. 4

Module with maximum result: Blockage

Reason: Long pipe length, low flow velocity, and high density of connections.

Discussion: Although there is no defect noted by the CCTV inspection, the length of the pipe, low flow velocity, small diameter, and a high number of lateral connections indicate this pipe segment would be prone to blockages.

Table G5-12. Pipe Segments # 9693

Parameter	Value	Unit
PIPEiD	9693	ID
Pipe Age	72	Years
Pipe Condition	2	PACP
Pipe Depth	0.412167	Feet
Pipe Diameter	10	Inch
Pipe Length	320.6	Feet
Pipe Location	0	Light Highway
Pipe Slope	2	%
Pipe Surcharging	0	Level
Lining Present	-1	Yes/No
Lining Type	0	Type
Flow Depth/Diameter	1	Ratio
Flow Velocity	1.979	Gal/Min
Density of Connections	4	Number

PACP vs. index output: 4 vs. 8

Module with maximum result: Capacity

Reason: High flow depth/diameter, moderate pipe diameter.

Discussion: Although the PACP grade for the pipe is 2, this specific segment of pipe is operating in full (100%) capacity level. This is a proof that the pipe has capacity issues.

Results with 6 or 7 Difference

There are 4 (3.70%) pipe segments where there is 6 or 7 difference between the PACP grade and the index output. Table G5-13 summarizes these results. Some significant pipe segments with a high difference between the index and the PACP grades are further investigated in the following case studies.

Table G5-13. Pipe segments where results are 6 or 7 difference between the normalized PACP grades.

Significant Parameter	PIPEiD	Index	PACP	Dif.	Diff. Module
Pipes operating in high capacity	381	6	0	6	Capacity
Pipe surcharging issues	2056	7	0	7	Capacity
Pipes operating in high capacity	5554	7	0	7	Capacity
Pipes operating in high capacity	9593	6	0	6	Capacity

<u>Case Studies</u>

Table G5-14. Pipe Segments # 381

Parameter	Value	Unit
PIPEiD	381	ID
Pipe Age	18	Years
Pipe Condition	0	PACP
Pipe Depth	2.90025	Feet
Pipe Diameter	8	Inch
Pipe Length	112.5	Feet
Pipe Location	4	Light Highway
Pipe Slope	5.59	%
Pipe Surcharging	0	Level
Lining Present	-1	Yes/No
Lining Type	0	Type

Flow Depth/Diameter	0.95	Ratio
Flow Velocity	1.853	Gal/Min
Density of Connections	0	Number

PACP vs. index output: 0 vs. 6

Module with maximum result: Capacity

Reason: High flow depth/diameter, small diameter.

Discussion: Although the PACP grade for the pipe is 0, this particular segment of pipe is operating in full (95%) capacity level. This proves that the pipe has capacity issues. Pipe section numbers 5554 and 9593 gave similar results.

Table G5-15. Pipe Segments # 2056

Parameter	Value	Unit
PIPEiD	2056	ID
Pipe Age	14	Years
Pipe Condition	0	PACP
Pipe Depth	2.04	Feet
Pipe Diameter	6	Inch
Pipe Length	110.6	Feet
Pipe Location	0	Light Highway
Pipe Slope	1.2	%
Pipe Surcharging	5	Level
Lining Present	-1	Yes/No
Lining Type	0	Type
Flow Depth/Diameter	0.0001	Ratio
Flow Velocity	0.404	Gal/Min
Density of Connections	1	Number

PACP vs. index output: 0 vs. 7

Module with maximum result: Capacity

Reason: High surcharging, small diameter.

Discussion: Although the PACP grade for the pipe is 2, this specific segment of pipe (Network proves that this particular section is prone to capacity issues. Additional parameters contributing to the difference are; small diameter.

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The initial results for gravity pipes suggest that the expected remaining life of these pipes is 94 years. Results of the time-dependent performance prediction are summarized in figures G5-3 and G5-4.

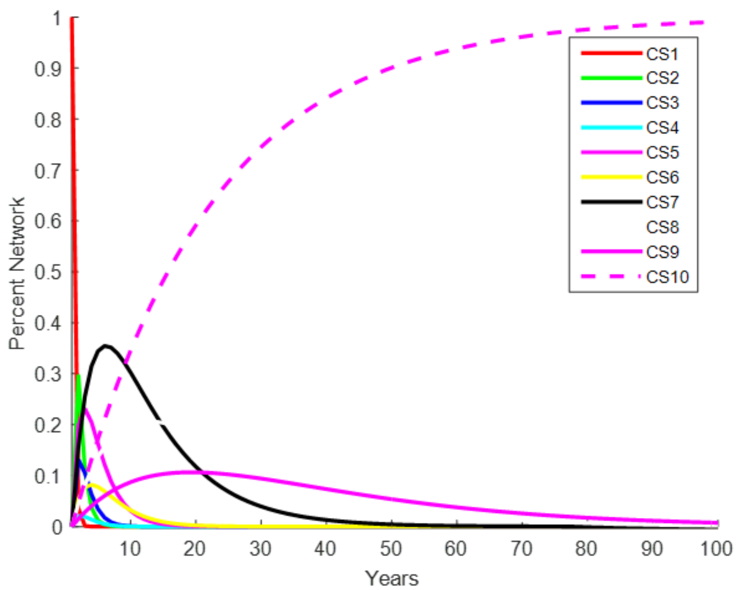

Figure G5-3. Preliminary State Dependent Performance Prediction Results

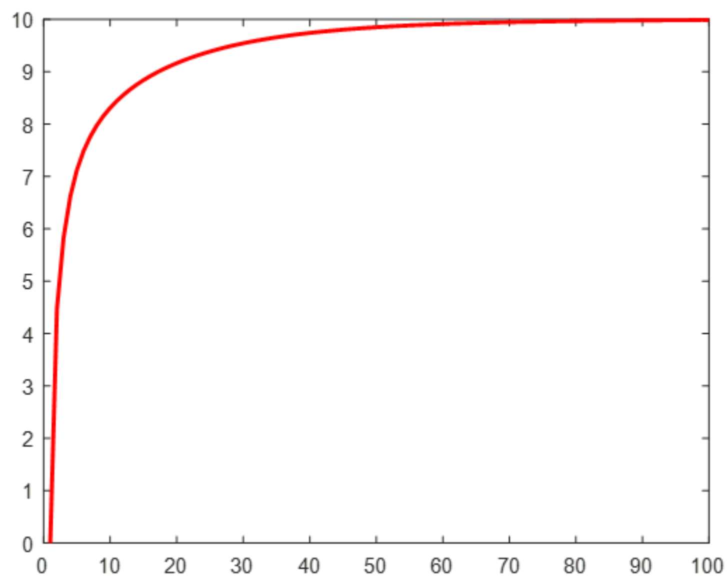

Figure G5-4. Preliminary State Dependent Performance Prediction Results

Appendix G6– Utility #6 Piloting Results

The research team has been piloting the developed performance index with the GIS, defect, and failure data received from participating utility #6. These records contain data for 34285 pipe segments. 108 of these pipes were randomly selected to be evaluated. Extracted data from utility records are summarized in Table G6–1.

Table G6–1. Parameters Extracted from Utility Data

Number	Parameter	Source
1	Pipe Age	Geodatabase
2	Pipe Condition	CCTV Inspection Data
3	Pipe Depth	Geodatabase
4	Pipe Diameter	Geodatabase
5	Pipe Length	CCTV Inspection Data
6	Pipe Location	Geodatabase
7	Pipe Slope	CCTV Inspection Data
8	Lining Present	Geodatabase
9	Flow Depth/Diameter	CCTV Inspection Data
10	Ground Cover	Geodatabase
11	Pipe Shape	CCTV Inspection Data
12	Pipe Material	Geodatabase

Performance Index Piloting Results Discussion

A focused dataset of 108 pipes was selected to calibrate the index further. This dataset includes the pipe samples with the highest and lowest ranges of the parameters and the pipe segments with the greatest results differences from the previous pass. The ranges and the number of pipe segment selected for the focused calibration dataset are summarized at Table G6–2.

Table G6–2. Focused Calibration Dataset.

	Parameter	Range	Unit
1	Pipe Age	44-86	Years
2	Pipe Condition	2-5	Utility Index

3	Pipe Depth	3.13-24.5	Feet
4	Pipe Diameter	6-42	Inches
5	Pipe Length	8.52-582.70	Feet
6	Pipe Location	Urban road, suburban road, rural road, footpath, fields, private property, woodland	Type
7	Pipe Slope	0.05-22	Percent
8	Lining Present	Yes-No	Yes/No
9	Flow Depth/Diameter	0-40	Percent
10	Ground Cover	Asphalt, Building, Concrete, Creek Crossing, Dirt, Grass, Gravel, Sod, Trees, Utility	Type
11	Pipe Shape	Circular	Type
12	Pipe Material	Concrete, Ductile Iron, Vitrified Clay	Type

After the model run with the dataset, the results between the utility defect index and the model outputs are compared. It is important to note that the pipe conditions received from the participating utility are normalized by multiplying by 2 to have a comparable scale with the index outputs (10-grade scale). The results differences between the utility defect index and performance index output range between 0-3. Table G6–3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G6–3. Final Piloting Results

Total Number of Segments	Segments with 0 difference	Segments with 1 difference	Segments with 2 Difference	Segments with 3 Difference
108	4	88	14	2
100%	3.70%	81.48%	12.96%	1.85%

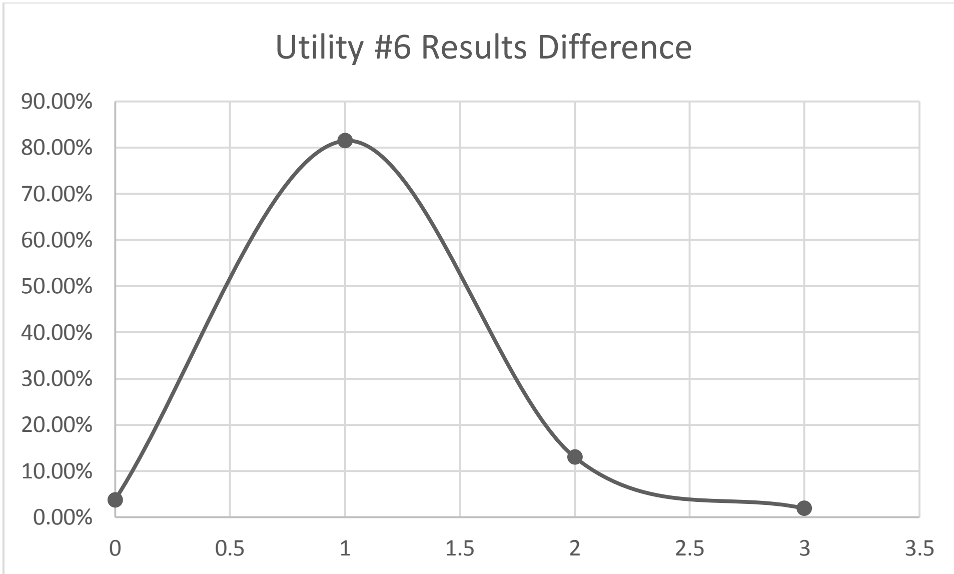

Figure G6–1. Utility #6 Results Difference

Results with 0 Difference

Pipes with utility index grade of 5 (failed) tend to give the same result for the index. The algorithm cannot further penalize the already failed pipe segments. Table G6–4 discuss summarize already failed pipes in the sample population.

Table G6–4. Segments with 0 Differences – Failed Pipes

PIPEiD	Performance Index	Utility Index (Norm)	Difference
23480303801T23480303101	10	10	0
23480306001T23480302301	10	10	0
23480310001T23480309301	10	10	0
23480314901T23480318701	10	10	0

Results with 1 Difference

There are 88 (81.48%) pipe segments with one difference between the normalized utility index and the performance index output. Pipe segments where results are one difference are summarized in Table G6–5. Results summarized indicate the utility index and performance index developed by the research team agrees.

Table G6–5. Segments with 1 Difference between the normalized utility index and the performance index output.

Number	PIPEiD	Performance Index	Utility Index (Norm)	Difference	Difference Module
1	23190213201T23190212301	9	8	1	Integrity
2	23190213501T23190213201	9	8	1	Integrity
3	23190213801T23190213601	9	8	1	Integrity
4	23190213901T23190213501	9	8	1	Integrity
5	23190214101T23190213801	9	8	1	Integrity
6	23190214201T23190212801	7	6	1	Integrity
7	23190222601T23190214101	7	6	1	Blockage
8	23470106601T23470100101	9	8	1	Integrity
9	23480101101T23480102001	9	8	1	Integrity
10	23480101301T23480101201	9	8	1	Integrity
11	23480300601T23480300701	9	8	1	Integrity
12	23480303101T23480301901	9	8	1	Integrity
13	23480304701T23480304101	9	8	1	Integrity
14	23480304801T23480303201	9	8	1	Integrity
15	23480305501T23480304401	9	8	1	Integrity
16	23480306701T23480310001	9	8	1	Integrity
17	23480306901T23480305501	9	8	1	Integrity
18	23480307501T23480304401	9	8	1	Integrity

19	23480308701T234803039 01	7	6	1	Blockage
20	23480308901T234803101 01	9	8	1	Integrity
21	23480309001T234803092 01	9	8	1	Integrity
22	23480309101T234803069 01	9	8	1	Integrity
23	23480310101T234803092 01	9	8	1	Integrity
24	23480311001T234803090 01	9	8	1	Integrity
25	23480311801T234803019 01	7	6	1	Blockage
26	23480312201T234803554 01	9	8	1	Integrity
27	23480312301T234803121 01	7	6	1	Blockage
28	23480312401T234803123 01	9	8	1	Integrity
29	23480312601T234803123 01	9	8	1	Integrity
30	23480313201T234803142 01	9	8	1	Integrity
31	23480313401T234803038 01	9	8	1	Integrity
32	23480313601T234803135 01	9	8	1	Integrity
33	23480313701T234803028 01	9	8	1	Integrity
34	23480314201T234803130 01	9	8	1	Integrity
35	23480314301T234803559 01	9	8	1	Integrity
36	23480316401T234803165 01	7	6	1	Blockage
37	23480316601T234803167 01	9	8	1	Integrity
38	23480316701T234803169 01	7	6	1	Blockage
39	24400303301T243004001 01	9	8	1	Integrity
40	23480318101T234803054	9	8	1	Integrity

	01				
41	23480348901T234803491 01	9	8	1	Surface Wear
42	23480349401T234803493 01	7	6	1	Blockage
43	23480349501T234803496 01	9	8	1	Integrity
44	23480350101T234803500 01	9	8	1	Integrity
45	23480354801T234803547 01	9	8	1	Integrity
46	23480355601T234803557 01	9	8	1	Integrity
47	24100402601T231902064 01	7	6	1	Integrity
48	24300205201T243002108 01	7	6	1	Integrity
49	24300210001T243002088 01	7	6	1	Integrity
50	24300210201T243002087 01	7	6	1	Integrity
51	24300210801T243002187 01	7	6	1	Integrity
52	24300213501T243002134 01	7	6	1	Integrity
53	24300213501T243002136 01	7	6	1	Integrity
54	24300213601T243002133 01	7	6	1	Integrity
55	24300213701T243004083 01	7	6	1	Integrity
56	24300213901T243002137 01	7	6	1	Integrity
57	24300214101T243004088 01	7	6	1	Integrity
58	24300214201T243002141 01	7	6	1	Integrity
59	24300217001T243002171 01	7	6	1	Integrity
60	24300217101T243002172 01	7	6	1	Integrity
61	24300217201T243002176 01	7	6	1	Integrity

62	24300218701T243002173 01	7	6	1	Integrity
63	24300400101T243004005 01	7	6	1	Blockage
64	24300400501T243004004 01	7	6	1	Blockage
65	24300400701T243004009 01	7	6	1	Blockage
66	24300400901T243004010 01	7	6	1	Blockage
67	24300401201T243004015 01	7	6	1	Integrity
68	24300401301T243004023 01	7	6	1	Integrity
69	24300401501T243004025 01	7	6	1	Integrity
70	24300401601T243004024 01	7	6	1	Integrity
71	24300401901T243004025 01	7	6	1	Integrity
72	24300402001T243004018 01	7	6	1	Integrity
73	24300402201T243004019 01	7	6	1	Integrity
74	24300402501T243004026 01	7	6	1	Integrity
75	24300402601T243004020 01	7	6	1	Blockage
76	24300402901T243004078 01	7	6	1	Blockage
77	24300407201T243004014 01	7	6	1	Blockage
78	24300407801T243004073 01	7	6	1	Blockage
79	24300408201T243004097 01	7	6	1	Integrity
80	24300408401T243004082 01	7	6	1	Integrity
81	24300408501T243004086 01	7	6	1	Integrity
82	24300408701T243004084 01	7	6	1	Integrity
83	24300408801T243004085	7	6	1	Integrity

	01				
84	24300409801T243004096 01	7	6	1	Integrity
85	24300411801T243004117 01	7	6	1	Blockage
86	24400300101T244003004 01	7	6	1	Blockage
87	24400300201T244003033 01	7	6	1	Integrity
88	24400301101T243004011 01	7	6	1	Blockage

Case Studies

Table G6–6. PIPEiD: 23190213501T23190213201

Parameter	Value	Unit
PIPEiD	23190213501T23190213201	ID
Pipe Age	57	Years
Pipe Condition	4	Utility Index
Pipe Depth	13.56	Feet
Pipe Diameter	8	Inches
Pipe Length	105.83	Feet
Pipe Location	Suburban Road	Type
Pipe Slope	2.1	Percent
Lining Present	No	Yes/No
Flow Depth/Diameter	2	Percent
Ground Cover	Asphalt	Type
Pipe Shape	Circular	Type
Pipe Material	Concrete	Type

Utility Index vs. Performance Index: 8 (poor) vs. 9 (failure)

Module with maximum result: Integrity

Reason: Moderate age (57), unlined, concrete pipe

Discussion: The utility index indicates that this pipe is in poor condition. Performance index results agree with the assessment of the utility index. This pipe is a moderately old, unlined concrete pipe located on a suburban road.

Table G6–7. PIPEiD: 23190222601T23190214101

Parameter	Value	Unit
PIPEiD	23190222601T23190214101	ID
Pipe Age	44	Years
Pipe Condition	3	Utility Index
Pipe Depth	9.43	Feet
Pipe Diameter	8	Inches
Pipe Length	193.58	Feet
Pipe Location	Suburban Road	Type
Pipe Slope	0.47	Percent
Lining Present	No	Yes/No
Flow Depth/Diameter	2	Percent
Ground Cover	Asphalt	Type
Pipe Shape	Circular	Type
Pipe Material	Concrete	Type

Utility Index vs. Performance Index: 6 (fair) vs. 7 (serious)

Module with maximum result: Blockage

Reason: Moderate age (44), unlined, concrete pipe, moderate length (193.58 ft.) and moderate flow depth over diameter.

Discussion: The utility index indicates that this pipe is in fair condition. Performance index results agree with the assessment of the utility index. This pipe is a moderately aged, unlined concrete pipe located under a suburban road which is relatively long (193.58 ft.). The length of the pipe indicates this segment might be prone to blockage issues.

Results with 2 Difference

There are 14 (12.96%) pipe segments with two difference between the normalized utility index and the performance index output. Pipe segments where results are two difference between the normalized utility index and the performance index output is summarized in Table G6-8.

Table G6-2. Pipe segments where results are 2 difference between the between the normalized utility index and the performance index output.

No	PIPEiD	Performance Index	Utility Index (Norm)	Difference	Difference Module
1	23480300501T23480300601	10	8	2	Capacity
2	23480303201T23480303101	10	8	2	Integrity
3	23480303301T23480303701	10	8	2	Integrity
4	23480317001T23480317101	8	6	2	Blockage
5	24300208901T24300217201	6	4	2	Blockage
6	24300217501T24300217401	6	4	2	Blockage
7	24300219301T24300217401	6	4	2	Blockage
8	24300401701T24300401201	6	4	2	Blockage
9	24300402701T24300401301	6	4	2	Blockage
10	24300403101T24300403001	6	4	2	Blockage
11	24300409701T24300409801	6	4	2	Blockage
12	24300411901T24300411801	6	4	2	Blockage
13	24400300901T24400300101	6	4	2	Blockage
14	24400301001T24400300901	6	4	2	Blockage

Case Studies

Table G6-11. PIPEiD: 23480300501T23480300601

Parameter	Value	Unit
PIPEiD	23480300501T23480300601	ID
Pipe Age	79	Years
Pipe Condition	4	Utility Index
Pipe Depth	16	Feet
Pipe Diameter	42	Inches

Pipe Length	475.45	Feet
Pipe Location	Field	Type
Pipe Slope	0.3	Percent
Lining Present	No	Yes/No
Flow Depth/Diameter	40	Percent
Ground Cover	Grass	Type
Pipe Shape	Circular	Type
Pipe Material	Concrete	Type

Utility Index vs. Performance Index: 8 (poor) vs. 10 (failed)

Module with maximum result: Capacity

Reason: Pipe with high flow depth over diameter

Discussion: The utility index indicates that this pipe is in poor condition. The fact that this pipe segment is running in high capacity (flow depth/diameter ratio is 40% suggest this pipe has failed in performance.

Table G6-12. PIPEiD: 23480300501T23480300601

Parameter	Value	Unit
PIPEiD	23480303201T23480303101	ID
Pipe Age	78	Years
Pipe Condition	4	Utility Index
Pipe Depth	4.77	Feet
Pipe Diameter	8	Inches
Pipe Length	185.014	Feet
Pipe Location	Suburban highway	Type
Pipe Slope	0.39	Percent
Lining Present	No	Yes/No
Flow Depth/Diameter	40	Percent
Ground Cover	Asphalt	Type
Pipe Shape	Circular	Type
Pipe Material	Concrete	Type

Utility Index vs. Performance Index: 8 (poor) vs. 10 (failed)

Module with maximum result: Integrity

Reason: Shallow pipe under high traffic load.

Discussion: This aged pipe (78 years) pipe buried shallow (4.77 feet) and is located on a suburban highway. The high dynamic loads and shallow burial of this aged pipe indicate this pipe would have integrity issues.

Table G6-13. PIPEiD: 23480317001T23480317101

Parameter	Value	Unit
PIPEiD	23480317001T23480317101	ID
Pipe Age	74	Years
Pipe Condition	3	Utility Index
Pipe Depth	7.17	Feet
Pipe Diameter	18	Inches
Pipe Length	388.97	Feet
Pipe Location	Field	Type
Pipe Slope	0.33	Percent
Lining Present	No	Yes/No
Flow Depth/Diameter	11	Percent
Ground Cover	Grass	Type
Pipe Shape	Circular	Type
Pipe Material	Concrete	Type

Utility Index vs. Performance Index: 6 (fair) vs. 8 (critical)

Module with maximum result: Blockage

Reason: Long pipe with low slope and moderate flow depth over diameter.

Discussion: This pipe segment is relatively long (388.97 ft.) with a low slope (0.33%) and high capacity. These facts indicate that this pipe segment would be prone to pipe blockages.

Results with 3 Difference

There are 4 (1.85%) pipe segments with three difference between the normalized utility index and the performance index output. Pipe segments where results are three difference between the normalized utility index and the performance index output is summarized in Table G6-14.

Table G6-14. Pipe segments where results are 3 difference between the normalized PACP grades.

No	PIPEiD	Performance Index	Utility Index (Norm)	Difference	Difference Module
1	23480302701T23480354601	9	6	3	Surface Wear
2	23480305001T23480302701	9	6	3	Capacity

Case Studies

Table G6-14. PIPEiD: 23480302701T23480354601

Parameter	Value	Unit
PIPEiD	23480302701T23480354601	ID
Pipe Age	79	Years
Pipe Condition	3	Utility Index
Pipe Depth	12.92	Feet
Pipe Diameter	42	Inches
Pipe Length	582.69	Feet
Pipe Location	Urban Road	Type
Pipe Slope	0.0515	Percent
Lining Present	No	Yes/No
Flow Depth/Diameter	0.15	Percent
Ground Cover	Asphalt	Type
Pipe Shape	Circular	Type
Pipe Material	Concrete	Type

Utility Index vs. Performance Index: 6 (fair) vs. 9 (failure)

Module with maximum result: Internal Corrosion

Reason: High aged concrete unlined pipe with very low slope and moderate flow depth over diameter.

Discussion: This pipe unlined concrete pipe segment is aged high (79 years) with low pipe slope (0.0515%) and moderate flow depth over diameter indicating that the wastewater flow and corrosion due to H2S buildup.

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The initial results for gravity pipes suggest that the expected remaining life of these pipes is 137 years. Results of the time-dependent performance prediction are summarized in figures G6-2 and G6-3.

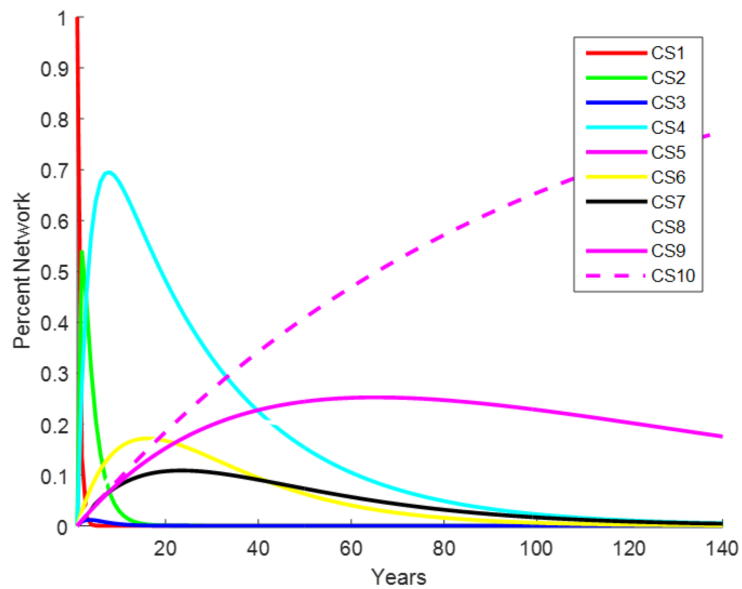

Figure G6-2. Preliminary State Dependent Performance Prediction Results

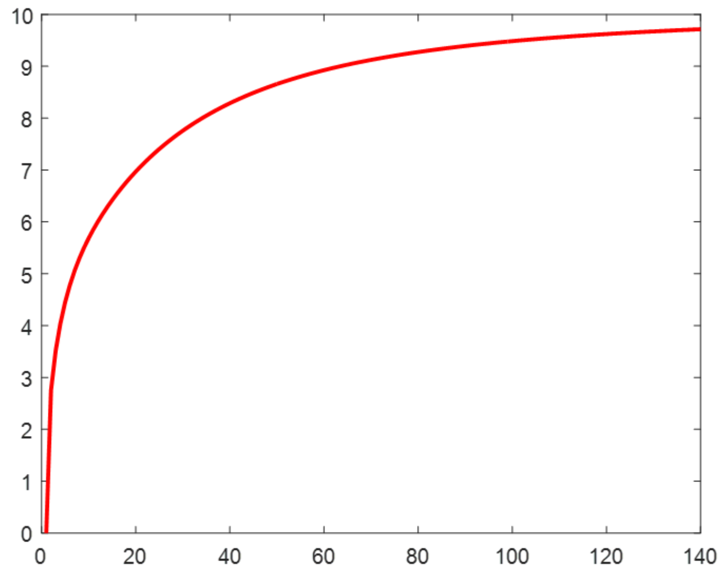

Figure G6-3. Preliminary State Dependent Performance Prediction Results

Appendix G7– Utility #7 Piloting Results

Overview

The research team has received data from participating Utility #7 in the form of;

- Overflow report

- Cleaning Report

- Asset Inventory

These databases contain records for 29153 pipe segments totaling 1208 miles in length. 249 segments were randomly selected for the piloting the performance index. Data is extracted for these 249 segments to pilot the performance index. Extracted data from utility records are summarized in Table G7–1.

Table G7–1. Parameters Extracted from Utility Data

Parameter	Source
Pipe ID	Asset Inventory
Pipe Age	Age Database
Pipe Diameter	Asset Inventory
Pipe Length	Asset Inventory
Pipe Slope	Asset Inventory
Pipe Material	Asset Inventory
Pipe Shape	Asset Inventory
Cleaning Type	Asset Inventory
Liner Present	Asset Inventory
Overflow	Overflow Database

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset are summarized at Table G7–2.

Table G7–2. Focused Calibration Dataset.

Parameter	Unit	Lower Range	Higher Range
Pipe Age	Years	3	28
Pipe Diameter	Inch	7.5	18
Pipe Length	Feet	6	523
Pipe Slope	%	0.09	33
Pipe Material	Type	PVC	
Pipe Shape	Type	Circular	
Cleaning Type	Type	Root Sawing, Jetting	
Liner Present	Yes/No	No	Yes
Overflow	Number	0	7

After the model run with the dataset, and the performance index outputs were ranged between 1-10. Table G7-3 and Figure G7-1 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G7–3. Final Piloting Results

Total Number of Segments	Segments in Condition (1)	Segments in Condition (2)	Segments in Condition (3)	Segments in Condition (4)	Segments in Condition (5)	Segments in Condition (6)	Segments in Condition (7)	Segments in Condition (8)	Segments in Condition (9)	Segments in Condition (10)
249	180	10	17	11	9	8	3	5	3	3
100%	72.29 %	4.02%	6.83%	4.42%	3.61%	3.21%	1.20%	2.01%	1.20%	1.20%

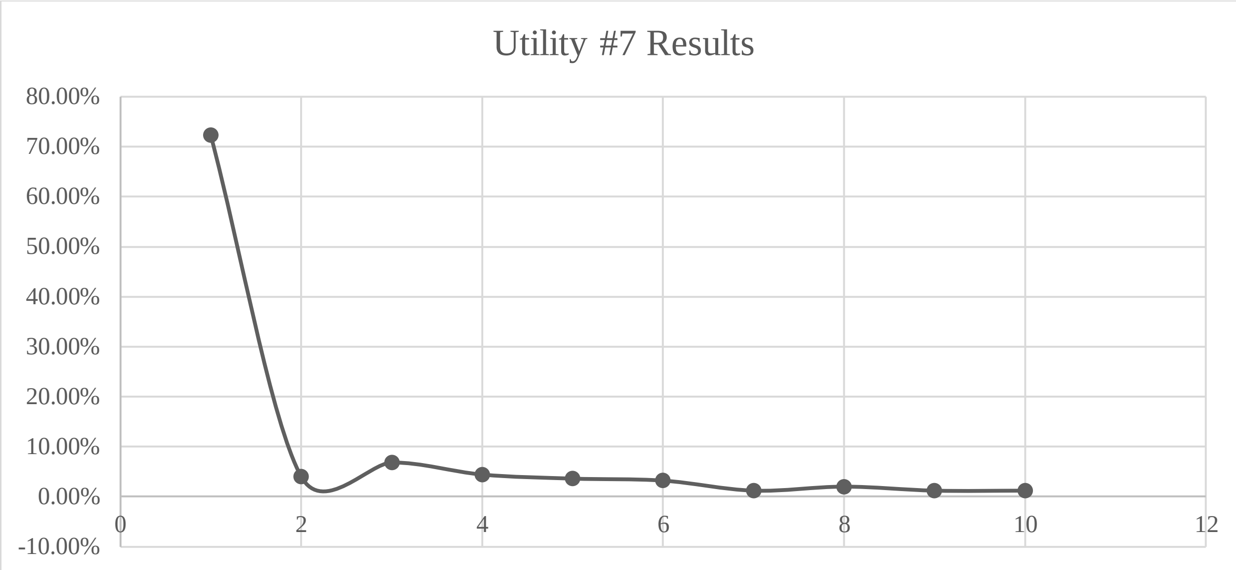

Figure G7-1. Utility #7 Results

Results with 1 (excellent) performance grade

Table G7–4 discuss summarize pipes with 1 (excellent) and 2 (very good) performance grade.

Table G7–4. Segments with 1 (excellent) and 2 (very good) performances

PIPEiD	Model
56728	1
56730	1
57321	1
57322	1
69468	2
70953	1
71225	1
71236	1
71732	2
71734	2
71742	1
71744	1
77768	1
77771	2
77775	2
77777	2
77786	1

77789	1
77791	1
77795	1
77797	1
77801	1
83528	1
84114	1
84115	1
84440	1
85335	1
85631	1
85632	1
85633	1
85991	1
85993	1
85995	1
87325	1
87327	1
88166	1
88979	1
88982	1
88984	1
88986	1
88988	1
88990	1
89109	1
90655	1
90965	1
91045	1
91048	1
91050	1
91052	1
91055	1
91061	1
91063	1
91065	1
91067	1
91069	1
91071	1
91073	1
91076	1
91078	1

91696	1
91699	1
91701	1
92127	1
92131	1
92369	1
96728	1
96749	1
96750	1
96751	1
96752	1
96824	1
96825	1
96826	1
96827	1
96828	1
96841	1
96842	1
96848	1
97233	1
111772	1
111792	1
114248	1
114337	1
114341	1
114342	1
114343	1
114344	1
114345	1
114346	1
114347	1
114348	2
114349	2
114350	1
116038	1
116040	1
116086	1
116088	1
116089	1
116090	1
116091	2
116092	1

116093	1
116094	1
116095	1
116096	1
116097	1
116098	1
116099	1
154115	1
154117	1
154119	1
154121	1
154123	1
154124	1
175839	1
175840	1
175842	1
180142	1
181113	1
194616	1
196791	1
205009	1
205023	1
205024	1
205025	1
206362	1
207580	1
207581	1
207583	1
207584	1
207589	1
207591	1
207592	1
207595	1
207599	1
207629	1
207630	1
223455	1
223456	1
223458	1
223459	1
223461	1
223462	1

223463	2
223464	1
223465	1
223467	1
223481	1
223485	1
223487	1
223557	1
223559	1
223560	1
223561	1
223563	1
223666	1
223669	1
223673	1
223675	1
223680	1
223681	1
223683	1
223684	1
223696	1
223697	1
223706	1
223734	1
223736	1
223763	1
223765	1
223813	1
245257	1
250672	1
263234	1
263287	1
263288	1
264237	1
264238	1
264241	1
264263	1
264264	1
264265	1
264332	1
264333	1
264753	1

264754	1
264755	1
264756	1
264757	1
264758	1

Results with 3 (good) and 4 (satisfactory) performance grade.

Pipe segments with 3 (good) and 4 (Satisfactory) performance grade are summarized in table G7–5.

Table G7–5. Segments with 3 (good) and 4 (Satisfactory) performance

PIPEiD	Model
71805	3
71807	3
69659	3
69661	3
69663	3
70951	3
56448	3
56450	3
56920	3
57071	3
57311	3
57314	3
57315	3
86739	3
57316	3
57318	3
57319	3
116039	4
223695	4
223682	4
77799	4
92138	4
85997	4
84441	4
57130	4
57132	4
71809	4

154113	4

Results with 5 (fair) and 6 (poor) performance grades.

Pipe segments with 5 (fair) and 6 (poor) performance grade are summarized in table G7–6.

Table G7–6. Segments with 5 (fair) and 6 (poor) performance grades.

PIPEiD	Model
57128	5
92132	5
175914	5
116087	5
92136	5
196788	5
77784	5
77782	5
77773	5
77793	6
223496	6
196789	6
175841	6
196790	6
92134	6
223668	6
223659	6

Results with 7 (serious) and 8 (critical) performance grade.

Pipe segments with 7 (serious) and 8 (critical) performance grade are summarized in table G7–7.

Table G7–7. Segments with 7 (serious) and 8 (critical) performance grade.

PIPEiD	Model
223730	7
223667	7
71740	7
223674	8
223658	8
205010	8

223480	8
223700	8

Results with 9 (failure) and 10 (failed) performance grades.

Pipe segments with 9 (failure) and 10 (failed) performance grade are summarized in table G7–8.

Table G7–8. Segments with 9 (failure) and 10 (failed) performance grades.

PIPEiD	Model	Module
204433	10	Capacity
89107	9	Integrity
223727	9	Integrity
223466	9	Blockage
223732	10	Integrity
223735	10	Integrity

Case Studies

Table G7–9. Pipe Segment 223466

Parameter	Value
Pipe ID	223466
Pipe Age	7.7835
Pipe Diameter	8
Pipe Length	523
Pipe Slope	0.6185
Pipe Material	PVC
Pipe Shape	Circular
Cleaning Type	None
Liner Present	No
Overflow	None

Index output: 10 (Failed)

Module with maximum result: Blockage

Reason: Small diameter, long length, low slope

Discussion: This PVC pipe is prone to blockage issues due to its small diameter (8 inches), length (523 ft.), and low slope (0.62%).

Table G7–10. Pipe Segment 204433

Parameter	Value
Pipe ID	204433
Pipe Age	9
Pipe Diameter	18
Pipe Length	156
Pipe Slope	0.5321
Pipe Material	PVC
Pipe Shape	Circular
Cleaning Type	None
Liner Present	No
Overflow	7

Index output: 10 (Failed)

Module with maximum result: Capacity

Reason: High overflow rate

Discussion: This PVC pipe is prone to capacity issues due to the high number of overflows recorded (7).

Prediction Model Piloting and Discussion

The data received from utility #7 was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The initial results for gravity pipes suggest that the expected remaining life of these pipes is 82 years. Results of the time-dependent performance prediction are summarized in Figures G7–3 and G7–4.

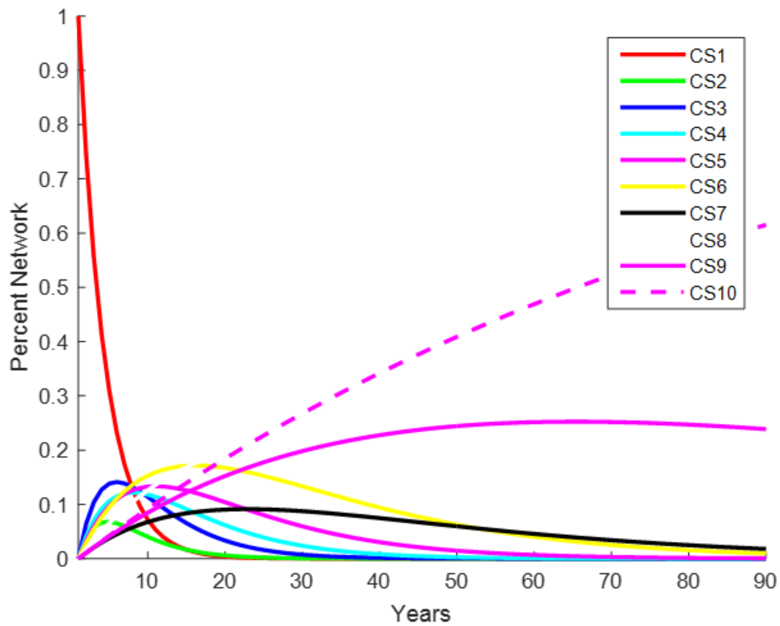

Figure G7–3. Preliminary State Dependent Performance Prediction Results

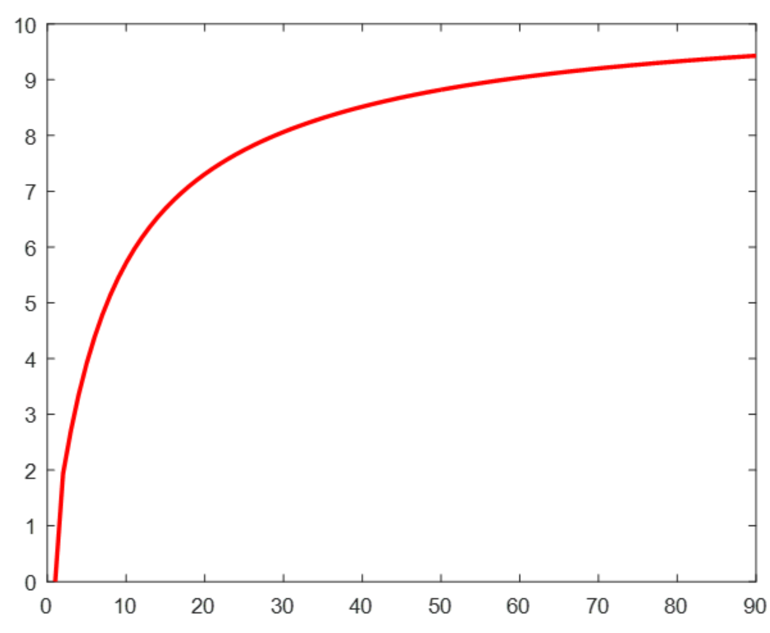

Figure G7–4. Preliminary State Dependent Performance Prediction Results

Appendix G8 – Utility #8 Piloting Results

Overview

The research team has received data from Utility #8 in the form of GIS geo-database. This GIS geodatabase contains records for 38816 pipe segments totaling in 1383.54 miles in length. Participating utility sewer system is summarized in Figure G8-1.

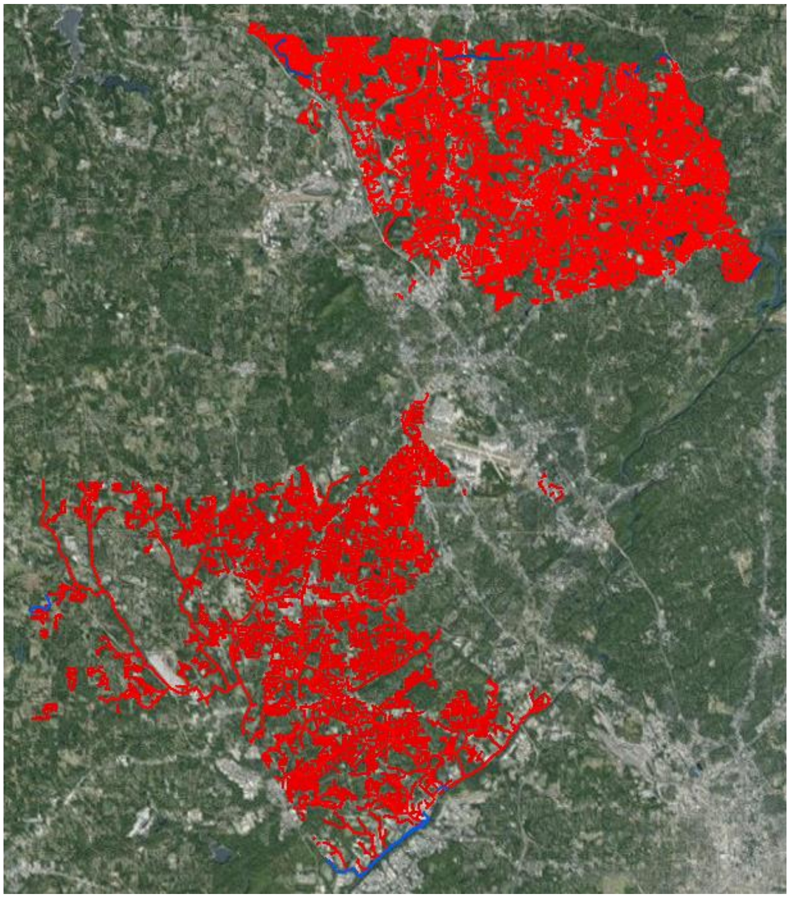

Figure G8-1. Participating Utility Sewer System

268 segments were randomly selected for the piloting the performance index. Data is extracted for these 268 segments to pilot the performance index. Extracted data from utility records are summarized in Table G8-1.

Table G8-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe ID	Geodatabase
Pipe Age	Geodatabase
Pipe Diameter	Geodatabase
Pipe Length	Geodatabase
Pipe Material	Geodatabase
Pipe Shape	Geodatabase

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset are summarized at Table G8-2.

Table G8-2. Focused Calibration Dataset.

Parameter	Unit	Lower Range	Higher Range
Pipe Age	Years	7	16
Pipe Diameter	Inch	4	72
Pipe Length	Feet	5	994
Pipe Material	Type	CO, DI,OR, PVC, RCP, VCP	
Pipe Shape	Type	Circular	

After the model run with the dataset, and the performance index outputs ranges between 1-10. Table G8-3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G8-3. Final Piloting Results

Total Number of Segments	Segments in Condition (1)	Segments in Condition (2)	Segments in Condition (3)	Segments in Condition (4)	Segments in Condition (5)	Segments in Condition (6)	Segments in Condition (7)	Segments in Condition (8)	Segments in Condition (9)	Segments in Condition (10)
316	227	26	14	13	14	13	3	2	2	2
100%	71.84	8.23%	4.43%	4.11%	4.43%	4.11%	0.95%	0.63%	0.63%	0.63%

	%									

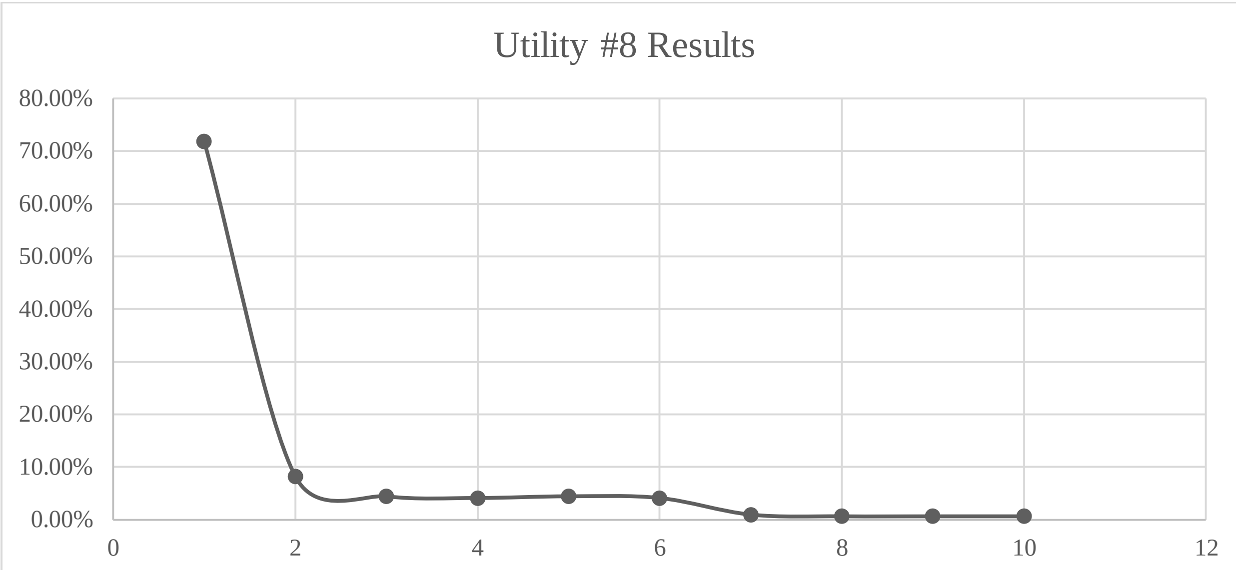

Figure G8-2. Utility #8 Results

Results with 1 (excellent) performance grade

Table G8-4 discuss summarize pipes with 1 (excellent) and 2 (very good) performance grade.

Table G8-4. Segments with 1 (excellent) and 2 (very good) performance grades

PIPEiD	Model
13	1
104	1
365	1
700	1
780	1
834	2
841	1
844	1
1354	1
1460	1
1496	1
1521	1
1522	1
1600	1
1658	1

1687	1
1704	2
1738	1
1748	1
1757	1
2451	1
2487	1
2854	1
2895	1
3167	1
3344	1
3474	1
3923	1
4491	1
4497	1
4545	1
4557	1
4740	2
4752	1
4900	1
4919	1
4921	1
4982	1
5008	1
5023	1
5092	1
5820	1
5866	1
6143	1
6184	1
6284	1
6339	1
6549	1
6617	1
6691	1
6777	1
6802	1
6901	1
6911	1
6973	1
7100	2
7296	1
7319	1

7391	1
7471	1
7556	1
7601	1
7603	1
7704	1
7839	1
7933	1
8026	1
8205	1
8262	1
8381	1
8388	1
8456	1
8537	1
8563	1
8590	1
8641	2
8746	1
8766	1
8926	2
9117	1
9174	1
9189	1
9193	1
9350	1
9487	1
9533	1
9845	1
9892	1
9895	1
9980	1
10189	1
10222	1
10223	1
10229	1
10257	1
10622	1
10699	1
10796	1
10837	1
10874	1
11147	1

11332	2
11358	1
11462	1
11571	2
11917	1
12012	1
12147	1
12568	1
12570	1
12584	1
12591	1
12634	1
12684	1
12849	1
12907	1
12922	1
12964	1
13072	1
13093	1
13108	1
13361	1
13370	1
13442	1
13513	1
13538	1
13539	1
13547	1
13738	1
13797	1
13800	1
13820	1
13902	1
13906	1
14095	1
14315	1
14328	1
14396	1
14405	1
14540	2
14545	1
14783	1
14870	1
15331	1

15675	2
15773	1
15943	1
16034	1
16313	1
16566	1
16715	1
16994	2
17048	1
17444	1
17479	1
17491	2
17517	1
17831	1
17990	1
18141	1
18141	1
18266	1
18274	1
18409	1
18425	1
18426	1
18439	1
18489	1
18605	1
18772	1
18777	1
18880	1
19191	1
19305	1
19376	1
19565	1
19752	1
19792	1
19844	1
19969	1
19975	1
20058	1
20205	1
20262	1
20297	1
20538	1
20577	1

20797	1
20938	1
20981	1
21027	1
21088	1
21102	1
21201	1
21352	1
21477	1
21561	1
21573	1
21616	1
21621	1
21636	1
21802	1
21939	1
22011	1
22040	1
22088	1
22181	1
22275	1
22350	1
22706	1
22906	1
23070	1
23182	1
23242	1
23259	1
23303	1
23465	1
23539	1
23713	1
23910	1
24149	1
24169	1
24242	1
24295	1
24414	1
24492	2
24535	1
24539	1
24562	1
24592	1

24711	1
24721	1
25025	1
25116	1
25474	1
25780	1
25897	1
26394	2
26406	2
26995	1
27278	2
27353	2
27498	1
27661	2
27896	2
27898	2
28081	2
28127	2
28248	2
28909	1
29070	2
29421	2
29542	2

Results with 3 (good) and 4 (satisfactory) performance grades.

Pipe segments with 3 (good) and 4 (Satisfactory) performance grade are summarized in table G8-5.

Table G8-5. Segments with 3 (good) and 4 (Satisfactory) performance grades.

PIPEiD	Model
29576	3
29640	3
29738	3
29754	3
30173	3
30236	3
30363	3
30475	3
30477	3

30487	3
30703	3
30716	3
30881	3
30912	3
31320	4
31567	4
31746	4
31792	4
31962	4
32013	4
32088	4
32234	4
32241	4
32350	4
32643	4
32653	4
32844	4

Results with 5 (fair) and 6 (poor) performance grades.

Pipe segments with 5 (fair) and 6 (poor) performance grade are summarized in table G8-6.

Table G8-6. Segments with 5 (fair) and 6 (poor) performance grades.

PIPEiD	Model
33042	5
33398	5
33561	5
33599	5
33668	5
33678	5
33765	5
33862	5
33997	5
34224	5
34850	5
35181	5
35711	5
35899	5
36106	6
36115	6

36218	6
36224	6
36528	6
36735	6
36860	6
36912	6
36922	6
36935	6
38739	6
38760	6
38779	6

Results with 7 (serious) and 8 (critical) performance grade.

Pipe segments with 7 (serious) and 8 (critical) performance grade are summarized in table G8-7.

Table G8-7. Segments with 7 (serious) and 8 (critical) performance grade.

PIPEiD	Model
10743	7
24873	7
10834	7
6984	8
297	8

Results with 9 (failure) and 10 (failed) performance grades.

Pipe segments with 9 (failure) and 10 (failed) performance grade are summarized in table G8-8.

Table G8-8. Segments with 9 (failure) and 10 (failed) performance grades.

PIPEiD	Model	Module
4	9	Blockage
1950	9	Blockage
3095	10	Blockage
731	10	Blockage

Case Studies

Table G8-9. Pipe Segment 4

Parameter	Value
Pipe ID	4
Pipe Age	15.56
Pipe Diameter	10
Pipe Length	400
Pipe Material	DI
Pipe Shape	Circular

Index output: 10 (Failed)

Module with maximum result: Blockage

Reason: High Length

Discussion: This ductile iron pipe is prone to blockage issues due to its long length (400 ft.).

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The initial results for gravity pipes suggest that the expected remaining life of these pipes is 71 years. Results of the time-dependent performance prediction are summarized in Figures G8-3 and G8-4.

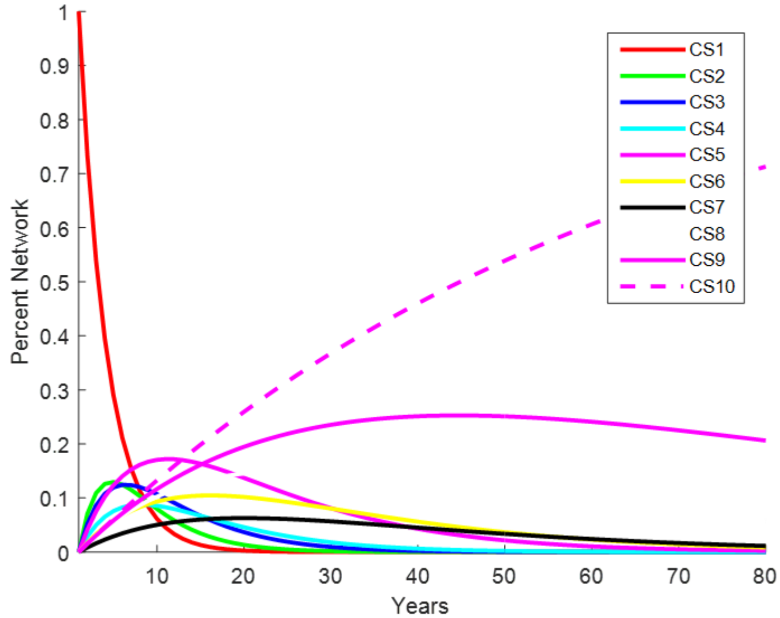

Figure G8-3. Preliminary State Dependent Performance Prediction Results

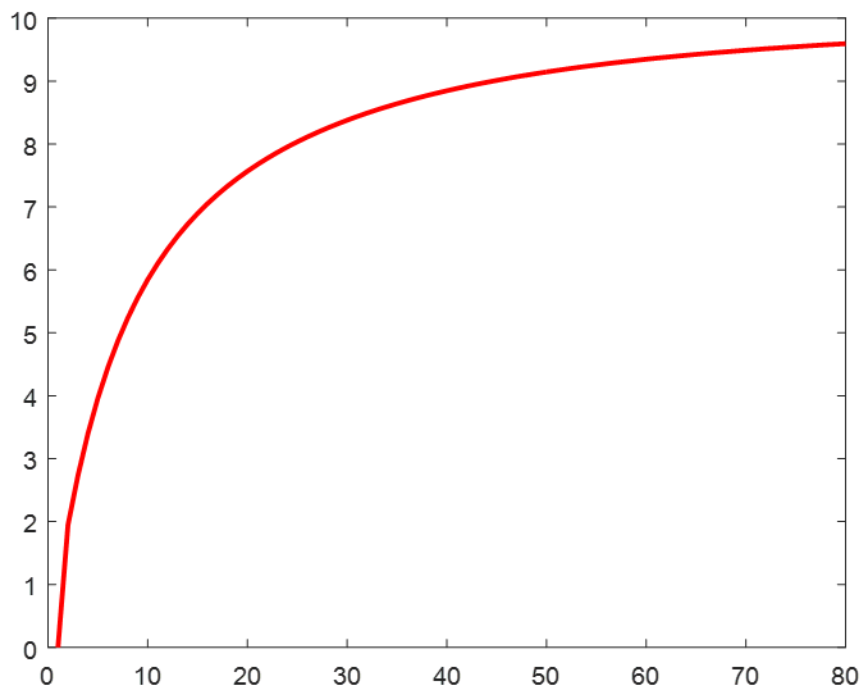

Figure G8-4. Preliminary State Dependent Performance Prediction Results

Appendix G9 – Utility #9 Piloting Results

Overview

The research team has received data from participating utility #9 in the form of;

- GIS geo-database.
- CCTV Inspections
- SSO's database

Participating utility sewer System is summarized in Figure G9-1.

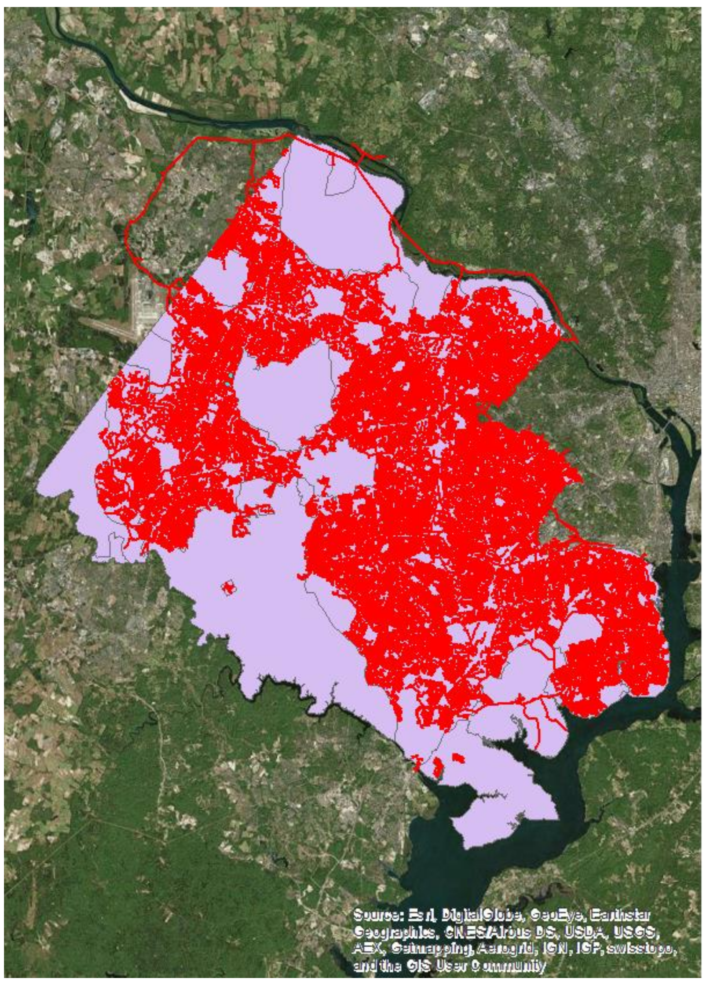

Figure G9-1. Utility #9 Sewer System

154 segments were randomly selected for the piloting the performance index. Data is extracted for these 154 segments to pilot the performance index. Extracted data from utility records are summarized in Table G9-1.

Table G9-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe ID	Geodatabase
Pipe Size	Geodatabase
Pipe Length	Geodatabase
Pipe Material	Geodatabase
Pipe Slope	Geodatabase
Pipe Age	Geodatabase
Pipe Location	GIS Map
Pipe Condition	CCTV Inspections
Pipe Shape	Geodatabase
Overflow	SSO's database
Tidal Influence	GIS Map

Participating utility used RJN, Hansen, and EAM defect indices for the CCTV inspections. The condition grades are calculated as follows;

Structural = 300[sum(RCs)+sum(LC)+sum(BJs)+sum(Ls)+(4*sum(CSs))+(4*sum(DSs))]/ Main Length

RC – Radial Cracks, LC – Longitudinal Cracks, BJ – Joint conditions, CS – Structural, DS - Structural

I/I = 300[sum(Is)/ Main Length

I – Inflow and Infiltration

Root= 300[sum(Rs)]/ Main length

R - Roots

Overall = a(Structural)+b(I/I)+c(Root)/a+b+c*

a=0.6, b=0.3, and c=0.1

The results of this defect index have been normalized to match to outputs with the performance index.

Table G9-2 summarizes the normalization process.

Hansen and EAM Grade	Normalized Grade
0	1
1 – 30	2
30-60	3
60-90	4
>90	5

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset are summarized at Table G9-3.

Table G9-3. Focused Calibration Dataset.

Parameter	Unit	Lower Range	Higher Range
Pipe Size	Inches	5	21
Pipe Length	Feet	12	496
Pipe Material	Type	AC, CON, DIP, PVC	
Pipe Slope	%	0.15	14.07
Pipe Age	Years	15	44
Pipe Location	Type	Field, Parking Lot, Building, Road, Highway	
Pipe Condition	Grade	1	5
Pipe Shape	Type	Circular	
Pipe Surcharging	Frequency	0	1
Tidal Influence	Yes/No	No	Yes

After the model run with the dataset, the performance index output and the utility index result differences range between 0-5. Table G9-3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G9-4 Final Piloting Results

Total Number of Segments	Segments with 0 difference	Segments with 1 difference	Segments with 2 difference	Segments with 3 difference	Segments with 5 difference
154	47	60	38	8	1
100%	30.52%	38.96%	24.68%	5.19%	0.65%

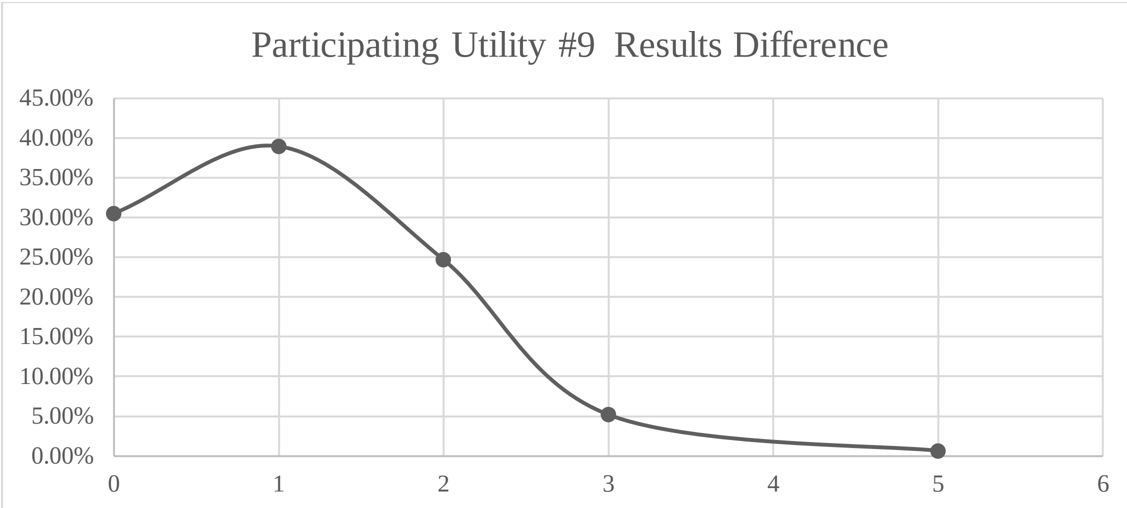

Figure G9-2. Utility #9 Results Difference

Results with 0 Difference

Table G9-5 summarizes pipes with 0 difference between the defect rating and the performance index.

Table G9-5. Segments with 0 difference

PIPEiD	Model	Defect Index	Difference
8	2	2	0
20	2	2	0
25	2	2	0
26	2	2	0
27	2	2	0
28	2	2	0
29	2	2	0
30	2	2	0
32	2	2	0
33	2	2	0
34	2	2	0
35	2	2	0
37	2	2	0
38	2	2	0
39	2	2	0

40	2	2	0
41	2	2	0
44	2	2	0
46	2	2	0
47	2	2	0
48	2	2	0
78	2	2	0
79	2	2	0
80	2	2	0
83	2	2	0
84	2	2	0
109	2	2	0
110	2	2	0
111	2	2	0
112	2	2	0
113	2	2	0
114	2	2	0
115	2	2	0
125	2	2	0
127	2	2	0
128	2	2	0
129	2	2	0
130	2	2	0
131	2	2	0
132	2	2	0
133	2	2	0
134	2	2	0
135	2	2	0
136	2	2	0
137	10	10	0
138	10	10	0
139	10	10	0

Results with 1 and 2 Differences

Table G9-6 summarizes pipes with 1 and 2 differences between the defect rating and the performance index.

Table G9-6. Segments with 1 and 2 differences

PIPEiD	Model	Defect Index	Difference
2	6	4	2
3	3	2	1
4	3	2	1
5	3	2	1
6	3	2	1
7	6	4	2
9	4	2	2
10	3	2	1
11	4	2	2
13	3	2	1
14	6	4	2
15	3	2	1
16	3	2	1
17	3	2	1
18	3	2	1
19	6	4	2
21	7	6	1
22	6	4	2
23	6	4	2
24	6	4	2
36	6	4	2
42	4	2	2
43	4	2	2
45	6	4	2
49	3	2	1
50	4	2	2
51	3	2	1
52	3	2	1
53	3	2	1
54	4	2	2
55	4	2	2
56	4	2	2
57	4	2	2
58	3	2	1
59	3	2	1
60	6	4	2
62	3	2	1
63	3	2	1
64	3	2	1

65	3	2	1
66	3	2	1
70	4	2	2
71	3	2	1
72	3	2	1
73	7	6	1
74	3	2	1
75	3	2	1
76	3	2	1
77	3	2	1
82	3	2	1
85	4	2	2
86	4	2	2
87	4	2	2
88	4	2	2
89	4	2	2
90	4	2	2
91	6	4	2
92	4	2	2
93	4	2	2
94	4	2	2
95	6	4	2
96	6	4	2
97	3	2	1
98	3	2	1
99	6	4	2
100	4	2	2
101	4	2	2
102	3	2	1
103	3	2	1
104	3	2	1
105	3	2	1
106	3	2	1
107	4	2	2
108	3	2	1
116	3	2	1
117	3	2	1
118	4	2	2
119	4	2	2
121	3	2	1
122	3	2	1
123	3	2	1

124	3	2	1
126	3	2	1
140	7	6	1
141	7	6	1
142	7	6	1
143	9	8	1
144	9	8	1
145	9	8	1
146	9	8	1
147	9	8	1
148	9	8	1
149	9	8	1
150	9	8	1
151	9	8	1
152	9	8	1
153	9	8	1
154	9	8	1

Results with 3 Difference

Table G9-7 summarizes pipes with 3 difference between the defect rating and the performance index.

Table G9-7. Segments with 3 difference.

PIPEiD	Model	Defect Index	Difference
1	5	2	3
12	5	2	3
31	5	2	3
61	5	2	3
67	5	2	3
68	5	2	3
69	5	2	3
81	5	2	3

Results with 5 Difference

Table G9-8 summarize pipes with 5 difference between the defect rating and the performance index.

Table G9-8. Segments with 5 difference.

PIPEiD	Model	Defect Index	Difference	Module
120	7	2	5	Integrity

Case Studies

Table G9-9. Pipe Segment 120

Parameter	Unit	Value
Pipe ID	ID	120
Pipe Size	Inches	15
Pipe Length	Feet	340
Pipe Material	Type	Asbestos Cement
Pipe Slope	%	0.87
Pipe Age	Years	43
Pipe Location	Type	Highway
Pipe Condition	Grade	1
Pipe Shape	Type	Circular
Pipe Surcharging	Frequency	0
Tidal Influence	Yes/No	No

Index output: 7 (Serious) vs. 2 (V, Good) Defect Index

Module with maximum result: Integrity

Reason: Moderate age, pipe location

Discussion: This moderate aged (43) AC pipe is prone to integrity issues due to its age and location (highway).

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The preliminary results for gravity pipes suggest that the expected remaining life of these pipes is 61 years. Results of the time-dependent performance prediction are summarized in Figures G9-3 and G9-4.

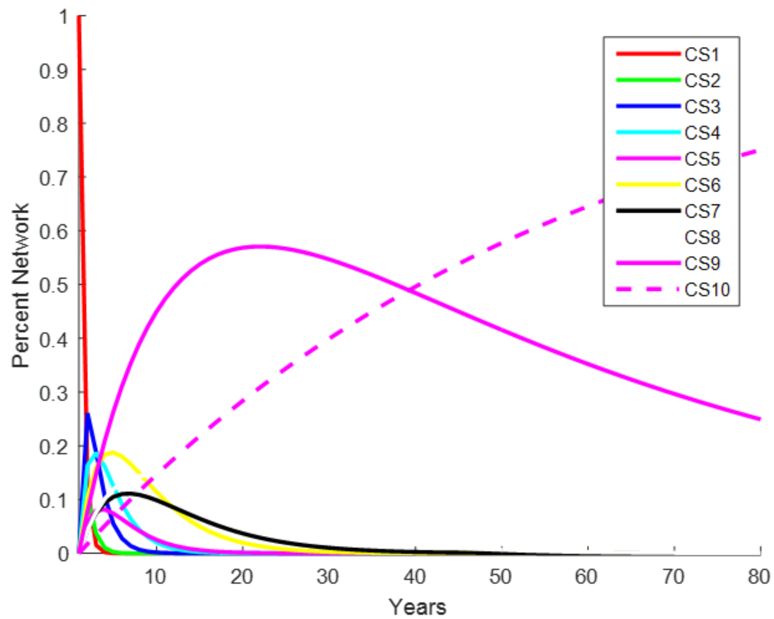

Figure G9-3. Preliminary State Dependent Performance Prediction Results

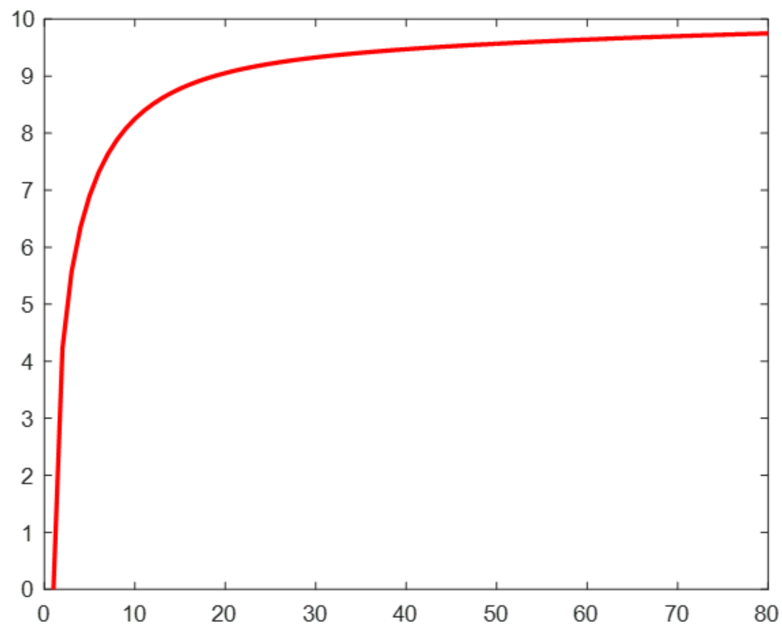

Figure G9-4. Preliminary State Dependent Performance Prediction Results

Appendix G10 – Utility #10 Piloting Results

Overview

The research team has received data from participating utility #10 in the form of GIS geodatabase. This GIS geodatabase contains records for 77145 pipe segments totaling in 3050 miles in length. Participating utility sewer system is summarized in Figure G10-1.

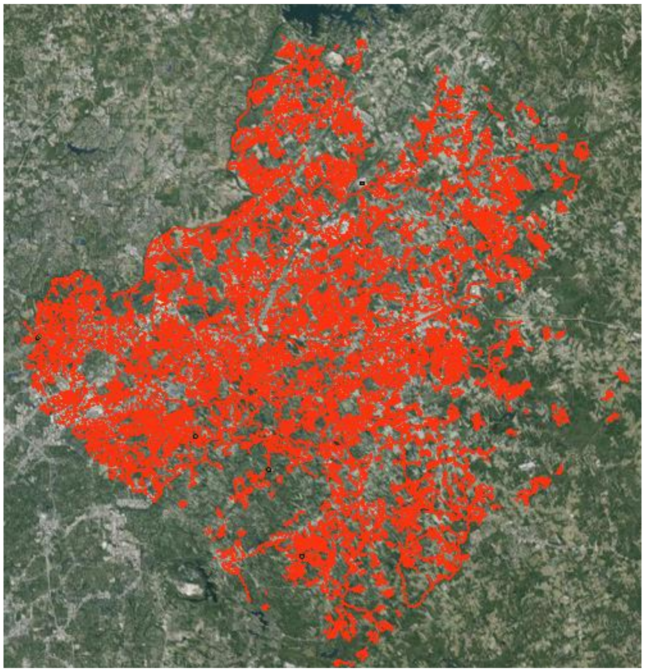

Figure G10-1. Participating Utility Sewer System

300 segments were randomly selected for the piloting the performance index. Data is extracted for these 300 segments to pilot the performance index. Extracted data from utility records are summarized in Table G10-1.

Table G10-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe ID	Geodatabase
Pipe Diameter	Geodatabase
Pipe Length	Geodatabase
Pipe Material	Geodatabase
Pipe Shape	Geodatabase
Pipe Slope	Geodatabase

Pipe Location	Geodatabase
Pipe Condition	Geodatabase
Liner Present	Geodatabase
Liner Type	Geodatabase
Cleaning Type	Geodatabase

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset are summarized at Table G10-2.

Table G10-2. Focused Calibration Dataset.

Parameter	Unit	Lower Range	Higher Range
Pipe Diameter	Inches	7	16
Pipe Length	Feet	4	72
Pipe Material	Type	CI, DI, PVC, RCP, RPM, VCP	
Pipe Shape	Type	Circular	
Pipe Slope	% Grade	0.02	0.43
Pipe Location	Type	Parking lot, Easement, Sidewalk, Highway, Yard, Woods	
Pipe Condition	Grade	1	5
Liner Present	Yes/No	No	Yes
Liner Type	Type	CIPP	
Cleaning Type	Type	Flushing, Jetting, Root Control	

After the model run with the dataset, and the performance index output range between 0-5. Table G10-3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G10-3. Final Piloting Results

Total Number of Segments	Segments with 0 difference	Segments with 1 difference	Segments with 2 difference	Segments with 3 difference	Segments with 5 difference
300	18	104	55	107	17
100%	6.00%	34.67%	18.33%	35.67%	5.67%

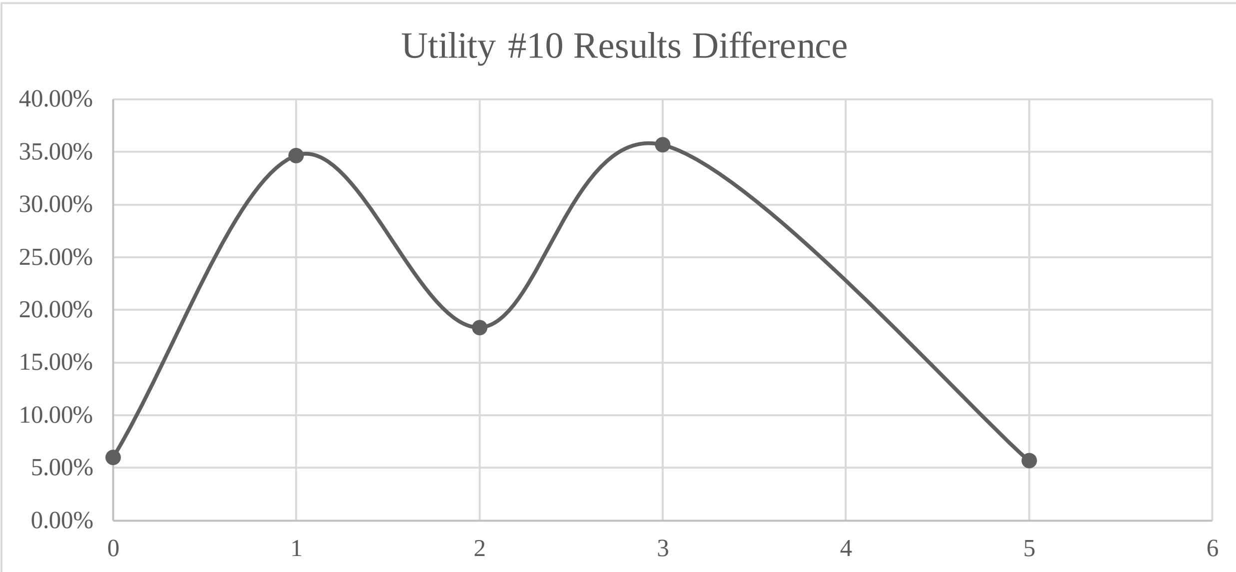

Figure G10-2. Utility #10 Results Difference

Results with 0 Difference

Table G10-4 summarizes pipes with 0 difference between the defect rating and the performance index.

Table G10-4. Segments with 0 difference

PIPEiD	Model	PACP	Difference
685014	10	10	0
686453	10	10	0
686575	10	10	0
687238	10	10	0
691389	10	10	0
692104	10	10	0
692234	10	10	0
692311	10	10	0
696249	10	10	0
696556	10	10	0
696802	10	10	0
699203	10	10	0
699205	10	10	0
705755	10	10	0

706991	10	10	0
707306	10	10	0
709704	10	10	0
709753	10	10	0

Results with 1 and 2 Difference

Table G10-5 summarizes pipes with 1 and 2 difference between the defect rating and the performance index.

Table G10-5. Segments with 1 and 2 differences

PIPEiD	Model	PACP	Difference
681147	3	2	1
681387	9	8	1
681406	7	6	1
681637	3	2	1
681647	9	8	1
681651	9	8	1
682144	6	4	2
682515	7	6	1
683183	3	2	1
684672	3	2	1
684755	3	2	1
684901	7	6	1
684992	9	8	1
685021	6	4	2
685029	6	4	2
685134	7	6	1
685226	9	8	1
685570	9	8	1
685833	3	2	1
685929	9	8	1
686088	6	4	2
686327	9	8	1
686515	3	2	1
686569	7	6	1
686655	7	6	1
686701	3	2	1
686705	3	2	1
686706	6	4	2

686707	9	8	1
686710	7	6	1
686799	6	4	2
686904	6	4	2
686959	6	4	2
687098	6	4	2
687104	7	6	1
687242	6	4	2
687868	7	6	1
688250	6	4	2
688468	6	4	2
688473	7	6	1
688495	6	4	2
688596	3	2	1
688611	7	6	1
688758	6	4	2
688970	7	6	1
689013	6	4	2
689020	6	4	2
689076	3	2	1
689147	6	4	2
689314	3	2	1
689694	9	8	1
690272	9	8	1
690342	9	8	1
690394	7	6	1
690398	9	8	1
690510	9	8	1
690597	3	2	1
690602	3	2	1
690741	9	8	1
690825	3	2	1
690932	3	2	1
690933	9	8	1
691409	9	8	1
691411	9	8	1
691414	6	4	2
691669	6	4	2
691694	7	6	1
691939	6	4	2
691967	6	4	2
692241	9	8	1

692242	6	4	2
692244	7	6	1
692246	9	8	1
692319	6	4	2
692345	6	4	2
692347	9	8	1
692349	7	6	1
692399	6	4	2
692411	6	4	2
692419	6	4	2
692539	9	8	1
692546	9	8	1
692991	7	6	1
695499	7	6	1
695632	6	4	2
696244	9	8	1
697113	7	6	1
697757	3	2	1
697935	7	6	1
697936	9	8	1
697937	7	6	1
697938	9	8	1
698098	9	8	1
698326	4	2	2
698418	3	2	1
698889	6	4	2
699124	3	2	1
700057	9	8	1
700496	3	2	1
700572	9	8	1
700716	7	6	1
700737	6	4	2
700898	7	6	1
701706	9	8	1
701770	7	6	1
702039	3	2	1
702923	6	4	2
703410	3	2	1
703504	3	2	1
703541	8	6	2
703607	6	4	2
703611	7	6	1

703616	6	4	2
703618	3	2	1
703619	3	2	1
703858	6	4	2
703964	6	4	2
703981	6	4	2
704029	6	4	2
704654	9	8	1
704655	9	8	1
704669	7	6	1
704690	3	2	1
704816	9	8	1
704988	3	2	1
704996	9	8	1
705204	3	2	1
705218	7	6	1
705219	6	4	2
705338	3	2	1
705437	7	6	1
705440	6	4	2
705441	6	4	2
705443	6	4	2
705481	6	4	2
706411	9	8	1
706629	6	4	2
706683	6	4	2
706700	7	6	1
707239	6	4	2
708477	6	4	2
708649	3	2	1
708686	6	4	2
709399	3	2	1
709484	6	4	2
709613	3	2	1
709752	7	6	1
709755	9	8	1
710042	3	2	1
710858	7	6	1
711139	6	4	2
711306	6	4	2
711717	6	4	2
712629	7	6	1

712640	7	6	1
713384	9	8	1
713385	3	2	1
713482	6	4	2
713584	6	4	2

Results with 3 Difference

Table G10-6 summarizes pipes with 3 difference between the defect rating and the performance index.

Table G10-6. Segments with 3 differences.

PIPEiD	Model	PACP	Difference
681650	5	2	3
681654	5	2	3
681769	5	2	3
682197	5	2	3
683094	5	2	3
683433	5	2	3
684884	5	2	3
684885	5	2	3
684986	5	2	3
685018	5	2	3
685027	5	2	3
685032	5	2	3
685035	5	2	3
685144	5	2	3
685167	5	2	3
685803	5	2	3
685830	5	2	3
685926	5	2	3
685932	5	2	3
685936	5	2	3
685941	5	2	3
685943	5	2	3
686066	5	2	3
686068	5	2	3
686069	5	2	3
686203	5	2	3
686330	5	2	3

686441	5	2	3
686574	5	2	3
687107	5	2	3
687227	5	2	3
688215	5	2	3
688219	5	2	3
688249	5	2	3
688299	5	2	3
688355	5	2	3
688380	5	2	3
688591	5	2	3
688612	5	2	3
688736	5	2	3
689179	5	2	3
689309	5	2	3
689310	5	2	3
689327	5	2	3
690183	7	4	3
690222	5	2	3
690416	7	4	3
690422	7	4	3
690856	5	2	3
690920	5	2	3
691726	5	2	3
691972	5	2	3
692119	5	2	3
692208	5	2	3
692227	5	2	3
692413	5	2	3
692684	5	2	3
693881	5	2	3
694003	5	2	3
694011	5	2	3
694101	7	4	3
694361	5	2	3
695695	5	2	3
697888	5	2	3
698178	5	2	3
698180	5	2	3
698181	5	2	3
698255	5	2	3
698895	5	2	3

699343	5	2	3
701514	7	4	3
702370	5	2	3
702833	5	2	3
702861	5	2	3
703917	5	2	3
704228	7	4	3
704232	5	2	3
704267	5	2	3
704371	5	2	3
704440	5	2	3
704441	5	2	3
704651	7	4	3
704652	5	2	3
704653	5	2	3
705383	5	2	3
705419	5	2	3
706645	5	2	3
708682	7	4	3
708683	7	4	3
708755	5	2	3
709754	5	2	3
709757	5	2	3
711432	5	2	3
711948	5	2	3
712200	5	2	3
713130	5	2	3
713132	5	2	3
713134	5	2	3
713180	5	2	3
713485	5	2	3
713579	5	2	3
713581	5	2	3
713582	5	2	3
713583	5	2	3

Results with 5 Difference

Table G10-7 summarizes pipes with 5 difference between the defect rating and the performance index.

Table G10-7. Segments with 5 difference.

PIPEiD	Model	PACP	Difference	Module
684997	7	2	5	Integrity
685168	7	2	5	Integrity
686561	7	2	5	Integrity
686571	7	2	5	Integrity
688470	7	2	5	Integrity
690475	7	2	5	Integrity
690618	7	2	5	Integrity
690771	7	2	5	Integrity
692168	7	2	5	Integrity
695671	7	2	5	Integrity
697401	7	2	5	Integrity
702892	7	2	5	Integrity
704550	7	2	5	Integrity
708771	7	2	5	Integrity
709837	7	2	5	Integrity
712042	7	2	5	Integrity

Case Studies

Table G10-8. Pipe Segment 684997

Parameter	Unit	Value
PIPEiD	ID	684997
Pipe Diameter	Inches	8
Pipe Length	Feet	208
Pipe Material	Type	Vitrified Clay
Pipe Shape	Type	Circular
Pipe Slope	% Grade	0.4
Pipe Location	Type	Highway
Pipe Condition	Grade	1
Liner Present	Yes/No	No
Liner Type	Type	None
Cleaning Type	Type	None

Index output: 7 (Serious) Vs. 2 Normalized PACP

Module with maximum result: Integrity

Reason: VCP under highway

Discussion: This VCP pipe is prone to integrity issues because of the high dynamic loads due to its location (under highway).

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The preliminary results for gravity pipes suggest that the expected remaining life of these pipes is 62 years. Results of the time dependent performance prediction is summarized in figures G10-3 and G10-4.

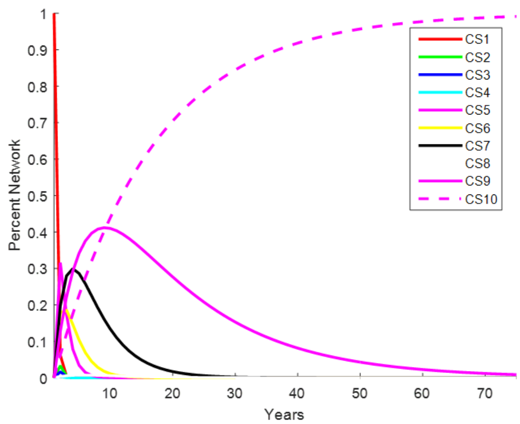

Figure G10-3. Preliminary State Dependent Performance Prediction Results

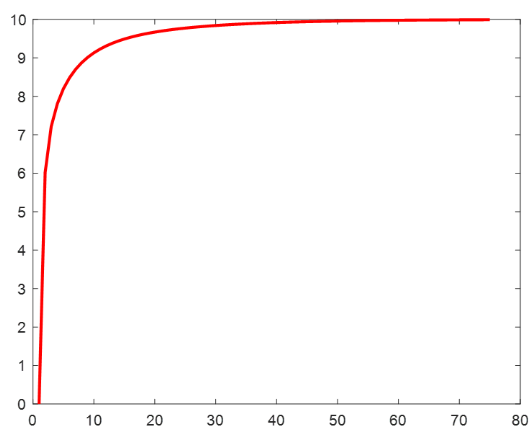

Figure G10-4. Preliminary State Dependent Performance Prediction Results

Appendix G11 – Utility #11 Piloting Results

The research team has been piloting the developed performance index with the GIS, defect, and failure data received from participating utility #11. These records contain data for 13018 pipe segments. 118 of this pipe were randomly selected to be evaluated. Extracted data from utility records are summarized in Table G11-1.

Table G11-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe Age	Geodatabase
Pipe Condition	Geodatabase
Pipe Diameter	Geodatabase
Pipe Length	CCTV Inspection Data
Pipe Location	Geodatabase
Pipe Slope	CCTV Inspection Data
Lining Present	Geodatabase
Ground Cover	Geodatabase
Pipe Shape	CCTV Inspection Data
Pipe Material	Geodatabase

Performance Index Piloting Results Discussion

A focused dataset of 118 pipes was selected to further calibrate the index this dataset includes the pipe samples with the highest and lowest ranges of the parameters and the pipe segments with the greatest results differences from the previous pass. The ranges and the number of pipe segment selected for the focused calibration dataset are summarized at Table G11-2.

Table G11-2. Focused Calibration Dataset.

Parameter	Lower Range	Higher Range
Pipe Age	0.098- 1	74.93-70.5
Pipe Diameter	2-6	72
Pipe Length	4.46-10.7	1122-652.71
Pipe Location	No Load	Highway
Pipe Slope	0.01-0.0355	112.40-6.83
Lining Present	No	Yes

Ground Cover	Open Field	Asphalt
Pipe Shape	Unknown	Circular

After the model run with the dataset, the results of the PACP coding and the model outputs are compared. It is important to note that the PACP coding results are normalized by multiplying by 2 to have a comparable scale with the index outputs. The results differences between the PACP defect coding and performance index output range between 0-5. Table G11-3 summarize the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G11-3. Final Piloting Results

Total Number of Segments	Segments with 0 difference	Segments with 1 difference	Segments with 2 Difference	Segments with 3 Difference	Segments with 4 Difference	Segments with 5 Difference
118	3	16	78	17	2	2
100%	2.54%	12.71%	66.10%	14.41%	2.54%	1.69%

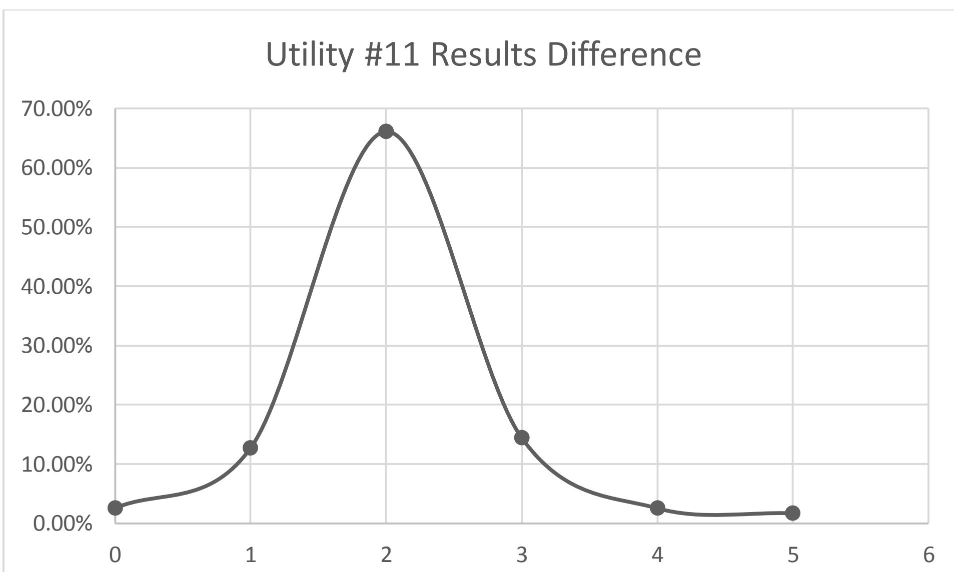

Figure G11-1. Utility #11 Results Difference

Results with 0 Difference

Pipes with PACP grade of 5 (failed) tend to give the same result for the index. The algorithm cannot further penalize the already failed pipe segments. Table G11-4 discuss summarize already failed pipes in the sample population.

Table G11-4. Segments with 0 Difference – Failed Pipes

Significant Parameter	PIPEiD	Model	PACP (Normalized)	Difference
Young Pipes	430	10	10	0
Young Pipes	434	10	10	0
Short Pipes	20062	10	10	0

Results with 1 Difference

Pipe segments where results are one difference between the normalized PACP grade and the index output is summarized in Table 5. Results summarized indicate the pipes with the desirable parameters (low range) are not penalized for the performance. Results also suggest that although there are undesirable parameters for some of the pipe segments, the effects of these parameters are not significant for the pipe performance due to various other parameters.

Table G11-5. Segments with 1 Difference

Significant Parameter	PIPEiD	Mode l	PACP Normalized	Difference
Young Pipes	158	7	6	1
Old Pipes	4697	3	2	1
Small Diameter	9282	7	6	1
Large Diameter	15346	7	6	1
Large Diameter	15568	7	6	1
Short Pipes	24699	7	6	1
Short Pipes	25614	7	6	1
Short Pipes	25618	7	6	1
Asphalt Cover	42024	7	6	1
Open Land	42500	7	6	1

Open Land	42502	9	8	1
Right-of-way	55260	7	6	1
No Liner	64990	7	6	1
No Liner	72270	7	6	1
No Liner	72601	7	6	1

Results with 2 Difference

There are 78 (66.10%) pipe segments with two difference between the PACP normalized grade and the index output. Pipe segments where results are two difference between the normalized PACP grade and the index output is summarized in Table 6. Most of the pipes which have two difference are pipes with no observed internal defect. The differences are caused by surface wear, integrity, capacity, and blockage modules. The explanations for the differences are noted below. Most of the pipes which have two difference are pipes with no internal defects observed by the CCTV inspections.

Table G11-6. Pipe segments where results are 2 difference between the normalized PACP grades.

Explanation	PIPEiD	Index	PACP	Difference	Difference Module
Low slope, Moderate Age	2148	2	0	2	Surface Wear
Moderate age	2636	2	0	2	Integrity
Young age, small diameter, low slope	3114	2	0	2	Capacity
Young age, small diameter, low slope	3251	2	0	2	Capacity
Moderate age	3342	2	0	2	Integrity
Moderate age	3470	2	0	2	Integrity
Moderate age	4692	2	0	2	Integrity
Young age, small diameter, low slope	6355	2	0	2	Capacity
Young age, small diameter, low slope	12628	2	0	2	Capacity
Young age, small diameter, low slope	12629	2	0	2	Capacity
Young age, small diameter, low slope	12632	2	0	2	Capacity
Young age, small diameter, low slope	12633	2	0	2	Capacity
Moderate age	12634	2	0	2	Integrity
Young age, small diameter, low slope	15203	2	0	2	Capacity

Young age, small diameter, low slope	15341	2	0	2	Capacity
Moderate age	15401	2	0	2	Integrity
Young age, small diameter, low slope	15445	2	0	2	Capacity
Young age, small diameter, low slope	15460	2	0	2	Capacity
Young age, small diameter, low slope	15493	8	6	2	Capacity
Long Pipe	15511	2	0	2	Blockage
Young age, small diameter, low slope	15522	2	0	2	Capacity
Young age, small diameter, low slope	16544	2	0	2	Capacity
Moderate age	20690	2	0	2	Integrity
Moderate age	21504	6	4	2	Integrity
Moderate age	22709	2	0	2	Integrity
Moderate age	23096	2	0	2	Integrity
Moderate age	25684	6	4	2	Integrity
Young age, small diameter, low slope	26441	2	0	2	Capacity
Young age, small diameter, low slope	28882	2	0	2	Capacity
Moderate age	37419	2	0	2	Integrity
Moderate age	38760	2	0	2	Integrity
Young age, small diameter, low slope	39007	2	0	2	Capacity
Moderate age	39171	2	0	2	Integrity
Young age, small diameter, low slope	39231	2	0	2	Capacity
Moderate age	40653	2	0	2	Integrity
Moderate age	40667	2	0	2	Integrity
Young age, small diameter, low slope	41475	2	0	2	Capacity
Moderate age	41637	6	4	2	Integrity
Long Pipe	41708	2	0	2	Blockage
Low slope, Moderate Age	41937	2	0	2	Surface Wear
Low slope, Moderate Age	43217	2	0	2	Surface Wear
Moderate age	43512	2	0	2	Integrity
Low slope, Moderate Age	49682	2	0	2	Surface Wear
Low slope, Moderate Age	59834	2	0	2	Surface Wear
Young age, small diameter, low slope	60631	2	0	2	Capacity
Young age, small diameter, low slope	60642	2	0	2	Capacity
Young age, small diameter, low slope	60647	2	0	2	Capacity
Young age, small diameter, low slope	60787	2	0	2	Capacity
Young age, small diameter, low slope	61390	2	0	2	Capacity
Young age, small diameter, low slope	61395	2	0	2	Capacity
Young age, small diameter, low slope	61547	2	0	2	Capacity
Young age, small diameter, low slope	61633	2	0	2	Capacity

Young age, small diameter, low slope	61683	2	0	2	Capacity
Young age, small diameter, low slope	61873	2	0	2	Capacity
Young age, small diameter, low slope	61939	2	0	2	Capacity
Young age, small diameter, low slope	61940	2	0	2	Capacity
Young age, small diameter, low slope	62522	2	0	2	Capacity
Young age, small diameter, low slope	62698	2	0	2	Capacity
Moderate age	62804	2	0	2	Integrity
Young age, small diameter, low slope	62907	2	0	2	Capacity
Young age, small diameter, low slope	63394	2	0	2	Capacity
Moderate age	63444	2	0	2	Integrity
Young age, small diameter, low slope	63454	2	0	2	Capacity
Moderate age	63465	2	0	2	Integrity
Young age, small diameter, low slope	63572	2	0	2	Capacity
Young age, small diameter, low slope	63592	2	0	2	Capacity
Young age, small diameter, low slope	63769	2	0	2	Capacity
Young age, small diameter, low slope	63794	2	0	2	Capacity
Young age, small diameter, low slope	63827	2	0	2	Capacity
Young age, small diameter, low slope	63828	2	0	2	Capacity
Young age, small diameter, low slope	63831	2	0	2	Capacity
Young age, small diameter, low slope	63833	2	0	2	Capacity
Young age, small diameter, low slope	64716	2	0	2	Capacity
Young age, small diameter, low slope	65171	2	0	2	Capacity
Young age, small diameter, low slope	65387	2	0	2	Capacity
Young age, small diameter, low slope	66033	2	0	2	Capacity
Young age, small diameter, low slope	72241	2	0	2	Capacity
Moderate age	72271	2	0	2	Integrity

G11-7. Pipe Segment #3114

Parameter	Value
PIPEiD	3114
Pipe Age	0.87
Pipe Condition	0
Pipe Diameter	8
Pipe Length	10.75
Pipe Location	Unknown
Pipe Slope	0.86
Lining Present	No
Ground Cover	Unknown
Pipe Shape	Unknown

Pipe Material	Unknown

PACP vs. index output: 0 (excellent) vs. 2 (very good)

Module with maximum result: Capacity

Reason: Young age, small diameter, low slope

Discussion: Although there is no defect noted by the CCTV inspection, and the age of the pipe is young, the small diameter and low slope indicate this pipe might have capacity issues.

Results with 3 Difference

There are 17 (14.41%) pipe segments with three difference between the PACP grade and the index output. Table G11-8 summarize these results. Some significant pipe segments with a high difference between the index and the PACP grades are further investigated in the following case studies.

Table G11-8. Pipe segments where results are 3 difference between the normalized PACP grades.

Explanation	PIPEiD	Index	PACP	Difference	Module
Low slope, high age	72	3	0	3	Surface Wear
Low slope, high age	419	3	0	3	Surface Wear
Long Pipe	423	3	0	3	Blockage
High age, under traffic	431	7	4	3	Integrity
Low slope high age	825	3	0	3	Surface Wear
Low slope high age	839	3	0	3	Surface Wear
Low slope high age	3115	3	0	3	Surface Wear
Long Pipe	12626	3	0	3	Blockage
Long Pipe	12627	3	0	3	Blockage
Long Pipe	12630	3	0	3	Blockage
Long Pipe	39509	3	0	3	Blockage
Long Pipe	39528	3	0	3	Blockage
Low slope high age	41365	3	0	3	Surface Wear
Low slope high age	42304	3	0	3	Surface Wear
Low Slope	42537	3	0	3	Blockage
Moderate age under traffic	48437	3	0	3	Integrity

Long Pipe	63699	3	0	3	Blockage

Case Studies

Table G11-9. Pipe Segment #419

Parameter	Value
PIPEiD	419
Pipe Age	71.50
Pipe Condition	0
Pipe Diameter	8
Pipe Length	185.47
Pipe Location	Unknown
Pipe Slope	0.71
Lining Present	No
Ground Cover	Unknown
Pipe Shape	Unknown
Pipe Material	Vitrified Clay

PACP vs. index output: 0 (excellent) vs. 3 (good)

Module with maximum result: Integrity

Reason: Low slope, high age

Discussion: Although there is no defect noted by the CCTV inspection, the pipe has a high age, and the slope is low indicating low flow velocity and possible internal corrosion issues.

Table G11-10. Pipe Segments # 423

Parameter	Value
PIPEiD	419
Pipe Age	70.51
Pipe Condition	0
Pipe Diameter	8
Pipe Length	411.02
Pipe Location	Unknown
Pipe Slope	0.44
Lining Present	No
Ground Cover	Unknown

Pipe Shape	Unknown
Pipe Material	Vitrified Clay

PACP vs. index output: 0 (excellent) vs. 3 (good)

Module with maximum result: Blockage

Reason: Long pipe

Discussion: Although there are no blockages issues noted by the PACP, the long length of the pipe indicate this segment might be prone to blockages.

Table G11-11. Pipe Segments # 431

Parameter	Value
PIPEiD	431
Pipe Age	70.51
Pipe Condition	2
Pipe Diameter	8
Pipe Length	80.2
Pipe Location	Under traffic
Pipe Slope	0.44
Lining Present	No
Ground Cover	Asphalt
Pipe Shape	Unknown
Pipe Material	Vitrified Clay

PACP vs. index output: 4 (satisfactory) vs. 7 (serious)

Module with maximum result: Integrity

Reason: High age, under traffic

Discussion: The CCTV inspection indicates that this pipe is in good condition (2). However, the fact that this vitrified clay pipe has a high age (70.51 years) and is located under traffic indicates there would be integrity issues.

Results with 4 or 5 Difference

There are 4 (3.39%) pipe segments where there is 4 or 5 difference between the PACP grade and the index output. Table G11-12 summarizes these results. Some significant pipe segments with the high difference between the index and the PACP grades are further investigated in the following case studies.

Table G11-12. Pipe segments where results are 4 or 5 difference between the normalized PACP grades.

Significant Parameter	PIPEiD	Index	PACP	Dif.	Diff. Module
Very Long pipe, moderate diameter	59406	4	0	4	Blockage
Very Long pipe, small diameter	63539	4	0	4	Blockage
High age, under traffic load	432	5	0	5	Integrity
Moderate age, under traffic load	12631	5	0	5	Integrity

<u>Case Studies</u>

Table G11-13. Pipe Segments # 59406

Parameter	Value
PIPEiD	59406
Pipe Age	10.09
Pipe Condition	0
Pipe Diameter	24
Pipe Length	500.93
Pipe Location	Unknown
Pipe Slope	1.27
Lining Present	No
Ground Cover	Unknown
Pipe Shape	Unknown
Pipe Material	PVC

PACP vs. index output: 0 (excellent) vs. 5 (fair)

Module with maximum result: Blockage

Reason: Very long pipe length, moderate pipe diameter.

Discussion: Although the PACP grade for the pipe is 0, the fact that this pipe segment has a very long length (500.93 ft.) indicates that this pipe would be prone to blockage issues.

Table G11-14. Pipe Segments # 63539

Parameter	Value
PIPEiD	63539
Pipe Age	6.94
Pipe Condition	0
Pipe Diameter	8
Pipe Length	489.95
Pipe Location	Unknown
Pipe Slope	5.94
Lining Present	No
Ground Cover	Unknown
Pipe Shape	Unknown
Pipe Material	RCP

PACP vs. index output: 0 (excellent) vs. 5 (fair)

Module with maximum result: Blockage

Reason: Very long pipe length, small pipe diameter.

Discussion: Although the PACP grade for the pipe is 0, the fact that this pipe segment has a very long length (489.95 ft.) indicates that this pipe would be prone to blockage issues.

Table G11-15. Pipe Segments # 432

Parameter	Value
PIPEiD	432
Pipe Age	70.50
Pipe Condition	0
Pipe Diameter	8
Pipe Length	122.99

Pipe Location	Under Traffic
Pipe Slope	0.6585
Lining Present	No
Ground Cover	Asphalt
Pipe Shape	Unknown
Pipe Material	Vitrified Clay

PACP vs. index output: 0 (excellent) vs. 5 (fair)

Module with maximum result: Integrity

Reason: High age, under traffic load

Discussion: Although the PACP grade for the pipe is 0, pipe segment had a high age and located under traffic. This indicated segment might have integrity issues.

Table G11-16. Pipe Segments # 12631

Parameter	Value
PIPEiD	12631
Pipe Age	26.51
Pipe Condition	0
Pipe Diameter	72
Pipe Length	381.73
Pipe Location	Under Traffic
Pipe Slope	0.212
Lining Present	No
Ground Cover	Asphalt
Pipe Shape	Unknown
Pipe Material	Reinforced Concrete

PACP vs. index output: 0 (excellent) vs. 5 (fair)

Module with maximum result: Integrity

Reason: High age, under traffic load

Discussion: Although the PACP grade for the pipe is 0, pipe segment has a moderate age and located under traffic. This indicated segment might have integrity issues.

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The preliminary results for gravity pipes suggest that the expected remaining life of these pipes is 134 years. Results of the time dependent performance prediction is summarized in figures G11-3 and G11-4.

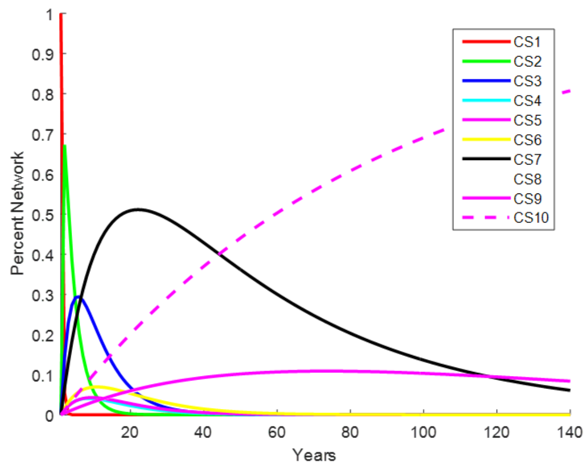

Figure G11-3. Preliminary State Dependent Performance Prediction Results

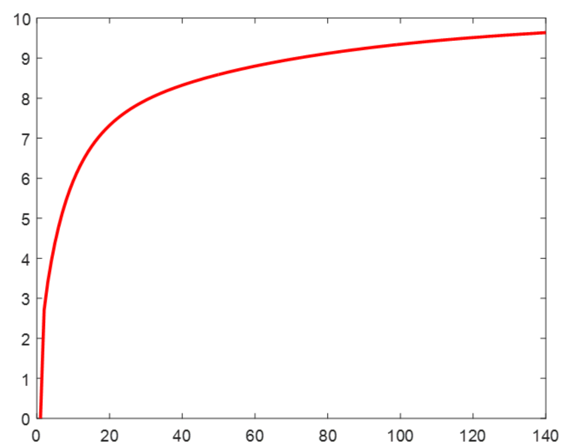

Figure G11-4. Preliminary State Dependent Performance Prediction Results

Appendix G12 – Utility #12 Piloting Results

Overview

The research team has received data from participating utility #12 in the form of;

- CCTV inspection report for the interceptor Line.

31 segments in this trunk sewer were inspected both in 2004 and 2014. Data is extracted for these 31 inspected segments to pilot the performance index and prediction model. Of these 31 segments, 26 were selected to develop the prediction model, and five were selected to assess the accuracy of the developed deterioration model. Extracted data from utility records are summarized in Table G12-1.

Table G12-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe ID	CCTV Inspection Report
Pipe Age	CCTV Inspection Report
Pipe Condition	CCTV Inspection Report
Pipe Depth	CCTV Inspection Report
Pipe Diameter	CCTV Inspection Report
Pipe Length	CCTV Inspection Report
Pipe Location	CCTV Inspection Report
Pipe Material	CCTV Inspection Report
Lining Presence	CCTV Inspection Report

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset are summarized in Table G12-2.

Table G12-2. Focused Calibration Dataset.

Parameter	Lower Range	Higher Range
Pipe Age	32	42
Pipe Condition	1	4

Pipe Depth	6.5	14.4
Pipe Diameter	8	24
Pipe Length	18.2	507.5
Pipe Location	Woodland	Under Highway
Pipe Material	RCP, DI	
Lining Presence	No	Yes

After the model run with the dataset, the results of the PACP coding and the model outputs are compared. It is important to note that the PACP coding results are normalized by multiplying by 2 to have a comparable scale with the index outputs. The results differences between the PACP defect coding and performance index output range between 0-2. Table G12-3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G12-3. Final Piloting Results

Total Number of Segments	Segments with 0 difference	Segments with 2 Difference
52	38	14
100%	73.08%	26.92%

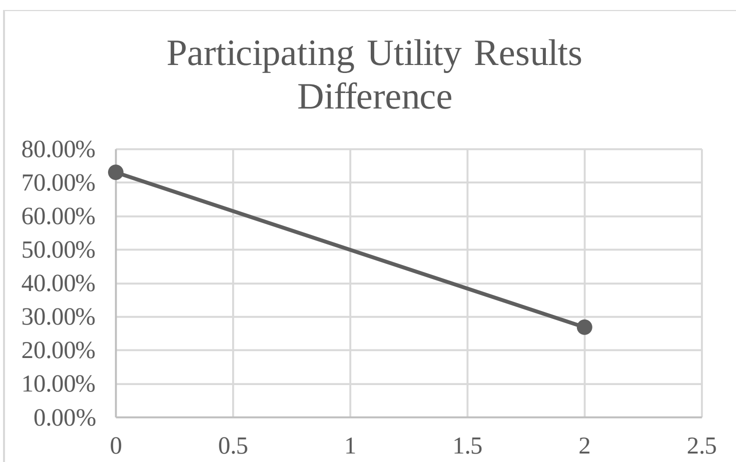

Figure G12-1. Participating Utility Results Difference

Results with 0 Difference

Table G12-4 discuss summarize already failed pipes in the sample population.

Table G12-4. Segments with 0 Difference

PIPEiD	Model	PACPNorm	Difference
1	2	2	0
2	2	2	0
3	2	2	0
5	2	2	0
6	2	2	0
7	2	2	0
8	2	2	0
9	6	6	0
10	6	6	0
11	6	6	0
15	6	6	0
16	6	6	0
17	6	6	0
19	6	6	0
22	6	6	0
23	6	6	0
24	2	2	0
25	2	2	0
26	2	2	0
27	2	2	0
28	2	2	0
29	2	2	0
30	2	2	0
32	2	2	0
1	2	2	0
2	2	2	0
3	2	2	0
4	6	6	0
5	2	2	0
6	2	2	0
7	2	2	0
8	2	2	0
9	6	6	0
10	6	6	0
11	6	6	0
15	6	6	0
16	6	6	0
17	6	6	0
19	6	6	0

22	6	6	0
23	6	6	0
25	2	2	0
26	2	2	0
27	2	2	0
28	2	2	0
29	2	2	0
30	2	2	0
32	2	2	0

Results with 2 Difference

Pipe segments where results are two difference between the normalized utility grade and the index output is summarized in table G12-5. Results summarized indicate the pipes with the desirable parameters (low range) are not penalized for the performance. Results also suggest that although there are undesirable parameters for some of the pipe segments, the effects of these parameters are not significant for the pipe performance due to various other parameters. Some significant pipe segments with a high difference between the index and the utility grades are further investigated in the following case studies.

Table G12-5. Segments with 2 Difference

PIPEiD	Model	PACPNorm	Difference	Module
4	6	4	2	Integrity
18	10	8	2	Integrity
20	10	8	2	Integrity
21	10	8	2	Integrity
33	4	2	2	Blockage
34	10	8	2	Blockage
35	10	8	2	Blockage
18	10	8	2	Integrity
20	10	8	2	Integrity
21	10	8	2	Integrity
24	6	4	2	Integrity
33	6	4	2	Blockage
34	10	8	2	Blockage

35	10	8	2	Blockage

Case Studies

Table G12-6. Pipe Segment 7.1-7.2

Parameter	Value
Pipe ID	21
Pipe Age	32
Pipe Condition	8
Pipe Depth	6.1
Pipe Diameter	24
Pipe Length	364
Pipe Location	Highway
Pipe Material	RCP
Lining Presence	No

PACP vs. index output: 0 vs. 4

Module with maximum result: Integrity

Reason: Shallow pipe, under highway.

Discussion: This pipe is buried shallow (6.1 ft.) and located under a highway. These parameters indicate that there is a high amount of dynamic loading on the pipe which makes it prone to integrity issues.

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The preliminary results for Gravity concrete pipes inspected at the Aldrich Interceptor suggest that the expected remaining life of these pipes is 126 years. Results of the time-dependent performance prediction are summarized in Figure G12-2. Validation dataset was also plotted to summarize the validation results in this figure.

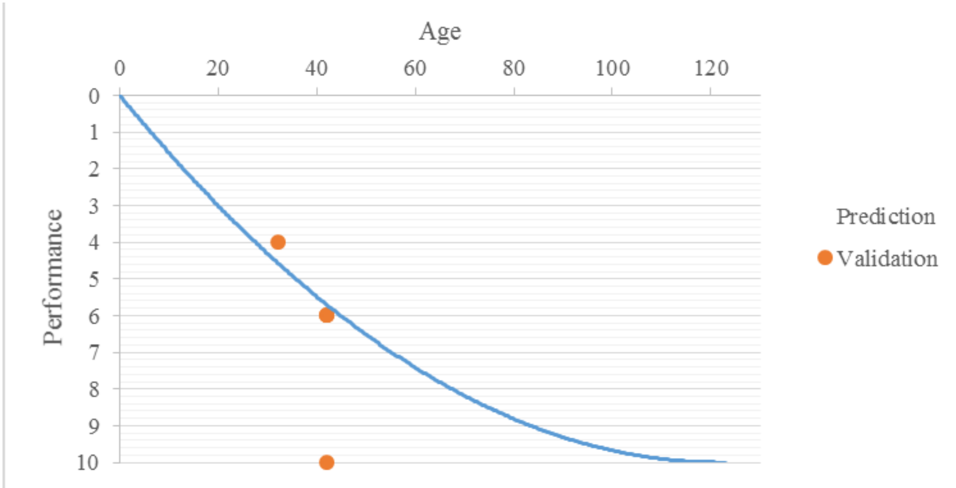

Figure G12-2. Preliminary Time Dependent Performance Prediction Results

Five segments (13.3%) were used as the testing dataset. Using this dataset, the accuracy of the predictions is measured with this dataset using confusion matrix. The accuracy of the predictions with the dataset used is 60%. Table G12-7 summarizes the selected segments, only one segment (26A-27) does not agree with the predictions.

Table G12-7. Validation Dataset

PIPEiD	Model	PACP (Norm.)	Diff.	Age
17	6	6	0	42
19	6	6	0	42
22	6	6	0	42
33	4	2	2	32
35	10	8	2	42

Appendix G13 – Utility #13 Piloting Results

Overview

The research team has received data from participating utility #13 in the form of asset inventory. This database contains records for 8460 pipe segments totaling in 564.45 miles in length. 161 segments were randomly selected for the piloting the performance index. Data is extracted for these 161 segments to pilot the performance index. Extracted data from utility records are summarized in Table G13-1.

Table G13-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe ID	Database
Pipe Age	Database
Pipe Diameter	Database
Pipe Length	Database
Pipe Slope	Database
Pipe Material	Database
Pipe Shape	Database
Soil Type	Database

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset are summarized at Table G13-2.

Table G13-2. Focused Calibration Dataset.

Parameter	Unit	Lower Range	Higher Range
Pipe Age	Years	10.66	63.57
Pipe Diameter	Inch	8	78
Pipe Length	Feet	7.28	1372.34
Pipe Slope	%	0.08	28.15
Pipe Material	Type	PVC, HDPE, RCP, VCP	
Pipe Shape	Type	Circular	
Soil Type	Type	Clay, Clay Loam, Loam, Sandy Loam	

After the index was run with the dataset, the performance index output ranged between 1 to 10. Table G13-3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G13-3 Final Piloting Results

Total Number of Segments	Segments in Condition (1)	Segments in Condition (2)	Segments in Condition (3)	Segments in Condition (4)	Segments in Condition (5)	Segments in Condition (6)	Segments in Condition (7)	Segments in Condition (8)	Segments in Condition (9)	Segments in Condition (10)
161	100	19	12	19	3	1	1	2	3	1
100%	62.11 %	11.80 %	7.45%	11.80 %	1.86%	0.62%	0.62%	1.24%	1.86%	0.62%

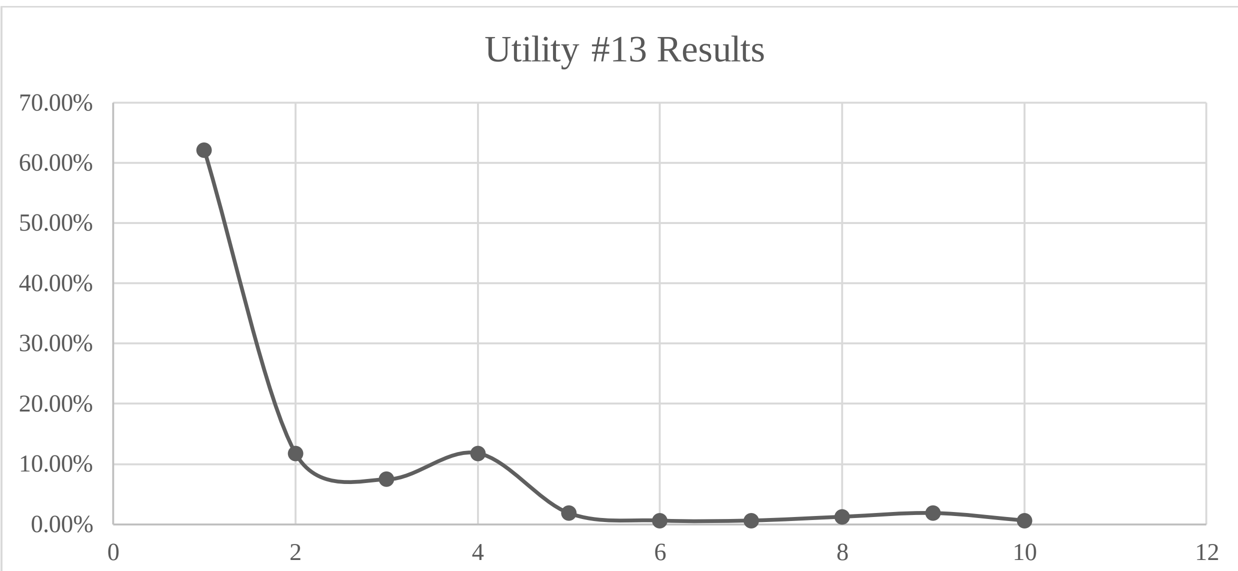

Figure G13-2. Utility #13 Results Difference

Results with 1 (excellent) performance grade

Table G13-4 discuss summarize pipes with 1 (excellent) and 2 (very good) performance grades.

Table G13-4. Segments with 1 (excellent) and 2 (very good) performance grades

PIPEiD	Model

77	1
195	2
204	2
205	2
212	2
219	2
220	1
221	2
222	2
223	2
224	2
225	2
227	1
230	2
2104	1
2105	1
2106	1
2107	1
2108	1
2109	1
2110	1
2111	1
2113	1
401	1
403	2
404	2
715	2
726	1
864	1
957	1
958	1
1141	1
1269	1
1719	1
1720	1
1725	1
2004	1
2005	1
2006	1
2007	1
2008	1
2120	1

2132	1
2133	1
2134	1
2135	1
2136	1
2137	1
2138	1
2139	1
2140	1
2141	1
2142	1
2143	1
2755	1
2756	1
2757	1
2821	1
2822	1
2823	1
2824	1
2825	1
2895	2
2936	1
3076	1
3293	1
3294	1
3295	1
3296	1
3297	1
3298	1
3299	1
5118	2
5251	2
5778	1
5779	1
6054	1
6554	1
6555	1
6403	1
6405	1
6406	1
6407	1
6410	1

6411	1
6412	1
6444	1
6445	1
6446	1
6447	1
6448	1
6449	1
6450	1
6453	1
6454	1
6562	1
6790	2
6874	1
6875	2
7127	1
8033	1
8124	1
8147	1
8266	1
8267	1
8268	1
8269	1
8270	1
8271	1
8272	1
8273	1
8274	1
8324	1
8325	1
8328	1
8330	1
8331	1
8332	1
8333	1

Results with 3 (good) and 4 (satisfactory) performance grade.

Pipe segments with 3 (good) and 4 (Satisfactory) performance grades are summarized in table G13-5.

Table G13-5. Segments with 3 (good) and 4 (Satisfactory) performance grades

PIPEiD	Model
194	3
213	4
226	3
398	4
400	4
2543	3
3117	3
3118	3
3119	3
3704	4
3705	4
3706	4
3707	4
3708	4
3709	4
3710	4
3711	4
3712	4
3713	4
3714	4
3715	4
3716	4
3717	4
3718	4
3719	4
4334	3
4335	3
4336	3
5975	3
8323	3
8338	3

Results with 5 (fair) and 6 (poor) performance grades.

Pipe segments with 5 (fair) and 6 (poor) performance grades are summarized in table G13-6.

Table G13-6. Segments with 5 (fair) and 6 (poor) performance grades.

PIPEiD	Model
6052	5
6402	6
8327	5
8329	5

Results with 7 (serious) and 8 (critical) performance grades.

Pipe segments with 7 (serious) and 8 (critical) performance grades are summarized in table G13-7.

Table G13-7. Segments with 7 (serious) and 8 (critical) performance grades.

PIPEiD	Model
5442	7
6404	8
8326	8

Results with 9 (failure) and 10 (failed) performance grades.

Pipe segments with 9 (failure) and 10 (failed) performance grade are summarized in table G13-8.

Table G13-8. Segments with 9 (failure) and 10 (failed) performance grades.

PIPEiD	Model	Module
231	10	Surface Wear
402	9	Blockage
2933	9	Blockage
8337	9	Blockage

Case Studies

Table G13-9. Pipe Segment 231

Parameter	Value
Pipe ID	231
Pipe Age	22
Pipe Diameter	20
Pipe Length	174.06
Pipe Slope	0.01
Pipe Material	HDPE

Pipe Shape	Circular
Soil Type	Unknown

Index output: 10 (Failed)

Module with maximum result: Surface Wear

Reason: High age, low slope

Discussion: This high aged (43) HDPE pipe is prone to integrity issues due to its age and low slope (0.01%).

Table G13-10. Pipe Segment 402

Parameter	Value
Pipe ID	402
Pipe Age	48
Pipe Diameter	33
Pipe Length	521.15
Pipe Slope	0.002
Pipe Material	VCP
Pipe Shape	Circular

Index output: 9 (Failing)

Module with maximum result: Blockage

Reason: High length, low slope, high age

Discussion: This VCP pipe is prone to blockage issues due to its high length (521.15 ft.), low slope (0.02%), and high age (48 years).

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The preliminary results for gravity pipes suggest that the expected remaining life of these pipes is 122 years. Results of the time-dependent performance prediction are summarized in Figures G13-3 and G13-4.

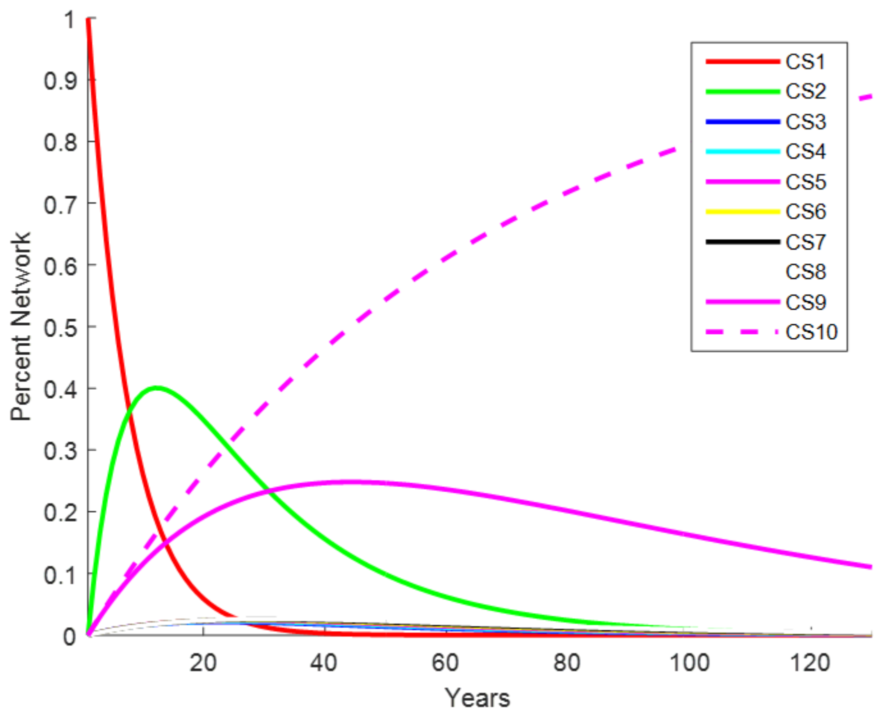

Figure G13-3. Preliminary State Dependent Performance Prediction Results

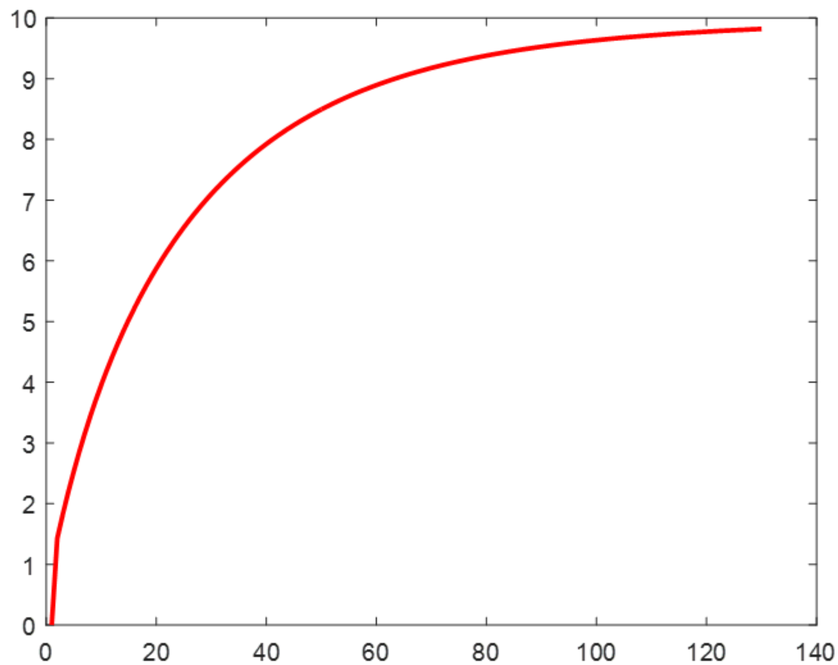

Figure G13-4. Preliminary State Dependent Performance Prediction Results

Appendix G14 – Utility #14 Piloting Results

Overview

The research team has received data from participating utility #14 in the form of GIS geo-database. This GIS geodatabase contains records for 15644 pipe segments totaling in 493.23 miles in length. Pittsburg sewer system is summarized in figure G14-1.

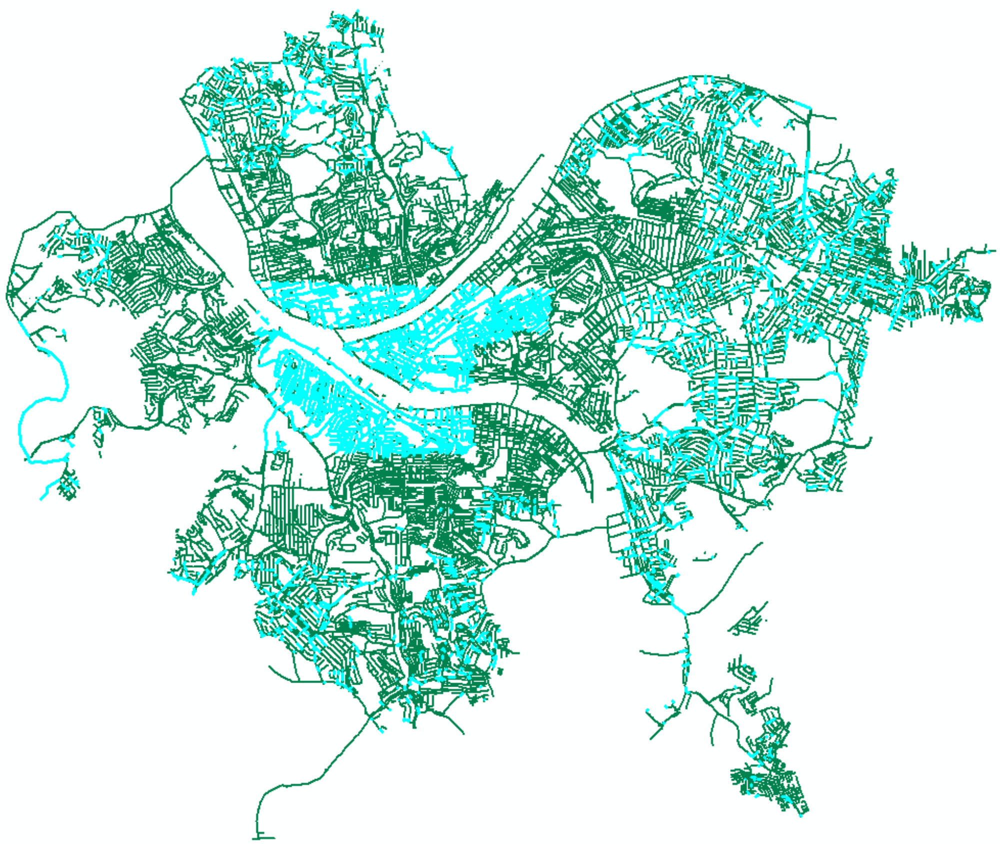

Figure G14-1. Participating Utility Sewer System

167 segments were randomly selected for the piloting the performance index. Data is extracted for these 167 segments to pilot the performance index. Extracted data from utility records are summarized in Table G14-1.

Table G14-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe ID	Geodatabase
Pipe Age	Geodatabase
Pipe Diameter	Geodatabase
Pipe Length	Geodatabase
Pipe Material	Geodatabase
Pipe Shape	Geodatabase
Pipe Depth	Geodatabase

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset are summarized at Table G14-2.

Table G14-2. Focused Calibration Dataset.

Parameter	Lower Range	Higher Range
Pipe Age	9	215
Pipe Diameter	8	108
Pipe Length	2.38	737
Pipe Material	AC, BR, CI, DI, PVC, RC, TC, VCP	
Pipe Shape	Circular	
Pipe Depth	4	817.5

After the index was run with the dataset, and the performance index outputs ranged between 1-10. Table G14-3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G14-3 Final Piloting Results

Total Number of Segments	Segments in Condition (1)	Segments in Condition (2)	Segments in Condition (3)	Segments in Condition (4)	Segments in Condition (5)	Segments in Condition (6)	Segments in Condition (7)	Segments in Condition (8)	Segments in Condition (9)	Segments in Condition (10)
167	39	12	4	19	21	23	17	12	8	12

100%	23.35 %	7.19%	2.40%	11.38 %	12.57 %	13.77 %	10.18 %	7.19%	4.79%	7.19%

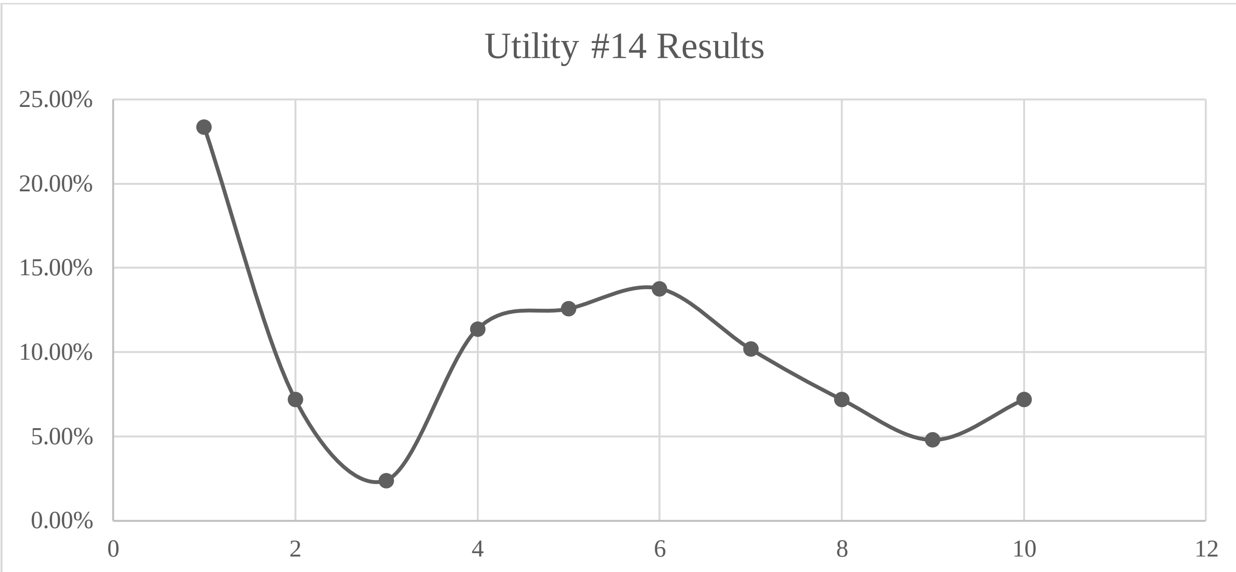

Figure G14-1. Utility #14 Results

Results with 1 (excellent) and 2 (very good) performance grade

Table G14-4 discuss summarize pipes with 1 (excellent) and 2 (very good) performance grades.

Table G14-4. Segments with 1 (excellent) and 2 (very good) performance grades

PIPEiD	Model
5004	2
5005	2
5090	2
5095	2
5096	2
5073	2
5074	2
1045	1
1267	1
1345	1
1385	1
1643	1
2307	1
3005	1

3462	1
3657	1
4198	1
4199	1
4971	1
4979	1
4982	1
4983	1
4984	1
4985	1
4988	1
4989	1
1013	2
1003	2
4996	2
5011	1
5012	1
5019	1
5020	1
7066	2
9043	2
5034	1
5038	1
5040	1
5067	1
5078	1
5099	1
5100	1
5109	1
5111	1
5112	1
5132	1
5163	1
5164	1
7237	1
7282	1
7286	1

Results with 3 (good) and 4 (satisfactory) performance grades.

Pipe segments with 3 (good) and 4 (Satisfactory) performance grades are summarized in table G14-5.

Table G14-5. Segments with 3 (good) and 4 (satisfactory) performance grade.

PIPEiD	Model
5091	3
1023	3
1011	3
4997	3
5070	4
5071	4
5072	4
5108	4
5069	4
5002	4
5003	4
5105	4
5106	4
5778	4
1104	4
5131	4
5103	4
5104	4
4976	4
4977	4
8021	4
8479	4
890	4

Results with 5 (fair) and 6 (poor) performance grades.

Pipe segments with 5 (fair) and 6 (poor) performance grades are summarized in table G14-6.

Table G14-6. Segments with 5 (fair) and 6 (poor) performance grades.

PIPEiD	Model
889	5
5156	5

1107	5
5142	5
5143	5
5148	5
5149	5
5177	5
5178	5
5176	5
1105	5
5794	5
8096	5
5062	5
8185	5
8188	5
8424	5
4981	5
5175	5
726	5
727	5
1060	6
5008	6
5009	6
5114	6
9057	6
1048	6
5777	6
8027	6
8032	6
8292	6
8302	6
5031	6
5032	6
5036	6
982	6
983	6
5025	6
5026	6
5110	6
5150	6
5151	6
5152	6
5153	6

Results with 7 (serious) and 8 (critical) performance grades.

Pipe segments with 7 (serious) and 8 (critical) performance grades are summarized in table G14-7.

Table G14-7. Segments with 7 (serious) and 8 (critical) performance grades.

PIPEiD	Model
873	7
882	7
888	7
892	7
931	7
5146	7
5147	7
1006	7
1014	7
5022	7
5154	7
1097	7
1100	7
1101	7
1102	7
1103	7
5155	7
5021	8
887	8
4972	8
4973	8
4974	8
4975	8
5158	8
5159	8
4980	8
1004	8
5000	8
5010	8

Results with 9 (failure) and 10 (failed) performance grades.

Pipe segments with 9 (failure) and 10 (failed) performance grades are summarized in table G14-8.

Table G14-8. Segments with 9 (failure) and 10 (failed) performance grades.

PIPEiD	Model
5013	9
5018	9
5027	9
5028	9
5075	9
5107	9
5165	9
5166	9
5167	10
5671	10
7829	10
7972	10
7973	10
8001	10
8084	10
8210	10
8228	10
8363	10
8377	10
9047	10

Case Studies

Table G14-9. Pipe Segment 5013

Parameter	Value
Pipe ID	8001
Pipe Age	91.05
Pipe Diameter	15
Pipe Length	136.731
Pipe Material	VCP
Pipe Shape	Circular

Pipe Depth	11

Index output: 10 (Critical)

Module with maximum result: Integrity

Reason: High age

Discussion: This high aged (91.05) vitrified clay pipe is prone to integrity issues.

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The preliminary results for gravity pipes suggest that the expected remaining life of these pipes is 160 years. Results of the time-dependent performance prediction are summarized in Figures G14-2 and G14-3.

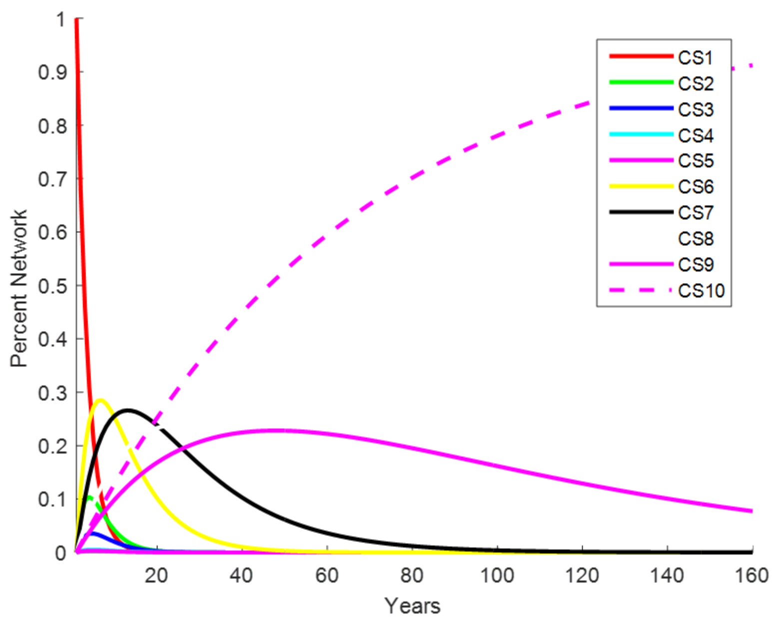

Figure G14-2. Preliminary State Dependent Performance Prediction Results

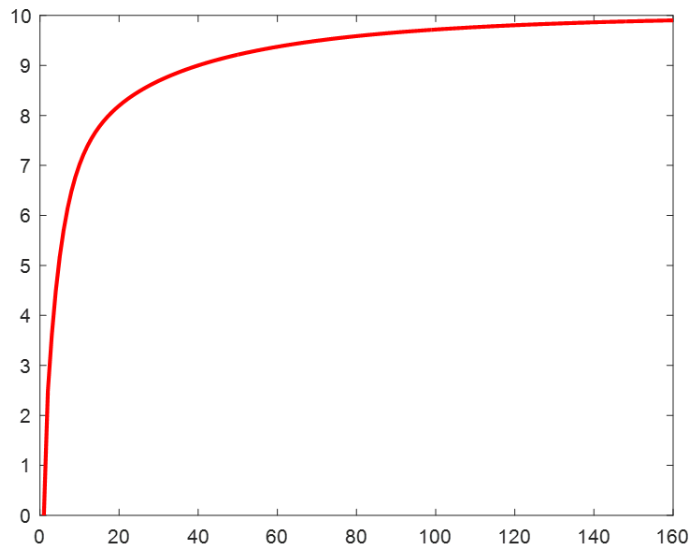

Figure G14-3. Preliminary State Dependent Performance Prediction Results

Appendix G15 – Utility #15 Piloting Results

Overview

The research team has received data from participating utility #15 in the form of asset database and CMMS files. This database contains records for 1195 pipe segments totaling in 365 miles in length. Pittsburg sewer system is summarized in figure 1. 154 segments were randomly selected for the piloting the performance index. Data is extracted for these 154 segments to pilot the performance index. Extracted data from utility records are summarized in Table G15-1.

Table G15-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe ID	Asset Database
Pipe Condition	CMMS
Pipe Depth	Asset Database
Pipe Length	Asset Database
Pipe Location	Asset Database
Pipe Material	Asset Database
Density of Connections	Asset Database
Pipe Diameter	Asset Database
Pipe Shape	Asset Database

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset are summarized at Table G15-2.

Table G15-2. Focused Calibration Dataset.

Parameter	Unit	Lower Range	Higher Range
Pipe Condition	Grade	1	5
Pipe Depth	Feet	4	20.8
Pipe Length	Feet	33.4	397.6
Pipe Location	Type	Alley, Street, Parking lot, Easement	
Pipe Material	Type	CON, DIP, PVC, RCP, VCP	
Density of Connections	Number	1	3

Pipe Diameter	Inches	8	18
Pipe Shape	Type	Circular	

After the index run with the dataset, the performance index outputs ranged between 1-10. Table G15-3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G15-3. Final Piloting Results

Total Number of Segments	Segments with 0 difference	Segments with 1 difference	Segments with 2 difference
154	17	122	15
100%	11.04%	79.22%	9.74%

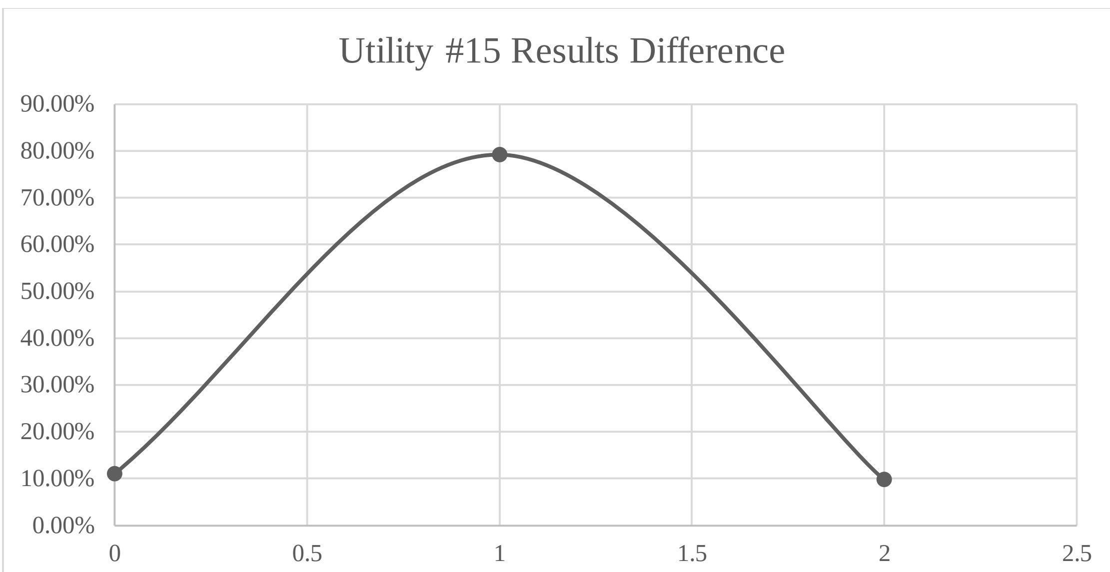

Figure G15-1. Utility #15 Results

Results with 0 Difference

Table G15-4 summarizes pipes with 0 difference between the defect rating and the performance index.

Table G15-4. Segments with 0 differences

PIPEiD	Model	PACP	Difference
23581	2	2	0
23584	2	2	0
23585	2	2	0
23591	2	2	0
23593	2	2	0
23594	2	2	0
23595	2	2	0
23580	10	10	0
23799	10	10	0
23917	10	10	0
24386	10	10	0
24216	10	10	0
24217	10	10	0
24227	10	10	0
24899	10	10	0
24900	10	10	0
24905	10	10	0

Results with 1 Difference

Table G15-5 summarizes pipes with 1 and 2 difference between the defect rating and the performance index.

Table G15-5. Segments with 1 difference

PIPEiD	Model	PACP	Difference
23596	3	2	1
23597	3	2	1
23599	3	2	1
23303	3	2	1
23304	3	2	1
23306	3	2	1
23307	3	2	1
23308	3	2	1
23312	3	2	1
23315	3	2	1
23316	3	2	1

23317	3	2	1
23318	3	2	1
23320	3	2	1
23323	3	2	1
23328	3	2	1
23335	3	2	1
23336	3	2	1
23337	3	2	1
23341	3	2	1
23347	3	2	1
23348	3	2	1
23349	3	2	1
23351	3	2	1
23352	3	2	1
23354	3	2	1
23357	3	2	1
23358	3	2	1
23359	3	2	1
23360	3	2	1
23361	3	2	1
23362	3	2	1
23364	3	2	1
23366	3	2	1
23367	3	2	1
23368	3	2	1
23370	3	2	1
23371	3	2	1
23372	3	2	1
23376	3	2	1
23378	3	2	1
23379	3	2	1
23381	3	2	1
23382	3	2	1
23383	3	2	1
23385	3	2	1
23386	3	2	1
23387	3	2	1
23388	3	2	1
23389	3	2	1
23390	3	2	1
23391	3	2	1
23392	3	2	1

23400	3	2	1
23401	3	2	1
23402	3	2	1
23403	3	2	1
23405	3	2	1
23406	3	2	1
23407	3	2	1
23408	3	2	1
23409	3	2	1
23410	3	2	1
23415	3	2	1
23416	3	2	1
23417	3	2	1
23418	3	2	1
23420	3	2	1
23421	3	2	1
23422	3	2	1
23423	3	2	1
23424	3	2	1
23425	3	2	1
23426	3	2	1
23427	3	2	1
23428	3	2	1
23436	3	2	1
23437	3	2	1
23438	3	2	1
23439	3	2	1
23442	3	2	1
23450	3	2	1
23452	3	2	1
23454	3	2	1
23455	3	2	1
23456	3	2	1
23309	3	2	1
23321	3	2	1
23325	3	2	1
23326	3	2	1
23333	3	2	1
23343	3	2	1
23350	3	2	1
23365	3	2	1
23369	3	2	1

23374	3	2	1
23375	3	2	1
23413	3	2	1
23414	3	2	1
23453	3	2	1
23433	3	2	1
23319	3	2	1
23451	3	2	1
23609	7	6	1
23610	7	6	1
23355	7	6	1
23395	7	6	1
23397	7	6	1
23398	7	6	1
23399	7	6	1
23411	7	6	1
23412	7	6	1
23441	7	6	1
23443	7	6	1
23444	7	6	1
23445	7	6	1
23446	7	6	1
23448	7	6	1
23449	7	6	1
23602	9	8	1
23394	9	8	1
23431	9	8	1

Results with 2 Difference

Table G15-6 summarize pipes with 2 difference between the defect rating and the performance index.

Table G15-6. Segments with 2 difference

PIPEiD	Model	PACP	Difference	Module
23573	6	4	2	Integrity
23583	6	4	2	Integrity
23592	6	4	2	Integrity
23300	6	4	2	Integrity
23301	6	4	2	Integrity

23305	6	4	2	Integrity
23313	6	4	2	Integrity
23329	6	4	2	Integrity
23330	6	4	2	Integrity
23331	6	4	2	Integrity
23332	6	4	2	Integrity
23338	6	4	2	Integrity
23345	6	4	2	Integrity
23363	6	4	2	Integrity
23440	6	4	2	Integrity

Case Studies

Table G15-7. Pipe Segment 23573

Parameter	Value
Pipe ID	23573
Pipe Condition	2
Pipe Depth	17.8
Pipe Length	158
Pipe Location	Easement
Pipe Material	DIP
Density of Connections	0
Pipe Diameter	8
Pipe Shape	Circular

Index output: 6 (Serious) vs. 4(Fair) PACP

Module with maximum result: Integrity

Reason: Pipe location

Discussion: This ductile iron pipe is prone to integrity issues due to its location.

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The preliminary results for gravity pipes suggest that the expected remaining life of these pipes is 57 years. Results of the time-dependent performance prediction are summarized in figures G15-2 and G15-3.

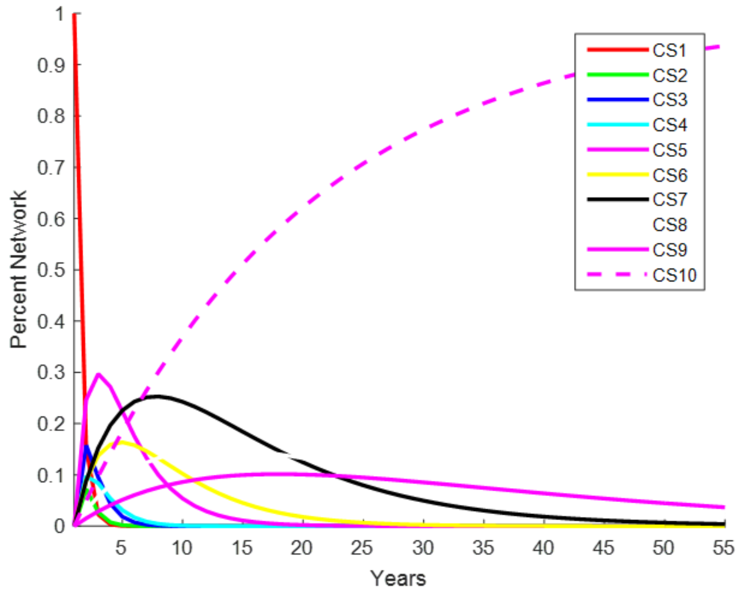

Figure G15-2. Preliminary State Dependent Performance Prediction Results

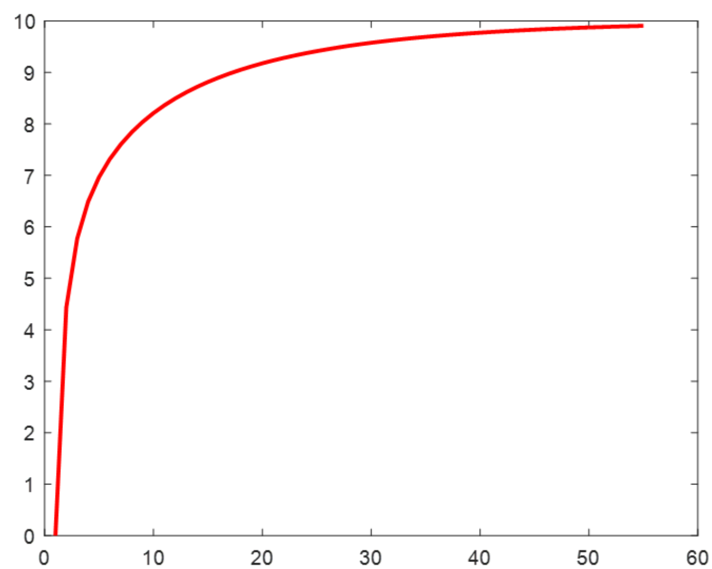

Figure G15-3. Preliminary State Dependent Performance Prediction Results

Appendix G16 – Utility #16 Piloting Results

Overview

The research team has received data from participating utility in the form of GIS geodatabase. This GIS geodatabase contains records for 1076 pipe segments totaling in 36.34 miles in length. Participating utility sewer system is summarized in Figure G16-1.

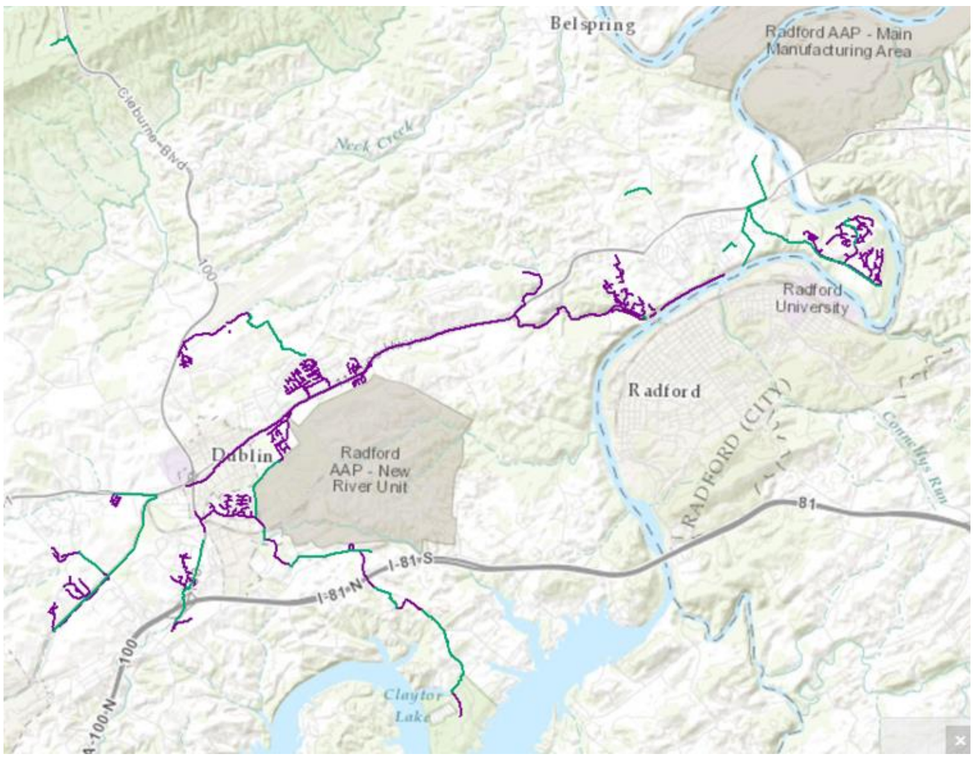

Figure G16-1. Participating Utility Sewer System

268 segments were randomly selected for the piloting the performance index. Data is extracted for these 268 segments to pilot the performance index. Extracted data from utility records are summarized in Table G16-1.

Table G16-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe ID	Geodatabase
Pipe Age	Geodatabase
Pipe Diameter	Geodatabase
Pipe Length	Geodatabase

Pipe Slope	Geodatabase
Pipe Material	Geodatabase
Pipe Shape	Geodatabase

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset are summarized at Table G16-2.

Table G16-2. Focused Calibration Dataset.

Parameter	Unit	Lower Range	Higher Range
Pipe Age	Years	0	43
Pipe Diameter	Inch	6	36
Pipe Length	Feet	10	400
Pipe Slope	%	0.04	32.1
Pipe Material	Type	Clay, PVC, RCP, DI	
Pipe Shape	Type	Circular	

After the index run with the dataset, the performance index outputs ranged between 1-10. Table G16-3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G16-3. Final Piloting Results

Total Number of Segments	Segments in Condition (1)	Segments in Condition (2)	Segments in Condition (3)	Segments in Condition (4)	Segments in Condition (5)	Segments in Condition (6)	Segments in Condition (7)	Segments in Condition (8)	Segments in Condition (9)	Segments in Condition (10)
268	183	57	2	3	3	2	7	5	4	1
100%	68.28%	21.27%	0.75%	1.12%	1.12%	0.75%	2.61%	1.87%	1.49%	0.37%

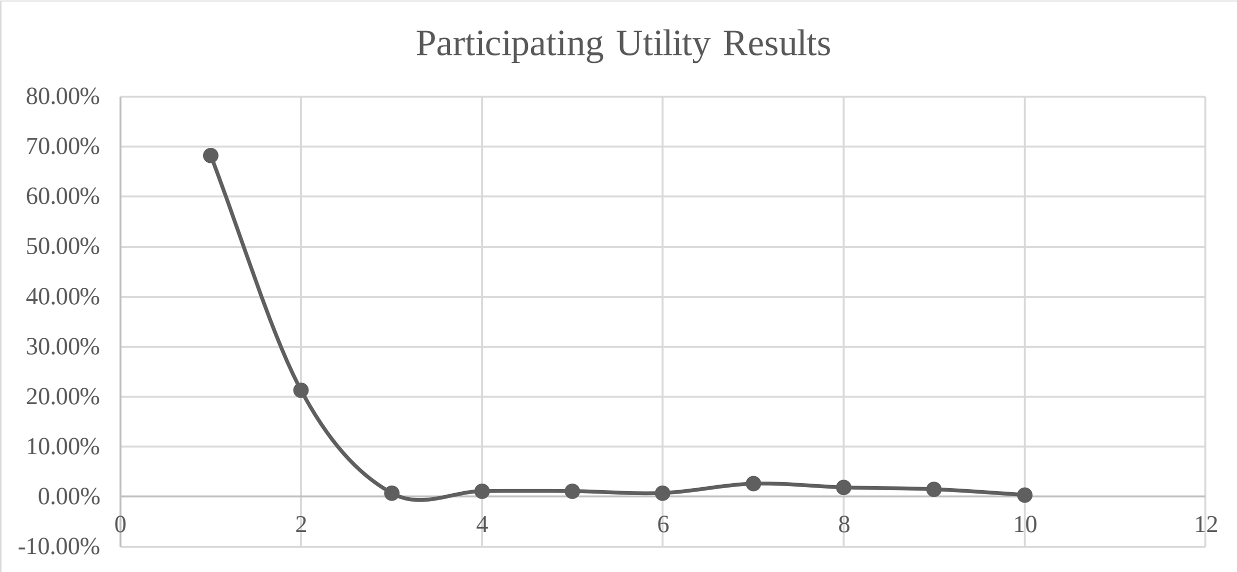

Figure 2. Participating Utility Results

Results with 1 (excellent) performance grade

Table G16-4 discuss summarize pipes with 1 (excellent) and 2 (very good) performance grades.

Table G16-4. Segments with 1 (excellent) and 2 (very good) performance grades

PIPEiD	Model
1	1
2	1
4	1
5	2
6	1
7	1
8	2
9	1
10	1
11	2
12	2
13	2
14	2
15	1
16	1
17	1
18	1

23	1
24	1
25	1
26	2
27	1
28	2
29	2
30	2
31	2
32	2
33	2
34	2
35	2
36	2
38	1
41	2
47	2
48	2
49	2
50	2
51	2
52	2
53	1
54	2
55	1
56	2
57	2
60	1
62	2
63	1
64	1
65	1
67	1
68	2
69	1
71	2
72	2
73	1
75	2
76	1
77	1
78	1

79	1
83	1
84	1
85	1
87	1
88	1
89	1
90	1
91	1
92	1
93	1
94	1
95	1
96	1
97	1
98	1
99	1
100	1
102	1
103	1
104	1
107	1
108	1
109	1
110	1
111	1
112	2
113	1
114	1
115	1
116	1
117	1
118	1
119	1
120	1
121	1
122	1
123	1
124	1
125	2
126	1
127	1

128	1
129	1
130	1
131	1
132	1
133	1
134	1
135	1
136	1
137	1
138	1
139	1
140	1
141	1
142	1
143	1
144	1
145	1
146	1
147	1
148	1
149	1
150	1
151	1
152	1
153	1
154	1
155	1
156	1
157	1
158	1
159	1
160	2
161	1
162	1
163	1
164	1
165	1
166	1
167	1
168	1
169	1

170	1
171	1
172	1
173	1
174	1
175	1
176	1
177	1
178	1
179	1
180	1
181	1
182	1
183	1
184	1
185	1
186	1
187	1
188	1
189	1
190	1
191	1
192	2
193	1
194	1
195	1
196	1
197	1
198	1
199	1
200	1
201	2
202	2
203	2
204	2
205	1
206	1
207	1
208	1
209	1
210	1
211	1

212	1
213	1
214	1
215	1
216	1
217	1
218	1
219	1
220	1
221	1
222	1
223	1
224	1
225	2
226	2
227	2
228	2
229	2
230	2
231	2
232	1
233	1
234	2
235	2
236	2
237	2
238	2
239	2
240	2
241	2
242	2
243	2
244	2
245	1
246	1
247	1
248	1
249	1
250	1
251	1
252	1
254	1

255	1
256	1
257	1
258	1
259	1
260	1
261	1
262	1
263	1
264	1
265	1

Results with 3 (good) and 4 (satisfactory) performance grades.

Pipe segments with 3 (good) and 4 (Satisfactory) performance grade are summarized in table G16-5.

Table G16-5. Segments with 3 and 4 performance grades.

PIPEiD	Model
3	3
80	4
81	4
82	4
86	3

Results with 5 (fair) and 6 (poor) performance grades.

Pipe segments with 5 (fair) and 6 (poor) performance grades are summarized in table G16-6.

Table G16-6. Segments with 5 (fair) and 6 (poor) performance grades.

PIPEiD	Model
58	6
59	6
61	5
70	5
74	5

Results with 7 (serious) and 8 (critical) performance grades.

Pipe segments with 7 (serious) and 8 (critical) performance grades are summarized in table G16-7.

Table G16-7. Segments with 7 (serious) and 8 (critical) performance grades.

PIPEiD	Model	Module
39	7	Integrity
40	7	Integrity
42	7	Integrity
43	7	Integrity
44	7	Integrity
45	7	Integrity
46	7	Integrity
66	8	Integrity
101	8	Blockage
105	8	Blockage
106	8	Blockage
253	8	Blockage

Results with 9 (failure) and 10 (failed) performance grades.

Pipe segments with 9 (failure) and 10 (failed) performance grade are summarized in table 6.

Table G16-8. Segments with 9 (failure) and 10 (failed) performance grades.

PIPEiD	Model	Module
19	9	Integrity
20	9	Integrity
21	9	Integrity
22	9	Integrity
37	10	Integrity

Case Studies

Table G16-9. Pipe Segment 37

Parameter	Value
Pipe ID	37
Pipe Age	43
Pipe Diameter	15

Pipe Length	181
Pipe Slope	0.28
Pipe Material	PVC
Pipe Shape	Circular

Index output: 10 (Failed)

Module with maximum result: Integrity

Reason: High age, low slope

Discussion: This high aged (43) PVC pipe is prone to integrity issues due to its age and low slope (0.28%).

Table G16-10. Pipe Segment 197

Parameter	Value
Pipe ID	1038
Pipe Age	17
Pipe Diameter	15
Pipe Length	2111
Pipe Slope	16.3
Pipe Material	PVC
Pipe Shape	Circular

Index output: 9 (Failing)

Module with maximum result: Blockage

Reason: High length

Discussion: This PVC pipe is prone to blockage issues due to its high length (2111 ft.)

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The preliminary results for gravity pipes suggest that the expected remaining life of these pipes is 61 years. Results of the time-dependent performance prediction are summarized in figures G16-3 and G16-4.

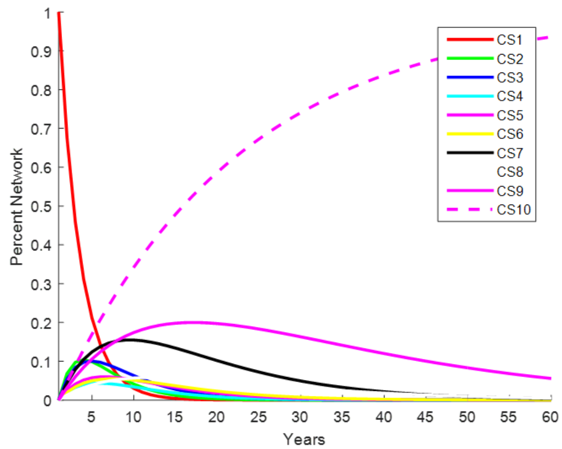

Figure G16-3. Preliminary State Dependent Performance Prediction Results

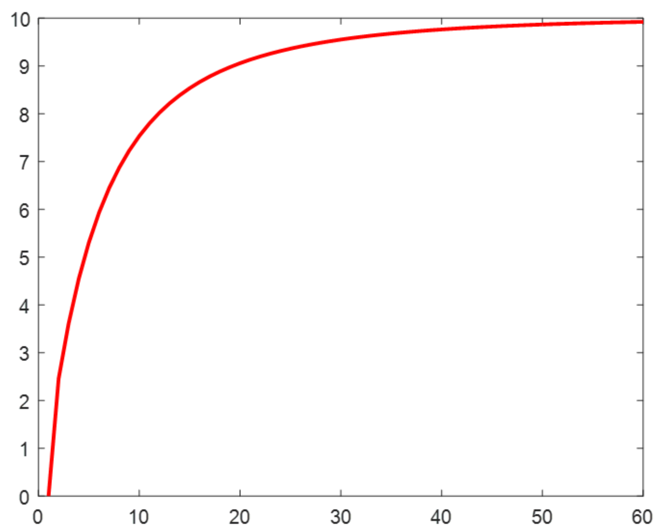

Figure G16-4. Preliminary State Dependent Performance Prediction Results

Appendix G17- Utility #17 Piloting Results

The research team has been piloting the developed performance index with the GIS, failure, and cleaning schedule data received from participating utility #17. These records contain data for 55091 pipe segments. 87 of these pipes were selected to represent the highest and lowest ranges of the extracted parameters. Extracted data from utility records are summarized in Table G17-1.

Table G17-1. Parameters Extracted from Utility Data

Number	Parameter	Source	Notes
1	Component ID	Geodatabase	
2	Node ID	Geodatabase	
3	Pipe Age	Geodatabase	
4	Pipe Condition*	Failure Database	Only failure data was available
5	Pipe Depth	Geodatabase	
6	Pipe Diameter	Geodatabase	
7	Pipe Length	Geodatabase	
8	Pipe Slope	Geodatabase	Derived from elevation and length data
9	Soil Type*	Failure Database	Only available for failed pipes
10	Maintenance Frequency*	Cleaning Database	Only available for pipes with cleaning schedule
11	Type of Cleaning*	Cleaning Database	Only available for pipes with cleaning schedule
12	Pipe Shape	Geodatabase	
13	Pipe Material	Geodatabase	

Performance Index Piloting Results Discussion

A focused dataset of 87 pipes was selected to calibrate the index further. This dataset includes the pipe samples with the highest and lowest ranges of the parameters and the pipe segments with the greatest results differences from the previous pass. The ranges and the number of pipe segment selected for the focused calibration dataset are summarized at Table G17-2.

Table G17-2. Focused Calibration Dataset.

Number	Parameter	Unit	Lowest Range	Highest Range
1	Component ID	ID	10	126
2	Node ID	ID	N/A	
3	Pipe Age	Year	N/A	
4	Pipe Condition*	Pipe Condition Grade	0 (Unknown)	5 (Failed)
5	Pipe Depth	Feet	0.19	376.8
6	Pipe Diameter	Inches	2	150
7	Pipe Length	Feet	1.15	2822.39
8	Pipe Slope	% Grade	0.0455	39.10
9	Soil Type*	Type	Clay, Sand, Gravel	
10	Maintenance Frequency*	Months	12	72
11	Type of Cleaning*	Type	Jetting, Rodding, Hydro	
12	Pipe Shape	Type	Circular	
13	Pipe Material	Type	AC, CIP, CMP, CON, DIP, HDP, RCP, REL, VC	

The sample dataset has been used to run the index. The results were further investigated. Since only inspection data was available for the failed pipes, only the index results for these failed pipes can be compared with inspection results. The rest of the results were ranging between 1 (Excellent) to 4 (Satisfactory).

Table G17-3 Final Piloting Results

Total Number of Segments	Segments with excellent performance (index score 1)	Segments with very good performance (index score 2)	Segments with good performance (index score 3)	Segments with satisfactory performance (index score 4)	Failed Segments (index score 10)
87	35	23	12	7	10
100%	40.23%	26.44%	13.79%	8.05%	11.49%

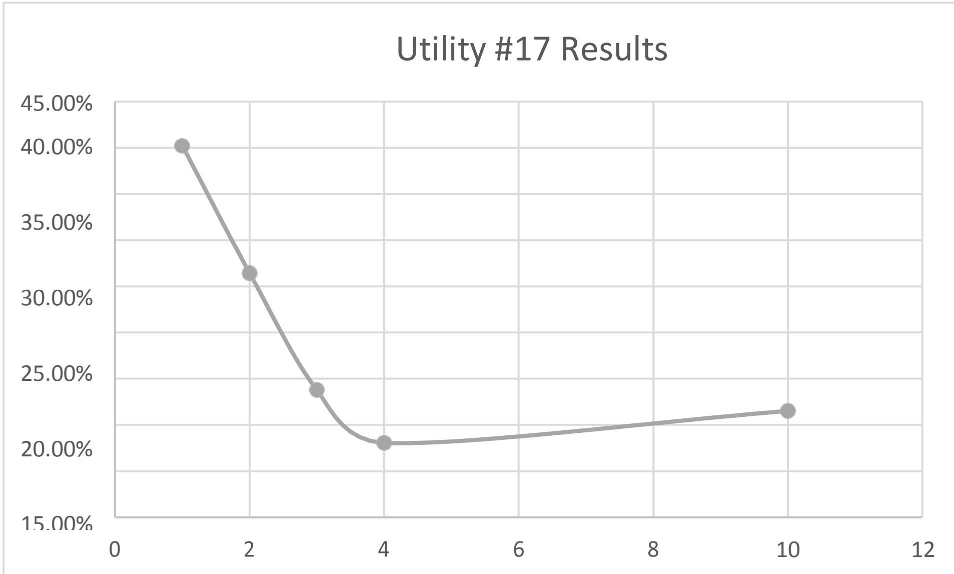

Figure G17-1. Utility #17 Results

Segments with Excellent Performance (Index Score 1)

Results indicate 35.63% of the pipes are in excellent performance grade (index score 1). Data extracted show there are no undesirable parameters for these segments. Thus, these pipe segments score excellently. Segments with excellent performance score are summarized in table G17-4.

Table G17-4. Segments with Excellent Performance Score (1)

PIPEiD	Index Score	Highest Module Grade
4242	1	Excellent
9407	1	Excellent
16288	1	Excellent
16582	1	Excellent
21532	1	Excellent
21995	1	Excellent
22505	1	Excellent
24142	1	Excellent
26079	1	Excellent
26987	1	Excellent
27238	1	Excellent

32174	1	Excellent
32278	1	Excellent
180694	1	Excellent
194281	1	Excellent
196061	1	Excellent
197738	1	Excellent
206072	1	Excellent
206086	1	Excellent
206583	1	Excellent
210713	1	Excellent
214350	1	Excellent
214858	1	Excellent
248474	1	Excellent
248475	1	Excellent
248476	1	Excellent
299596	1	Excellent
300262	1	Excellent
307097	1	Excellent
307113	1	Excellent
309849	1	Excellent
309854	1	Excellent
310368	1	Excellent
310395	1	Excellent
311362	1	Excellent

Segments with Very Good Performance (index score 2)

Results indicate 26.44% of the pipes are in very good performance grade (index score 2). These pipes are slightly penalized for a single or a combination of undesirable parameters. The segments with very good performance index score are summarized in Table G17-5.

Table G17-5. Segments with Very Good Performance Score (2)

PIPEiD	Index Score	Highest Module Grade	Significant Parameters
11187	2	Blockage	Moderate Length, Small Diameter, Low Slope
13587	2	Surface Wear	Moderate age, Cleaning (jetting), moderate slope
24143	2	Capacity	Moderate diameter, moderate slope,
24839	2	Surface Wear	Moderate age, moderate slope
24919	2	Surface Wear	Moderate age, moderate slope
24925	2	Surface Wear	Moderate age, moderate slope
27723	2	Surface Wear	Moderate age, moderate slope
27724	2	Surface Wear	Moderate age, moderate slope
27730	2	Surface Wear	Moderate age, moderate slope

27742	2	Surface Wear	Moderate age, moderate slop69e
27745	2	Surface Wear	Moderate age, moderate slope
27888	2	Surface Wear	Moderate age, moderate slope
28069	2	Blockage	Moderate Length, Small Diameter, Low Slope
178541	2	Surface Wear	Moderate age, moderate slope
180430	2	Surface Wear	Moderate age, moderate slope
180432	2	Surface Wear	Moderate age, moderate slope
184761	2	Blockage	Moderate Length, Small Diameter, Low Slope
215836	2	Surface Wear	Moderate age, moderate slope
217424	2	Surface Wear	Moderate age, moderate slope
300143	2	Blockage	Moderate Length, Small Diameter, Low Slope
309157	2	Surface Wear	Moderate age, moderate slope
309841	2	Surface Wear	Moderate age, moderate slope
310064	2	Blockage	Moderate Length, Small Diameter, Low Slope

Segments with Good Performance (index score 3)

Results indicate 13.79% of the pipes are in good performance grade (index score 3). These pipes are slightly penalized for a single or a combination of undesirable parameters. The segments with good performance index score are summarized in Table G17-6.

Table G17-6. Segments with Good Performance Score (3)

PIPEiD	Index Score	Highest Module Grade	Significant Parameters
17864	3	Surface Wear	Concrete Pipe, high age (69), small diameter,
19754	3	Internal Corrosion	Ductile Iron, high age (73), small diameter,
184713	3	Surface Wear	Concrete Pipe, high age (67), small diameter,
196059	3	Surface Wear	Reinforced Concrete Pipe, high age (74), small diameter,
257336	3	Surface Wear	Reinforced Concrete Pipe, high age (82), small diameter,
257338	3	Surface Wear	Reinforced Concrete Pipe, high age (82), small diameter,
303013	3	Surface Wear	Reinforced Concrete Pipe, high age (85), small diameter,
307372	3	Surface Wear	Vitrified Clay, high age (85), small diameter,
311668	3	Surface Wear	Concrete Pipe, high age (85), small diameter,

Table G17-7. Pipe Segment # 17864

Number	Parameter	Unit	Value

1	Component ID	ID	17864
2	Node ID	ID	030-353 023-245
3	Pipe Age	Year	69
4	Pipe Condition*	Pipe Condition Grade	Unknown
5	Pipe Depth	Feet	23.18
6	Pipe Diameter	Inches	8
7	Pipe Length	Feet	1018.06
8	Pipe Slope	% Grade	2.6
9	Soil Type*	Type	Unknown
10	Maintenance Frequency*	Months	Unknown
11	Type of Cleaning*	Type	Unknown
12	Pipe Shape	Type	Circular
13	Pipe Material	Type	Concrete Pipe

Index output: 3 (good)

Module with maximum result: Surface Wear

Reason: High age, low slope

Discussion: This high aged concrete pipe has a low slope. The high age and low slope indicates that this pipe might be prone to surface wear issues.

Table G17-8. Pipe Segment # 19754

Number	Parameter	Unit	Value
1	Component ID	ID	19754
2	Node ID	ID	026-015 026-020
3	Pipe Age	Year	73
4	Pipe Condition*	Pipe Condition Grade	Unknown
5	Pipe Depth	Feet	24.57
6	Pipe Diameter	Inches	12
7	Pipe Length	Feet	1603.34
8	Pipe Slope	% Grade	2.93
9	Soil Type*	Type	Unknown
10	Maintenance Frequency*	Months	Unknown
11	Type of Cleaning*	Type	Unknown
12	Pipe Shape	Type	Circular
13	Pipe Material	Type	Concrete Pipe

Index output: 3 (good)

Module with maximum result: Internal Corrosion

Reason: High age, low slope

Discussion: This high aged ductile iron pipe has a low slope. The high age and low slope indicates that this pipe might be prone to surface wear issues.

Segments with Satisfactory Performance (index score 4)

Results indicate 8.05% of the pipes are in good performance grade (index score 3). These pipes are penalized for a single or a combination of undesirable parameters. The segments with good performance index score are summarized in Table G17-6.9.

Table G17-9. Segments with Good Performance Score (4)

PIPEiD	Index Score	Highest Module Grade	Significant Parameters
21941	4	Surface Wear	Vitrified Clay, High age (109)
25564	4	Surface Wear	Vitrified Clay, High age (109)
197264	4	Surface Wear	Concrete Pipe, High age (91),
213579	4	Surface Wear	Concrete Pipe, High age (95),
307731	4	Surface Wear	Asbestos Cement, High age
309667	4	Surface Wear	Reinforced Concrete, High
310072	4	Surface Wear	Reinforced Concrete, High

Table G17-10. Pipe Segment # 213579

Number	Parameter	Unit	Value
1	Component ID	ID	213579
2	Node ID	ID	D080-180 D081-031
3	Pipe Age	Year	95
4	Pipe Condition*	Pipe Condition Grade	Unknown
5	Pipe Depth	Feet	12
6	Pipe Diameter	Inches	3
7	Pipe Length	Feet	122.39
8	Pipe Slope	% Grade	0.8166
9	Soil Type*	Type	Unknown
10	Maintenance Frequency*	Months	Unknown
11	Type of Cleaning*	Type	Unknown
12	Pipe Shape	Type	Circular
13	Pipe Material	Type	Concrete Pipe

Index output: 4 (Satisfactory)

Module with maximum result: Surface Wear

Reason: High age, low slope

Discussion: This high very aged concrete pipe (95 years) has a very low slope (0.8166%). The high age and low slope indicates that this pipe might be prone to surface wear issues.

Segments with Failed Performance (index score 10)

Pipes which are failed according to utility inspection data tend to give the same result for the index. The algorithm cannot further penalize the already failed pipe segments. Table G17-11 summarize already failed pipes in the sample population.

Table G17-11. Segments with Failed Performance Score (10).

PIPEiD	Index Score	Notes
14101	10	Failed
15219	10	Failed
18308	10	Failed
20866	10	Failed
21442	10	Failed
21444	10	Failed
22251	10	Failed
23561	10	Failed
24122	10	Failed
24243	10	Failed

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The preliminary results for gravity pipes suggest that the expected remaining life of these pipes are 52 years. Results of the time-dependent performance prediction are summarized in figures G17-3 and G17-4.

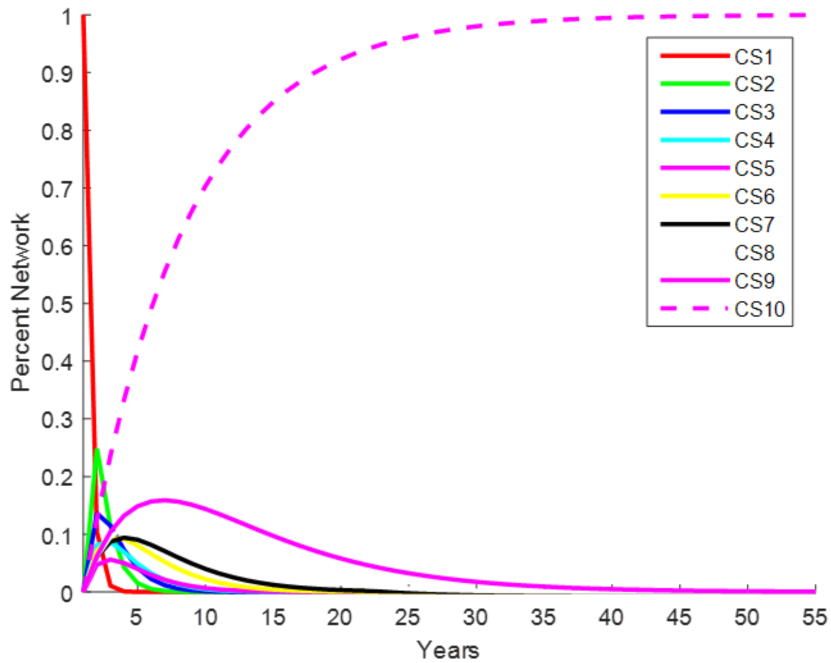

Figure G17-3. Preliminary State Dependent Performance Prediction Results

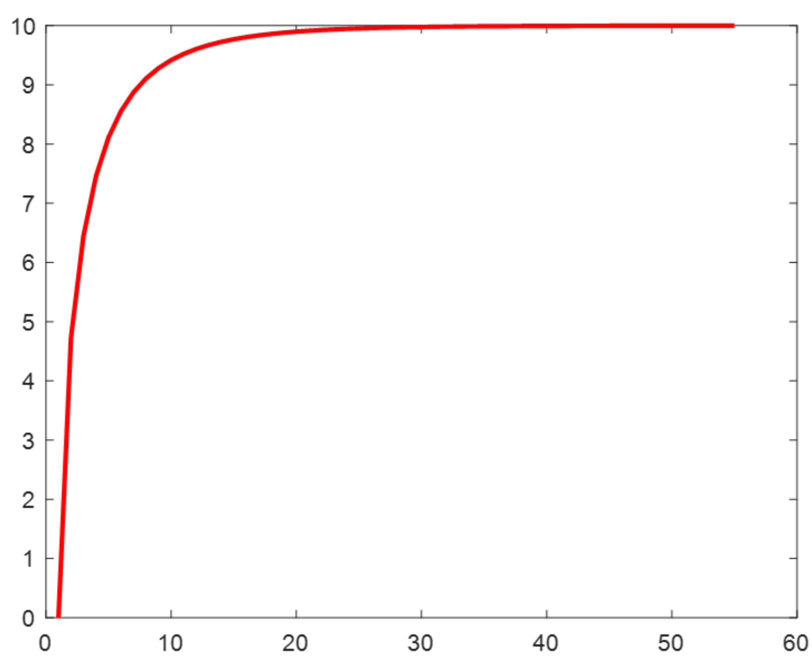

Figure G17-4. Preliminary State Dependent Performance Prediction Results

Appendix G18 – Utility #18 Piloting Results

Overview

The research team has received data from participating utility #18 in the form of asset inventory. This database contains records for 225 pipe segments totaling in 6.825 miles in length. All the 225 segments were selected for the piloting the performance index. Data is extracted for these 225 segments to pilot the performance index. Extracted data from utility records are summarized in Table G18-1.

Table G18-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe ID	Database
Pipe Condition	Database
Pipe Diameter	Database
Pipe Length	Database
Pipe Material	Database
Pipe Shape	Database
Lining Present	Database
Lining Type	Database

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset are summarized at Table G18-2.

Table G18-2. Focused Calibration Dataset.

Parameter	Unit	Lower Range	Higher Range
Pipe Condition	Defect Rating	0	139
Pipe Diameter	Inch	6	12
Pipe Length	Feet	1.4	426
Pipe Material	Type	VCP, DIP, PVC, RCP	
Pipe Shape	Type	Circular	
Lining Present	Yes/No	No	Yes
Lining Type	Type	CIPP	

After the index was run with the dataset, outputs ranged between 1-10. Table G18-3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G18-3 Final Piloting Results

Total Number of Segments	Segments with 0 difference	Segments with 1 difference	Segments with 2 difference	Segments with 3 difference
225	2	42	180	1
100%	0.89%	18.67%	80.00%	0.44%

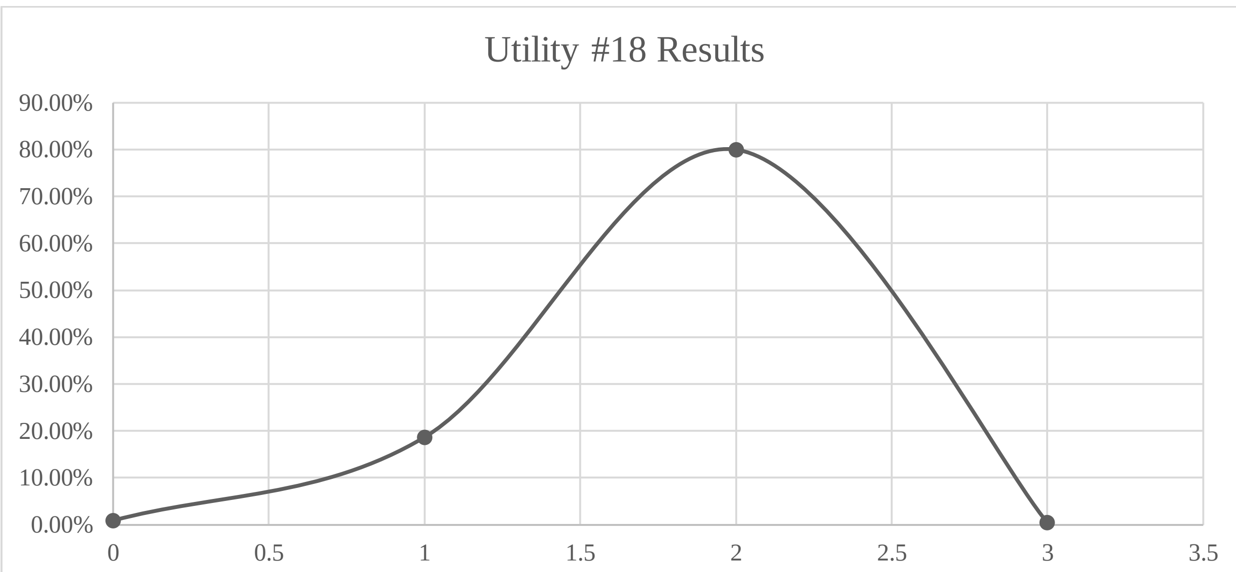

Figure G18-1. Utility #18 Results Difference

Results with 0 Difference

Table G18-4 summarizes pipes with 0 difference between the defect rating and the performance index.

Table G18-4. Segments with 0 difference

PIPEiD	Model	Defect Norm	Difference
413	10	10	0
1619	2	2	0

Results with 1 and 2 Difference

Table G18-5 summarizes pipes with 1 and 2 difference between the defect rating and the performance index.

Table G18-5. Segments with 1 and 2 difference

PIPEiD	Model	Defect	Difference
496	7	5	2
446	7	5	2
511	6	4	2
1617	5	4	1
572	5	3	2
517	5	3	2
1622	5	3	2
387	4	3	1
429	3	2	1
640	3	2	1
633	3	2	1
425	3	2	1
515	3	2	1
1630	3	2	1
639	3	2	1
1839	3	2	1
428	2	1	1
1627	2	1	1
493	2	1	1
445	2	1	1
226	2	1	1
1629	2	1	1
413	2	1	1
493	2	1	1
653	2	1	1
590	2	1	1
632	2	1	1
413	2	1	1
497	2	1	1
1840	2	1	1
1619	2	1	1
618	2	1	1

437	2	1	1
415	2	1	1
180	2	1	1
1614	2	1	1
603	2	1	1
589	2	1	1
514	2	1	1
1618	2	1	1
459	2	1	1
641	2	1	1
591	2	1	1
498	2	1	1
535	2	1	1
494	2	1	1
1711	2	1	1
641	2	1	1
607	2	1	1
1829	2	1	1
423	2	1	1
611	2	1	1
507	2	1	1
519	2	0	2
417	2	0	2
635	2	0	2
1607	2	0	2
500	2	0	2
1615	2	0	2
620	2	0	2
512	2	0	2
579	2	0	2
153	2	0	2
601	2	0	2
633	2	0	2
398	2	0	2
1612	2	0	2
1624	2	0	2
596	2	0	2
573	2	0	2
495	2	0	2
518	2	0	2
1623	2	0	2
401	2	0	2

387	2	0	2
397	2	0	2
540	2	0	2
414	2	0	2
575	2	0	2
596	2	0	2
155	2	0	2
575	2	0	2
516	2	0	2
508	1	0	1
568	1	0	1
459	1	0	1
599	1	0	1
576	1	0	1
538	1	0	1
608	1	0	1
424	1	0	1
602	1	0	1
226	1	0	1
592	1	0	1
513	1	0	1
571	1	0	1
579	1	0	1
541	1	0	1
456	1	0	1
527	1	0	1
516	1	0	1
499	1	0	1
1521	1	0	1
606	1	0	1
621	1	0	1
1619	1	0	1
605	1	0	1
634	1	0	1
393	1	0	1
604	1	0	1
546	1	0	1
638	1	0	1
1628	1	0	1
412	1	0	1
1841	1	0	1
600	1	0	1

586	1	0	1
1822	1	0	1
526	1	0	1
1620	2	0	2
567	1	0	1
402	1	0	1
579	1	0	1
580	1	0	1
389	1	0	1
418	1	0	1
391	1	0	1
390	1	0	1
1608	1	0	1
1609	1	0	1
1610	1	0	1
1611	1	0	1
544	1	0	1
1613	1	0	1
461	1	0	1
462	1	0	1
1616	1	0	1
1828	1	0	1
522	1	0	1
545	1	0	1
543	1	0	1
1842	1	0	1
578	1	0	1
577	1	0	1
419	1	0	1
536	1	0	1
588	1	0	1
1830	1	0	1
1605	1	0	1
395	1	0	1
524	1	0	1
619	1	0	1
594	1	0	1
521	1	0	1
570	1	0	1
506	1	0	1
394	1	0	1
449	1	0	1

520	1	0	1
1712	1	0	1
569	1	0	1
597	1	0	1
598	1	0	1
502	1	0	1
593	1	0	1
581	1	0	1
584	1	0	1
437	1	0	1
1831	1	0	1
523	1	0	1
537	1	0	1
1606	1	0	1
585	1	0	1
388	1	0	1
390	1	0	1
392	1	0	1
454	1	0	1
1714	1	0	1
448	1	0	1
436	1	0	1
451	1	0	1
452	1	0	1
610	1	0	1
450	1	0	1

Results with 3 Difference

Table G18-6 summarize pipes with 3 difference between the defect rating and the performance index.

Table G18-6. Segments with 3 difference.

PIPEiD	Model	Defect	Difference
542	3	0	3

Case Studies

Table G18-7. Pipe Segment 542

Parameter	Value
Pipe ID	542
Pipe Condition	0
Pipe Diameter	8
Pipe Length	426
Pipe Material	PVC
Pipe Shape	Circular
Lining Present	No
Lining Type	NA

Index output: 3 (Very Good)

Module with maximum result: Blockage

Reason: Long Pipe

Discussion: This PVC pipe is prone to blockage issues because of the high length (436 ft.)

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The preliminary results for gravity pipes suggest that the expected remaining life of these pipes is 147 years. Results of the time-dependent performance prediction are summarized in Figures G18-3 and G18-4.

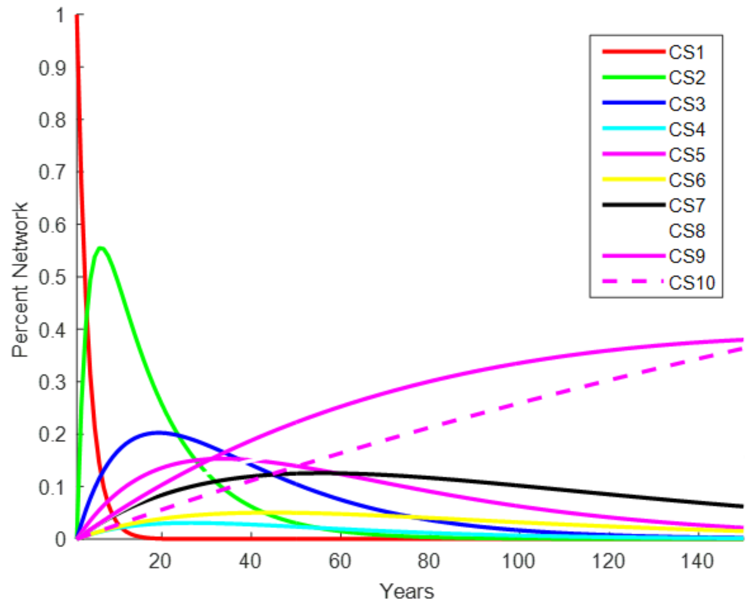

Figure G18-3. Preliminary State Dependent Performance Prediction Results

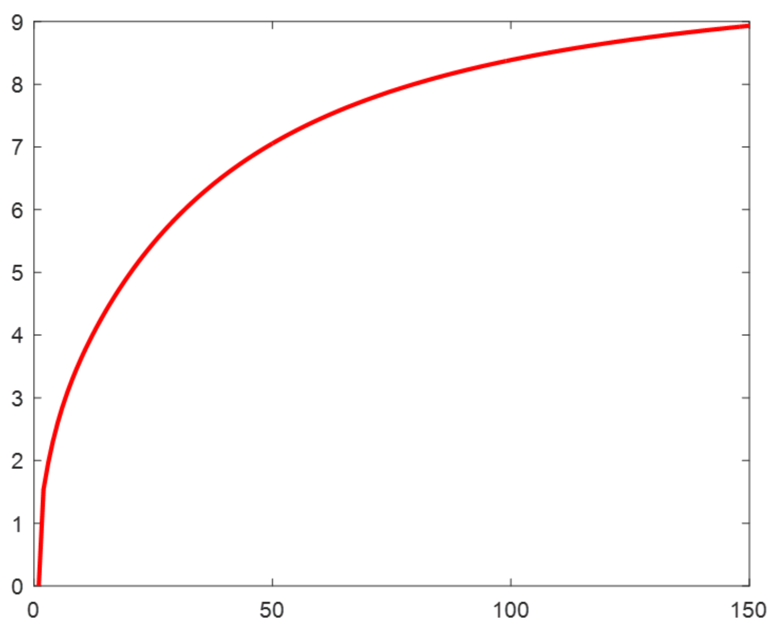

Figure G18-4. Preliminary State Dependent Performance Prediction Results

Appendix G-19 Utility #19 Piloting Results

The research team has been piloting the developed performance index with the GIS, defect, and failure data received from participating utility #19. These records contain data for 33824 pipe segments. The pipe segment classifications are summarized in Table G19-1.

Table G19-1. Pipe Segment Classifications

Sewer Type	Number of Segments
Collector	30803
Interceptor	1646
Outfall	4
Trunk	599
Syphon	122
Vent	104
Force Main	207
Storm	269
Unknown	70
Total	**33824**

Only collector, trunk, and interceptor sewers with determined installation dates are chosen to be evaluated. This elimination brings the sample size to 25183. 142 of the pipes were selected to represent the highest and lowest ranges of the parameters evaluated. Extracted data from utility records are summarized in Table G19-2.

Table G19-2. Parameters Extracted from Utility Data

	Parameter	Lower Range	Higher Range	Unit
1	Pipe Age	0.4575	110.901	Years
2	Pipe Condition	0	5	PACP Index
3	Pipe Depth	0.5	27.5	Feet
4	Pipe Diameter	4	48	Inches
5	Pipe Length	0.96	898.133	Feet
6	Pipe Location	Field, not-road, Pavement, Road		Type
7	Pipe Slope	0.00128	95.573	Percent Grade
8	Surcharging Height	0	131.99	Feet
9	Lining Present?	Yes	No	Yes/No

10	Lining age	0	19	Years
11	Lining Material	EXP, PVC, HDPE		
12	Lining Type	CP, FI, FF		
13	Flow Depth/Diameter	0	26	%
14	Concrete Encasement	Yes	No	Yes/No
16	Ground Cover	Field, not-road, Pavement		Type
17	Pipe Shape	Circular		Type
18	Pipe Material	AC, CAS, CP, DIP, HDPE, PE, PP, PVC, RCP, VCP		Type
19	Pipe Function	Collector, trunk, interceptor		Type

3. Performance Index Piloting Results Discussion

After the model run with the dataset, the results between the utility defect index and the model outputs are compared. It is important to note that the results from the index used by the utility were normalized by multiplying by 2 to have a comparable scale with the index outputs (10-grade scale). The results differences between the utility defect index and performance index output range between 0-4. There are also some pipe segments which do not have inspection records but significant defects included in the evaluation. Table G19-3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G19-3. Final Piloting Results

Total Number of Segments	Segments with 0 difference	Segments with 1 difference	Segments with 2 Difference	Segments with 3 Difference	Segments with 4 Difference	Segment with Unknown Condition
142	9	44	47	18	11	13
100%	6.34%	30.99%	33.10%	12.68%	7.75%	9.15%

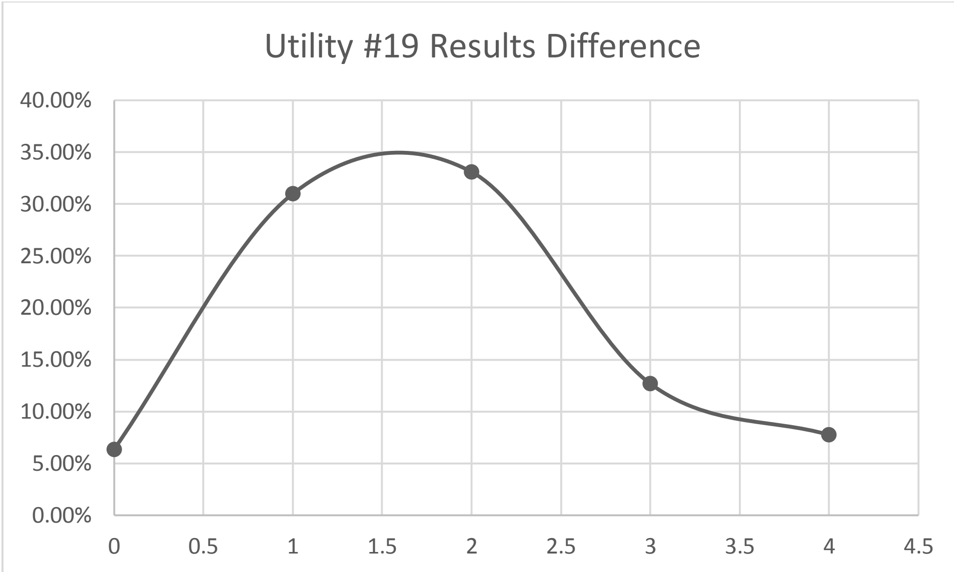

Figure G19-1. Utility #19 Results Difference

Results with No Inspection Records.

13 segments (9.15%) were evaluated by the performance index. Table G19-4 summarizes these results.

Table G19-4. Segments with no inspection records

PIPEiD	Index	PACP Norm	Difference	Max Module
1155	10	Unknown	NA	lining
1311	5	Unknown	NA	Integrity
1490	6	Unknown	NA	Blockage
2430	5	Unknown	NA	Integrity
2433	10	Unknown	NA	lining
11344	10	Unknown	NA	Surface
11348	10	Unknown	NA	Surface
11496	10	Unknown	NA	Surface
15446	10	Unknown	NA	Integrity
22052	10	Unknown	NA	Blockage
23511	10	Unknown	NA	Capacity
23630	10	Unknown	NA	Capacity

Results with 0 Difference

27 segments (19.15%) had no difference between the observed PACP defect index and developed performance index. The results indicate that the instances where there are no differences are when there are no defects observed, and other parameters are desirable. Also, pipes with utility index grade of 5 (failed) tend to give the same result with the index. The algorithm cannot further penalize the already failed pipe segments. Table G19-4 summarizes the results where there are no differences between the PACP index and the Performance Index.

Table G19-4. Segments with 0 Difference

Significant factor	PIPEiD	Index	PACPNorm	Difference
High Surcharging	6370	1	1	0
Short Pipe	6950	1	1	0
Short Pipe	9425	1	1	0
Low Flow Depth	3799	1	1	0
Low Flow Depth	2470	1	1	0
Low Flow Depth	9365	1	1	0
Low Flow Depth	813	1	1	0
Short Pipe	4192	1	1	0
High Slope	4192	1	1	0
High Slope	9433	1	1	0
High Slope	5392	1	1	0
High Slope	2221	1	1	0
High Slope	1565	1	1	0
High Slope	5920	1	1	0
High Surcharging	6233	1	1	0
High Surcharging	8837	1	1	0
Shallow Pipe	8831	1	1	0
Young Pipe	7836	1	1	0
High Surcharging	8967	1	1	0
Short Pipe	5560	1	1	0
Shallow Pipe	8900	1	1	0
Failed Pipe	6375	10	10	0
Failed Pipe	4288	10	10	0
Failed Pipe	8265	10	10	0
Failed Pipe	4286	10	10	0
Failed Pipe	7140	10	10	0

Failed Pipe	8601	10	10	0

Results with 1 Difference

There are 70 (70%) pipe segments with one difference between the normalized utility index and the performance index output. Pipe segments where results are one difference is summarized in Table 5. Results summarized indicate the index used by the utility and performance index developed by the research team agrees.

Table G19-5. Segments with 1 Difference between the normalized utility index and the performance index output.

PIPEiD	Index	PACPNorm	Difference
7667	3	2	1
7644	3	2	1
2913	7	6	1
7668	2	1	1
7645	7	6	1
6493	2	1	1
6493	2	1	1
7646	2	1	1
8640	2	1	1
6572	7	6	1
150	7	6	1
150	7	6	1
10557	3	2	1
7844	2	1	1
6339	2	1	1
8082	2	1	1
3771	2	1	1
8314	7	6	1
510	3	2	1
8338	3	2	1
7847	7	6	1
7312	2	1	1
8316	2	1	1
6600	2	1	1

10553	2	1	1
6914	2	1	1
2046	9	8	1
6252	2	1	1
9255	2	1	1
5740	2	1	1
2301	7	6	1
8155	2	1	1
804	2	1	1
8775	9	8	1
7865	7	6	1
1051	3	2	1
2918	2	1	1
8117	2	1	1
7856	3	2	1
7926	2	1	1
8893	2	1	1
2902	2	1	1
188	7	6	1
2893	2	1	1
8894	2	1	1
8356	9	8	1
8356	9	8	1
8895	2	1	1
8892	2	1	1
10314	2	1	1
6046	2	1	1
8771	7	6	1
6144	2	1	1
9203	2	1	1
8891	2	1	1
7698	2	1	1
7701	2	1	1
9285	2	1	1
8781	7	6	1
7609	2	1	1
7609	2	1	1
2712	2	1	1
7710	2	1	1
9417	2	1	1
8196	2	1	1
4990	2	1	1

3607	2	1	1
7889	2	1	1
7702	2	1	1
7062	3	2	1

Results with 2 Difference

There are 29 (20.57%) pipe segments with two difference between the normalized PACP index and the performance index output. Pipe segments where are two difference are summarized in Table G19-6.

Table G19-6. Pipe segments where results are 2 difference between the normalized PACP index and the performance index output.

Explanation	PIPEiD	Index	PACP Norm	Difference	Module
High flow depth	8236	6	4	2	Capacity
Moderate age under pavement	5688	6	4	2	Integrity
Moderate age under pavement	6750	6	4	2	Integrity
High length	6162	6	4	2	Blockage
DIP, High age, low slope, low flow depth	8782	3	1	2	Internal Corrosion
High length	6935	6	4	2	Blockage
PVC, low slope, low flow depth	8776	3	1	2	Surface Wear
VCP, High age, low slope, low flow depth	7859	6	4	2	Surface Wear
PVC, low slope, low flow depth	7845	6	4	2	Surface Wear
High length	6088	6	4	2	Blockage
Moderate age, Shallow Depth, under unpaved road	7317	6	4	2	Integrity
PE, moderate age, low flow depth, low slope	658	3	1	2	Surface Wear
PVC, moderate age, low flow depth, low slope	6751	6	4	2	Surface Wear
AC, high age, high slope	859	6	4	2	Surface Wear
DIP, high age, under unpaved road	588	3	1	2	Integrity
VCP, shallow, under unpaved road.	7807	3	1	2	Integrity
PVC, High length, low slope	1640	3	1	2	Blockage
VCP, moderate age, low slope	4776	3	1	2	Surface Wear
CIP, high age, low slope	8784	3	1	2	Surface Wear

VCP, high age, moderate depth, under traffic.	779	4	2	2	Integrity
CP, moderate age, under traffic	576	6	4	2	Integrity
CP, high age, low slope	6874	3	1	2	Surface Wear
VCP, high age, low slope	8791	3	1	2	Surface Wear
CP, moderate age, low slope	6569	6	4	2	Surface Wear
VCP, high length	7613	3	1	2	Blockage
VCP, high age, low slope	233	3	1	2	Surface Wear

Results with 3 Difference

There are 13 (9.22%) pipe segments with three difference between the normalized utility index and the performance index output. Pipe segments where results are three difference between the normalized utility index and the performance index output is summarized in table G19-7.

Table G19-7. Pipe segments where results are 3 difference between the normalized PACP grades.

PIPEiD	Index	PACPNorm	Difference	Module
7511	4	1	3	Capacity
7512	4	1	3	Capacity
6244	4	1	3	Capacity
4030	4	1	3	Blockage
8774	5	2	3	Integrity
8777	7	4	3	Blockage
5230	4	1	3	Blockage
5230	4	1	3	Blockage
739	4	1	3	Blockage
739	4	1	3	Blockage
8780	7	4	3	Blockage
7795	4	1	3	Blockage
7795	4	1	3	Blockage

<u>Case Studies</u>

Table G19-8. PIPEiD: 7511

	Parameter	Value	Unit
	Network ID	16-3233.0 to 16-3230.0	ID
1	Pipe Age	7.19	Years
2	Pipe Condition (PACP)	0	Utility Index
3	Pipe Depth	10.16	Feet
4	Pipe Diameter	8	Inches
5	Pipe Length	9.66	Feet
6	Pipe Location	Not Road	Type
7	Pipe Slope	5.48	Percent Grade
8	Flow Depth/Diameter	26.04	%
9	Pipe Surcharging height	0	Percent
10	Ground Cover	Not Road	Type
11	Pipe Shape	Circular	Type
12	Pipe Material	VCP	Type

PACP Normalized vs. Performance Index: 1 (Excellent) vs. 4 (Satisfactory)

Module with maximum result: Capacity

Reason: High flow depth/ diameter ratio.

Discussion: This young aged vitrified clay pipe has a high flow depth/diameter ratio (26.04%). This high ratio indicates this pipe is prone to capacity issues.

Table G19-9. PIPEiD: 4030

	Parameter	Value	Unit
1	Network ID	05A-4080.0 to 05A-2066.0	ID
2	Pipe Age	6.48	Years
3	Pipe Condition (PACP)	0	Utility Index
4	Pipe Depth	15.785	Feet
5	Pipe Diameter	8	Inches
6	Pipe Length	481.381	Feet
7	Pipe Location	Pavement	Type
8	Pipe Slope	2.39	Percent Grade
9	Flow Depth/Diameter	2.08	%
10	Pipe Surcharging height	0	Percent
11	Ground Cover	Pavement	Type
12	Pipe Shape	Circular	Type
13	Pipe Material	PVC	Type

PACP Normalized vs. Performance Index: 1 (Excellent) vs. 4 (Satisfactory)

Module with maximum result: Blockage

Reason: High pipe length, low flow depth/diameter, moderate pipe slope.

Discussion: This young aged PVC pipe has a high length (481.381 feet) and low flow depth over diameter (2.08%) and moderate slope. These factors indicate pipe segment is prone to blockage issues.

Table G19-10. PIPEiD: 8774

	Parameter	Value	Unit
1	Network ID	20B-3211.5 to 20B-3211.0	ID
2	Pipe Age	110.55	Years
3	Pipe Condition (PACP)	1	Utility Index
4	Pipe Depth	6.135	Feet
5	Pipe Diameter	18	Inches
6	Pipe Length	183.04	Feet
7	Pipe Location	Pavement	Type
8	Pipe Slope	0.74	Percent Grade
9	Flow Depth/Diameter	2.08	%
10	Pipe Surcharging height	0	Percent
11	Ground Cover	Pavement	Type
12	Pipe Shape	Circular	Type
13	Pipe Material	Vitrified Clay	Type

PACP Normalized vs. Performance Index: 2 (Very Good) vs. 5 (Fair)

Module with maximum result: Integrity

Reason: High aged pipe under traffic load.

Discussion: This high aged (110.55 years) vitrified clay pipe with a shallow depth (6.135 feet) in under pavement. The location and depth of this pipe indicate that it is under high dynamic loads and would be prone to integrity issues.

Results with 4 Difference

There are 13 (9.22%) pipe segments with three difference between the normalized utility index and the performance index output. Pipe segments where results are three difference between the normalized utility index and the performance index output is summarized in table G19-11.

Table G19-11. Pipe segments where results are 3 difference between the normalized PACP grades.

PIPEiD	Index	PACPNorm	Difference	Module
635	6	2	4	Integrity
8216	6	2	4	Integrity

<u>Case Studies</u>

Table G19-12. PIPEiD: 635

	Parameter	Value	Unit
1	Network ID	01B-3885.0 to 01B-3884.5	ID
2	Pipe Age	85.53	Years
3	Pipe Condition (PACP)	1	Utility Index
4	Pipe Depth	7.325	Feet
5	Pipe Diameter	8	Inches
6	Pipe Length	141.127	Feet
7	Pipe Location	Pavement	Type
8	Pipe Slope	13.68	Percent Grade
9	Flow Depth/Diameter	0.0833	%
10	Pipe Surcharging height	0	Percent
11	Ground Cover	Pavement	Type
12	Pipe Shape	Circular	Type
13	Pipe Material	PVC	Type

PACP (Normalized) vs. Performance Index: 2 (good) vs. 6 (poor)

Module with maximum result: Integrity

Reason: High aged PVC pipe under traffic with moderate depth.

Discussion: This PVC pipe segment is aged high (85.53) under pavement and moderate depth (7.325 ft.). With the assumption of this high aged pipe is under dynamic loading due to its location, it would be prone to integrity issues.

Case Studies

Table G19-13. PIPEiD: 8216

	Parameter	Value	Unit
1	Network ID	200-3064.0 to 200-3065.0	ID
2	Pipe Age	87.54	Years
3	Pipe Condition (PACP)	1	Utility Index
4	Pipe Depth	6.35	Feet
5	Pipe Diameter	8	Inches
6	Pipe Length	45.47	Feet
7	Pipe Location	Pavement	Type
8	Pipe Slope	39.39	Percent Grade
9	Flow Depth/Diameter	0	%
10	Pipe Surcharging height	0	Percent
11	Ground Cover	Pavement	Type
12	Pipe Shape	Circular	Type
13	Pipe Material	PVC	Type

PACP (Normalized) vs. Performance Index: 2 (good) vs. 6 (poor)

Module with maximum result: Integrity

Reason: High aged PVC pipe under traffic with moderate depth.

Discussion: This cast iron pipe segment is aged high (87.54) under pavement and moderate depth (6.35ft.). With the assumption of this high aged pipe is under dynamic loading due to its location, it would be prone to integrity issues.

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. Two different state dependent and time depended models were developed.

State Depended Models

State Dependent Model #1 – MHA

Figure G19-2 are the results of the deterioration prediction for participating utility sewer shed #1 PVC pipe class #3 (collection, less than 18" diameter, construction era 1998 to present). The preliminary results for gravity pipes suggest that the expected remaining life of these pipes is 53 years.

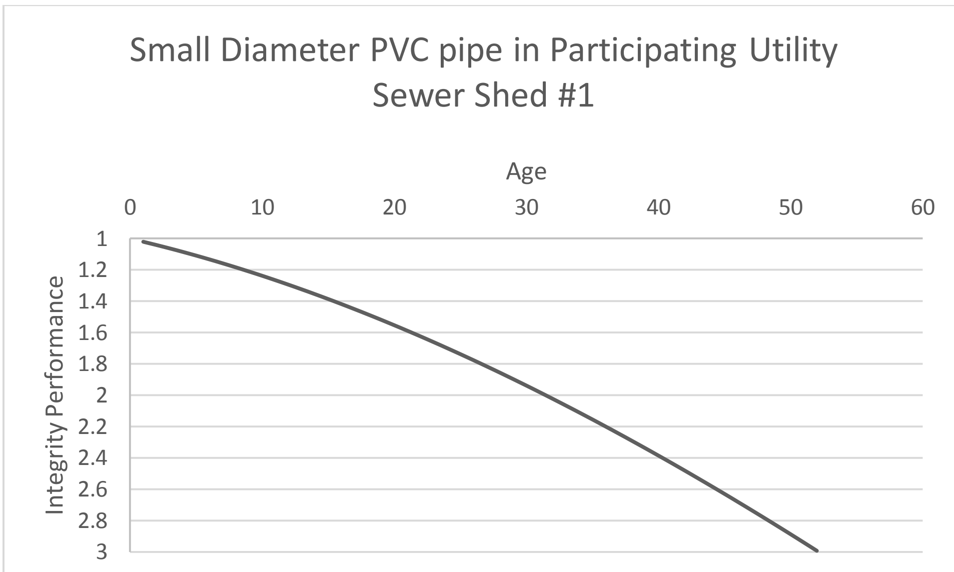

Figure G19-2. State Dependent Deterioration Model for Participating Utility

State Dependent Model #2 – Ordered Logit

Figure G19-3 are the results of the deterioration prediction for participating utility sewer shed #1 PVC pipe class #3 (collection, less than 18" diameter, construction era 1998 to present). The preliminary results for gravity pipes suggest that the expected remaining life of these pipes are 62 years.

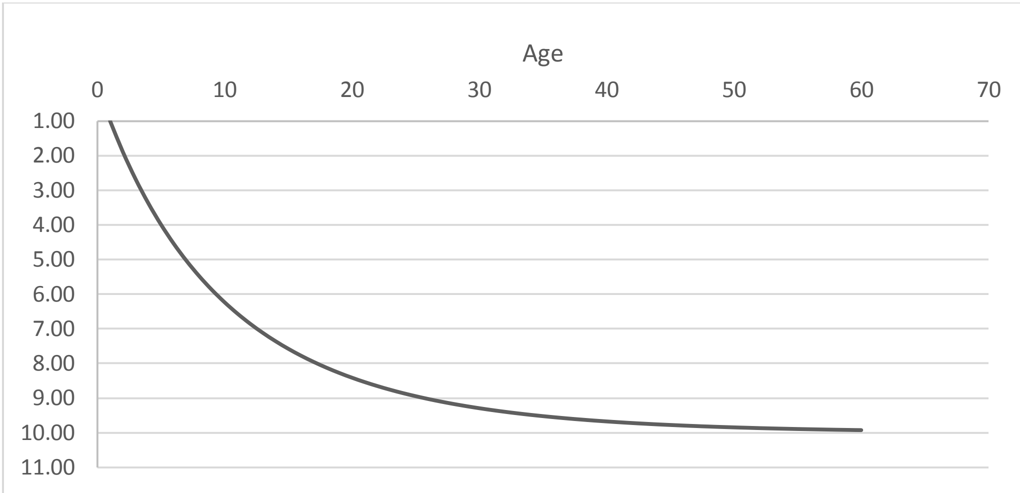

Figure G19-3. Preliminary State Dependent Performance Prediction Results

Time Depended Models

Time Dependent Model #1 – K-M Method

Figure G19-4 are the results of the deterioration prediction for participating utility sewer shed #1 PVC pipe class #3 (collection, less than 18" diameter, construction era 1998 to present).

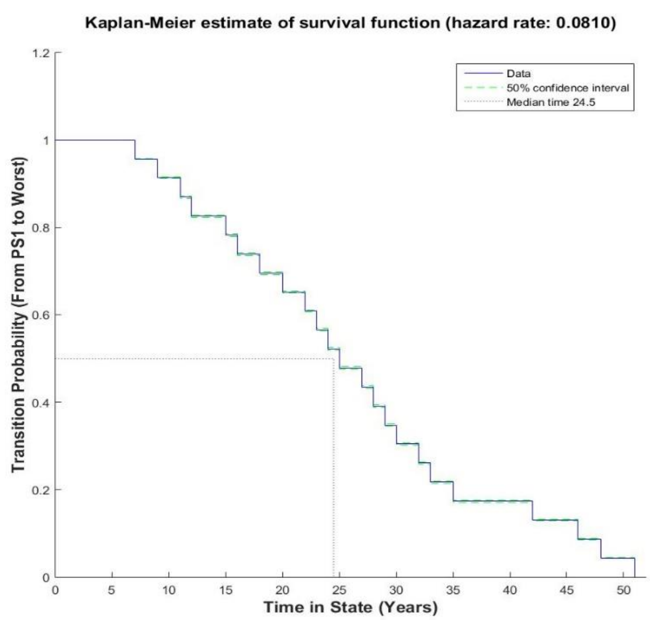

Figure G19-4. K-M Method Estimates for Transition Probability Performance State 1.

Time Dependent Model #2 – Exponential Regression

us_node_id	ds_node_id	Install Date	Length	material	pacp_overall_index_rating	Integrity Index	date_completed	joined_pipe_type	Age at Inspection
01A-3657.0	01A-3652.0	1/2/1960	152.0445	VCP	1.14	2.28	6/14/2012	COLLECTOR	52.4865
01A-3657.0	01A-3652.0	1/2/1960	152.0445	VCP	1	2	10/5/2010	COLLECTOR	50.79355

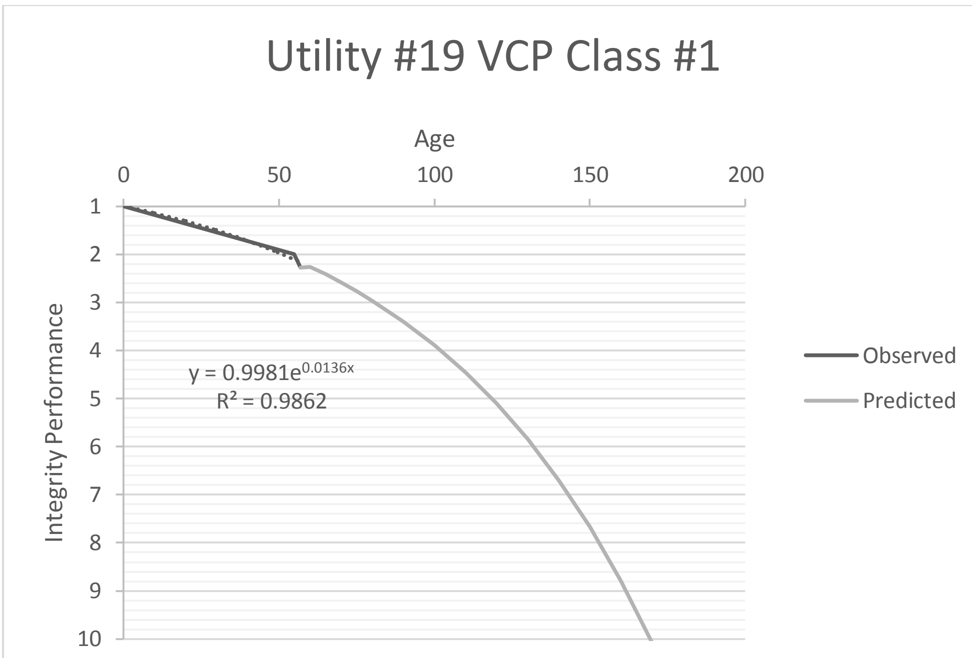

Figure G19-5. Time Dependent Model for Utility #19 VC pipe class #1 (collection, less than 24” diameter, construction era 1955 to 1975).

Appendix G 20 – Utility #20 Piloting Results

The research team has been piloting the developed performance index with the GIS, defect, and failure data received from participating utility #20. These records contain data for 154,675 pipe segments. 114 of this pipe were randomly selected to be evaluated. Extracted data from utility records are summarized in Table G20-1.

Table G20-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe Age	Geodatabase
Pipe Condition	CCTV Inspection Data
Pipe Depth	CCTV Inspection Data
Pipe Diameter	CCTV Inspection Data
Pipe Length	CCTV Inspection Data
Pipe Location	Geodatabase
Pipe Slope	CCTV Inspection Data
Pipe Surcharging	Failure Reports
Lining Presence	CCTV Inspection Data
Lining Type	CCTV Inspection Data
Flow Depth/Diameter	CCTV Inspection Data
Density of Connections	CCTV Inspection Data
Flow Velocity	Geodatabase

Performance Index Piloting Results Discussion

A focused dataset of 114 pipes was selected to further calibrate the index this dataset includes the pipe samples with the highest and lowest ranges of the parameters and the pipe segments with the greatest results differences from the previous pass. The ranges and the number of pipe segment selected for the focused calibration dataset are summarized at Table G20-2.

Table G20-2. Focused Calibration Dataset.

Parameter	Lower Range	Number of Segments	Higher Range	Number of Segments
Pipe Age	6	5	86-84	10
Pipe Depth	0.3-1.4	9	4.5-8.3	5
Pipe Diameter	4-6	4	60-66	4
Pipe Length	1	5	758.2-568.9	5
Pipe Location	No Load	3	Under Highway	12
Pipe Slope	41.45-82.8	6	0.03-0.09	5
Pipe Surcharging	High frequency (3-4 per 10 year)	4	No Surcharging issues	0
Flow Depth/Diameter	0.05	3	1-0.9	7
Density of Connections	0	2	23-26	8
Flow Velocity	0.007-0.014	5	68.60-88.5	6

After the model run with the dataset, the results of the PACP coding and the model outputs are compared. It is important to note that the PACP coding results are normalized by multiplying by 2 to have a comparable scale with the index outputs. The results differences between the PACP defect coding and performance index output range between 0-7. Table G20-3 summarize the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G20-3. Final Piloting Results

Total Number of Segments	Segments with 0 difference	Segments with 1 difference	Segments with 2 Difference	Segments with 3 Difference	Segments with 4 Difference	Segments with 5 Difference	Segments with 6 Difference	Segments with 7 Difference
108	11	32	29	25	6	1	2	2
100%	10.19%	29.63%	26.85%	23.15%	5.56%	0.93%	1.85%	1.85%

Results with 0 Difference

Pipes with PACP grade of 5 (failed) tend to give the same result for the index. The algorithm cannot further penalize the already failed pipe segments. Table G20- 4 summarizes already failed pipes in the sample population.

Table G20-4. Segments with 0 Difference – Failed Pipes

Significant Parameter	PIPEiD	Model	PACP (Normalized)	Difference
Pipes with high density connections	1002	10	10	0
Short pipes	1144	10	10	0
Pipes with high density connections	1267	10	10	0
High velocity pipe	1359	10	10	0
High velocity pipe	1366	10	10	0
Shallow pipes under highway	1423	10	10	0
Pipes operating in high capacity	4528	10	10	0
Pipes operating in high capacity	6884	10	10	0
Deep pipes	8571	10	10	0
Old pipes	9274	10	10	0
Long length pipe	9889	10	10	0

Results with 1 Difference

Pipe segments where results are one difference between the normalized PACP grade and the index output is summarized in Table G20-5. Results summarized indicate the pipes with the desirable parameters (low range) are not penalized for the performance. Results also suggest that although there are undesirable parameters for some of the pipe segments, the effects of these parameters are not significant for the pipe performance due to various other parameters.

Table G20-5. Segments with 1 Difference

Significant Parameter	PIPEiD	Model	PACP Normalized	Difference
Under Highway	1	3	2	1
Metallic pipe with moderate flow depth and low flow velocity	12	9	8	1
Low Capacity	39	9	8	1

No Load	68	7	6	1
Shallow Pipe under light/heavy traffic	83	7	6	1
No Load	226	1	0	1
No Load	301	9	8	1
small diameter	484	7	6	1
Shallow Pipes	1231	9	8	1
Large Diameter	1389	5	4	1
High Velocity Pipe	1702	1	0	1
Pipes with High Slopes	2398	3	2	1
Shallow Pipe under light/heavy traffic	2703	9	8	1
Shallow Pipe under light/heavy traffic	2741	7	6	1
small diameter	2822	1	0	1
small diameter	2831	1	0	1
Newer Pipes	2833	7	6	1
Newer Pipes	2834	7	6	1
Low Velocity Pipe	5676	7	6	1
Newer Pipes	5895	1	0	1
Short Pipes	6786	1	0	1
Low Velocity Pipe	6862	9	8	1
Pipes with High Slopes	6893	3	2	1
Short Pipes	7150	1	0	1
Short Pipes	7644	7	6	1
Deep Pipes	7742	9	8	1
Pipes with High Slopes	8161	3	2	1
Low Velocity Pipe	9090	1	0	1
Old Pipes	9268	9	8	1
Large Diameter	9378	5	4	1
Pipes operating in high capacity	9573	9	8	1
Long Length Pipe	9900	9	8	1

Results with 2 or 3 Difference

Pipe segments where results are 2 or 3 difference between the normalized PACP grade and the index output is summarized in table G20-6. Results summarized indicate that although for some segments have undesirable parameters and the performance of these segments are calculated by considering these parameters. Some significant pipe segments with a high difference between the index and the PACP grades are further investigated in the following case studies.

Table G20-6. Pipe segments where results are 2 or 3 difference between the normalized PACP grades.

Explanations	PIPE iD	Model	PACP (Norm.)	Diff.	Diff. Modul
Under highway, moderate depth	2	2	0	2	Integrity
High slope, high velocity, and moderate flow depth/diameter	65	6	4	2	Integrity
Under highway, moderate depth, high velocity and moderate flow depth/diameter	67	2	0	2	Integrity
Under highway, moderate depth	82	3	0	3	Integrity
Under highway, moderate depth	84	2	0	2	Integrity
Shallow Pipe under light/heavy traffic	85	6	4	2	Integrity
Moderate diameter, high density connections	485	6	4	2	Blockage
Long pipe with high density of connections	540	3	0	3	Blockage
Moderate diameter, high density connections	733	8	6	2	Blockage
Moderate diameter, high density connections	736	8	6	2	Blockage
Long Pipe, Very low flow depth/diameter and low flow velocity	861	3	0	3	Blockage
High slope, high velocity, and moderate flow depth/diameter	1133	6	4	2	Integrity
Very high pipe age	1142	7	4	3	Integrity
Long pipe, Very low flow depth/diameter and low flow velocity	1170	3	0	3	Blockage
Very high Velocity, moderate flow depth/diameter	1230	2	0	2	Surface
Metallic pipe with moderate flow depth and low flow velocity	1232	2	0	2	Internal
Metallic pipe with moderate flow depth and low flow velocity	1233	2	0	2	Internal
Under highway, moderate depth	1307	2	0	2	Integrity
Moderate age, shallow pipe under light highway	1390	3	0	3	Integrity

High Velocity Pipe, moderate flow depth/diameter	1424	2	0	2	Integrity
Under highway, moderate depth	2165	6	4	2	Integrity
High age, low flow velocity	2535	3	0	3	Surface
Metallic pipe with moderate flow depth and low flow velocity	2584	6	4	2	Internal
Under highway, moderate depth	2704	6	4	2	Integrity
Long pipe, low flow velocity	2835	6	4	2	Blockage
High surcharging	3023	7	4	3	IandE
Large diameter, moderate age	3241	6	4	2	Root Intrusi
Pipe surcharging issues	3574	8	6	2	IandE
High density of connections, long pipe, low flow velocity	4355	3	0	3	Blockage
High density of connections, long pipe, low flow velocity	4630	3	0	3	Blockage
Small diameter, high pipe surcharging, moderate flow depth/diameter	4652	7	4	3	Capacity
Long pipe, low flow velocity	4658	3	0	3	Blockage
Moderate density of connections, long pipe, low flow velocity	5092	3	0	3	Blockage
Newer Pipes	5896	6	4	2	Integrity
Pipes with low slopes	6250	2	0	2	Blockage
Low Velocity Pipe	6852	6	4	2	Integrity
Low Velocity Pipe	6861	6	4	2	Integrity
pipes with high density connections	7170	7	4	3	Blockage
Short Pipes	7871	4	2	2	Capacity
Pipes with low slopes	8222	6	4	2	Integrity
Moderate number of connections	8560	3	0	3	Blockage

Moderate flow depth/diameter	857 0	3	0	3	Capaci ty
Moderate flow depth/diameter	857 9	2	0	2	Capaci ty
Pipes with high density of connections but large diameter	894 5	8	6	2	Blocka ge
Old, shallow pipe under moderate traffic	926 9	5	2	3	Integri ty
Old Pipes	927 3	7	4	3	Integri ty
Old, shallow pipe under moderate traffic	927 5	5	2	3	Integri ty
Old Pipes	931 8	7	4	3	Integri ty
Low velocity and moderate flow depth/diameter	932 3	3	0	3	Surfac e
Old pipe with low flow velocity and moderate flow depth/diameter	933 9	3	0	3	Surfac e
Old Pipes	934 1	7	4	3	Integri ty
Pipes with low slopes	937 9	2	0	2	Integri ty
Pipes with high density of connections but large diameter	938 0	3	0	3	Blocka ge
Long Length Pipe, moderate number of connections	989 0	3	0	3	Blocka ge

Table G20-7. Pipe Segment #1390

Parameter	Value
PIPEiD	1390
Pipe Age	42
Pipe Condition	0
Pipe Depth	0.338417
Pipe Diameter	8
Pipe Length	264.5
Pipe Location	4
Pipe Slope	0.73913
Pipe Surcharging	0
Pipe Grade	0.73913
Lining Present	-1
Lining Type	0

Flow Depth/Diameter	0.1
Flow Velocity	0.554
Density of Connections	2

PACP vs. index output: 0 vs. 3

Module with maximum result: Integrity

Reason: Shallow pipe under major highway

Discussion: Although there is no defect noted by the CCTV inspection, the pipe is located under a major highway, and pipe depth is shallow. These parameters indicate that there is a high amount of dynamic loading on the pipe which makes it prone to integrity issues.

Table G20-8. Pipe Segment # 2535

Parameter	Value
PIPEiD	2535
Pipe Age	115
Pipe Condition	0
Pipe Depth	2.217583
Pipe Diameter	10
Pipe Length	619.8
Pipe Location	0
Pipe Slope	3.35
Pipe Surcharging	0
Pipe Grade	3.35
Lining Present	-1
Lining Type	0
Flow Depth/Diameter	0.0001
Flow Velocity	2.562
Density of Connections	0

PACP vs. index output: 0 vs. 3

Module with maximum result: Surface Wear

Reason: Aged pipe, low flow velocity, low flow depth/diameter.

Discussion: Although there is no defect noted by the CCTV inspection, the high age, low flow velocity, and low flow depth/diameter means this pipe is prone to surface wear.

Table G20-9. Pipe Segments # 3023

Parameter	Value
PIPEiD	3023
Pipe Age	48
Pipe Condition	2
Pipe Depth	2.091667
Pipe Diameter	6
Pipe Length	106.9
Pipe Location	0
Pipe Slope	4.68
Pipe Surcharging	4
Pipe Grade	4.68
Lining Present	-1
Lining Type	0
Flow Depth/Diameter	0.05
Flow Velocity	0.798
Density of Connections	0

PACP vs. index output: 4 vs. 7

Module with maximum result: Infiltration and Exfiltration

Reason: High surcharging rate, low flow velocity, small diameter.

Discussion: Although the PACP grade for the pipe is 2, this specific segment of pipe (Network id: 02016031S) had three surcharging issues in the last ten years. This is proof that this particular segment is prone to exfiltration problems. Additional parameters contributing to the difference are; small diameter and low flow velocity.

Results with 4 or 5 Difference

There are 7 (15.43%) pipe segments where there is 4 or 5 difference between the PACP grade and the index output. Table G20-10 summarizes these results. Some significant pipe segments with a high difference between the index and the PACP grades are further investigated in the following case studies.

Table G20-10. Pipe segments where results are 4 or 5 difference between the normalized PACP grades.

Significant Parameter	PIPEiD	Model	PACP Norm.	Diff.	Diff. Module
Shallow Pipe under Major highway	1143	6	2	4	Integrity
Very low flow depth/diameter and low flow velocity	1301	4	0	4	Blockage
High density of connections, long pipe, low flow velocity	3151	4	0	4	Blockage
Very high density of connections, long pipe, low flow velocity	3889	6	2	4	Blockage
Long pipe, low flow velocity	5540	4	0	4	Blockage
Very high density of connections, Long pipe, low flow velocity	8193	5	0	5	Blockage
High flow depth/diameter, moderate diameter	9693	8	4	4	Capacity

Case Studies

Table G20-11. Pipe Segment #3151

Parameter	Value	Unit
PIPEiD	3151	ID
Pipe Age	53	Years
Pipe Condition	0	PACP
Pipe Depth	2.186667	Feet
Pipe Diameter	8	Inch
Pipe Length	408.1	Feet
Pipe Location	4	Light Highway
Pipe Slope	4.33	%
Pipe Surcharging	0	Level
Lining Present	-1	Yes/No
Lining Type	0	Type
Flow Depth/Diameter	0.1	Ratio
Flow Velocity	1.631	Gal/Min

Density of Connections	21	Number

PACP vs. index output: 0 vs. 4

Module with maximum result: Blockage

Reason: Long pipe length, low flow velocity, and high density of connections.

Discussion: Although there is no defect noted by the CCTV inspection, the length of the pipe, low flow velocity, small diameter, and high number of lateral connections indicate this pipe segment would be prone to blockages.

Table G20-11. Pipe Segments # 9693

Parameter	Value	Unit
PIPEiD	9693	ID
Pipe Age	72	Years
Pipe Condition	2	PACP
Pipe Depth	0.412167	Feet
Pipe Diameter	10	Inch
Pipe Length	320.6	Feet
Pipe Location	0	Light Highway
Pipe Slope	2	%
Pipe Surcharging	0	Level
Lining Present	-1	Yes/No
Lining Type	0	Type
Flow Depth/Diameter	1	Ratio
Flow Velocity	1.979	Gal/Min
Density of Connections	4	Number

PACP vs. index output: 4 vs. 8

Module with maximum result: Capacity

Reason: High flow depth/diameter, moderate pipe diameter.

Discussion: Although the PACP grade for the pipe is 2, this specific segment of pipe is operating in full (100%) capacity level. This is a proof that the pipe has capacity issues.

Results with 6 or 7 Difference

There are 4 (3.70%) pipe segments where there is 6 or 7 difference between the PACP grade and the index output. Table G20-12 summarizes these results. Some significant pipe segments with a high difference between the index and the PACP grades are further investigated in the following case studies.

Table G20-12. Pipe segments where results are 6 or 7 difference between the normalized PACP grades.

Significant Parameter	PIPEiD	Index	PACP	Dif.	Diff. Module
Pipes operating in high capacity	381	6	0	6	Capacity
Pipe surcharging issues	2056	7	0	7	Capacity
Pipes operating in high capacity	5554	7	0	7	Capacity
Pipes operating in high capacity	9593	6	0	6	Capacity

Case Studies

Table G20-13. Pipe Segments # 381

Parameter	Value	Unit
PIPEiD	381	ID
Pipe Age	18	Years
Pipe Condition	0	PACP
Pipe Depth	2.90025	Feet
Pipe Diameter	8	Inch
Pipe Length	112.5	Feet
Pipe Location	4	Light Highway
Pipe Slope	5.59	%
Pipe Surcharging	0	Level
Lining Present	-1	Yes/No
Lining Type	0	Type
Flow Depth/Diameter	0.95	Ratio
Flow Velocity	1.853	Gal/Min
Density of Connections	0	Number

PACP vs. index output: 0 vs. 6

Module with maximum result: Capacity

Reason: High flow depth/diameter, small diameter.

Discussion: Although the PACP grade for the pipe is 0, this specific segment of pipe is operating in full (95%) capacity level. This high capacity is proof that the pipe has capacity issues. Pipe segment numbers 5554 and 9593 gave similar results.

Table G20-14. Pipe Segments # 2056

Parameter	Value	Unit
PIPEiD	2056	ID
Pipe Age	14	Years
Pipe Condition	0	PACP
Pipe Depth	2.04	Feet
Pipe Diameter	6	Inch
Pipe Length	110.6	Feet
Pipe Location	0	Light Highway
Pipe Slope	1.2	%
Pipe Surcharging	5	Level
Lining Present	-1	Yes/No
Lining Type	0	Type
Flow Depth/Diameter	0.0001	Ratio
Flow Velocity	0.404	Gal/Min
Density of Connections	1	Number

PACP vs. index output: 0 vs. 7

Module with maximum result: Capacity

Reason: High surcharging, small diameter.

Discussion: Although the PACP grade for the pipe is 2, this specific segment of pipe (Network id: 02008085S) had four surcharging issues in the last ten years. These issues are proof that this particular segment is prone to capacity issues. Additional parameters contributing to the difference are; small diameter.

4. Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The initial results for gravity pipes suggest that the expected remaining life of these pipes is 64 years. Results of the time-dependent performance prediction are summarized in figures G20-5 and G20-6.

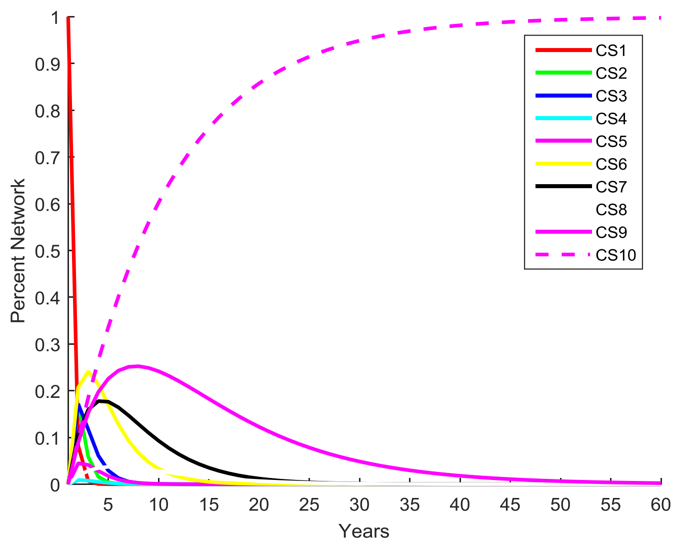

Figure G20-5. Preliminary State Dependent Performance Prediction Results

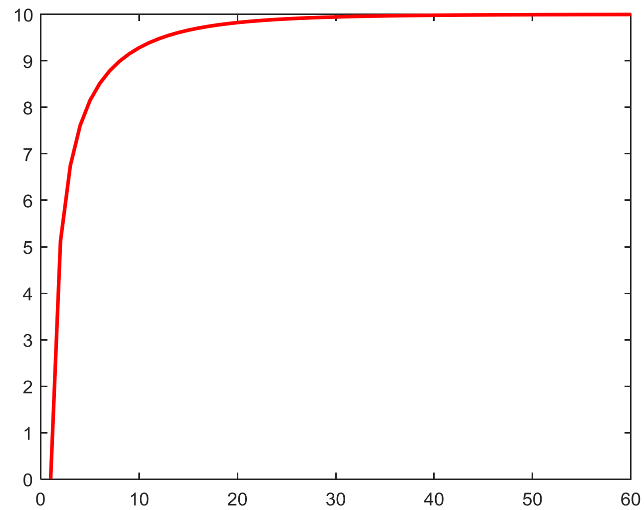

Figure G20-6. Preliminary State Dependent Performance Prediction Results

Appendix G21 – Utility #21 Force Main Piloting Results

Overview

Research team has received data from participating utility #21 in the form of;

- GIS Geo-database

- Asset inventory for force mains

- Force Main Break Records

This database contains records for 57 pipe segments. Data is extracted for these 57 segments to pilot the performance index. Extracted data from utility records are summarized in Table G21-1.

Table G21-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe ID	Asset inventory
Pipe Age	Asset inventory
Working Pressure	Asset inventory
Surge Pressure	Asset inventory
Remaining Wall Thickness	Asset inventory
H2S	Asset inventory
Pipe Material	Asset inventory
Pipe Shape	Asset inventory
Pipe Size	Asset inventory
Number of Breaks	Break Records
Breaks <5 Years	Break Records

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset are summarized at Table G21-2.

Table G21-2. Focused Calibration Dataset.

Parameter	Unit	Lower Range	Higher Range
Pipe Age	Year	8	74
Working Pressure	psi	4.4	175
Surge Pressure	psi	100	

Remaining Wall Thickness	%	49	100
H2S	ppm	0	2
Pipe Material	Type	CIP, DIP	
Pipe Shape	Type	Circular	
Pipe Size	Inch	4	36
Number of Breaks	Frequency	0	10
Breaks <5 Years	Frequency	0	1

After the index run with the dataset, the performance index outputs ranged between 1-10. Table G21-3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G21-3 Final Piloting Results

Total Number of Segments	Segments in Condition (1)	Segments in Condition (2)	Segments in Condition (3)	Segments in Condition (4)	Segments in Condition (5)	Segments in Condition (6)	Segments in Condition (7)	Segments in Condition (8)	Segments in Condition (9)	Segments in Condition (10)
57	6	5	6	9	8	5	6	6	4	2
100%	10.53%	8.77%	10.53%	15.79%	14.04%	8.77%	10.53%	10.53%	7.02%	3.51%

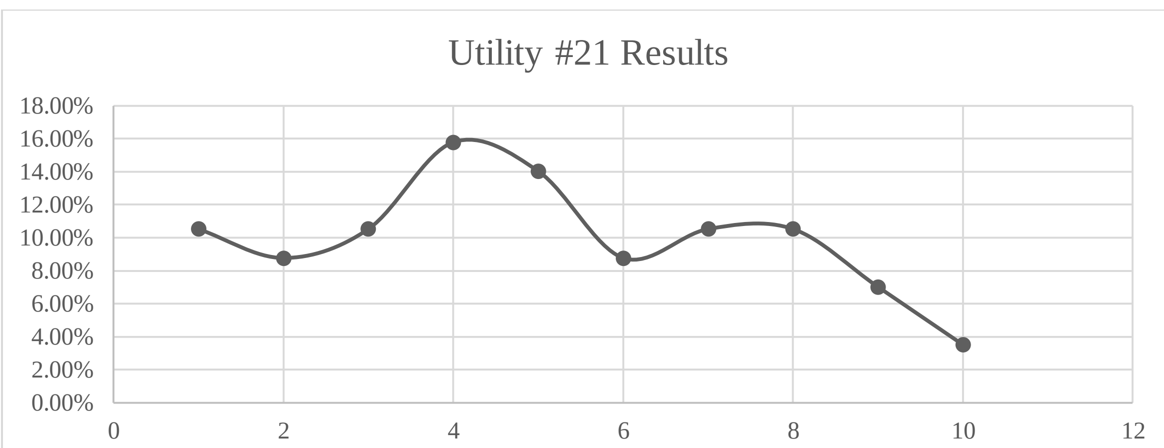

Figure G21-1. Utility #21 Results

Results with 1 (excellent) and 2 (very good) performance grades

Table G21-4 discuss summarize pipes with 1 (excellent) and 2 (very good) performance grades.

Table G21-4. Segments with 1 (excellent) and 2 (very good) performance grades

PIPEiD	Model
CV1039	2
CV1041	1
CV2324	1
CV2348	2
CV516	2
CV784	1
CV786	1
CV787	1
CV925 (north)	2
CV925 (south)	1
CV932	2

Results with 3 (good) and 4 (satisfactory) performance grades.

Pipe segments with 3 (good) and 4 (Satisfactory) performance grades are summarized in table G21-5.

Table G21-5. Segments with 3 (good) and 4 (Satisfactory) performance grades.

PIPEiD	Model
CV1042	3
CV1051	4
CV1062	4
CV1079	4
CV1081	3
CV1085	4
CV1095	4
CV1097	3
CV1680	4
CV1682	4
CV513	4
CV701	4
CV705	3
SV1544	3

SV1545	3

Results with 5 (fair) and 6 (poor) performance grades.

Pipe segments with 5 (fair) and 6 (poor) performance grade are summarized in table G21-6.

Table G21-6. Segments with 5 (fair) and 6 (poor) performance grades.

PIPEiD	Model
CV1045	5
CV1047	5
CV1076	5
CV1087	6
CV1089	6
CV1681	5
CV2300	6
CV2301	6
CV510	5
CV511	5
CV703	6
CV831	5
CV933	5

Results with 7 (serious) and 8 (critical) performance grade.

Pipe segments with 7 (serious) and 8 (critical) performance grade are summarized in table G21-7.

Table G21-7. Segments with 7 (serious) and 8 (critical) performance grade.

PIPEiD	Model
CV1031	7
CV1033	7
CV1082	7
CV1093	8
CV1099	7
CV2303	8
CV2321	7
CV2323	8
CV832	7

NS950	8
NS950	8
NS951	8

Results with 9 (failure) and 10 (failed) performance grades.

Pipe segments with 9 (failure) and 10 (failed) performance grade are summarized in table G21-8.

Table G21-8. Segments with 9 (failure) and 10 (failed) performance grade.

PIPEiD	Model	Module
CV1035	9	Integrity
CV1037	9	Integrity
CV1043	10	Integrity
CV2305	9	Integrity
CV2307	9	Integrity
CV835	10	Integrity

Case Studies

Table G21-8. Pipe Segment CV2303

Parameter	Unit	Value
Pipe Age	Year	46
Working Pressure	psi	4.35
Surge Pressure	psi	100
Remaining Wall Thickness	%	49
H2S	ppm	0
Pipe Material	Type	DIP
Pipe Shape	Type	Circular
Pipe Size	Inch	18
Number of Breaks	Frequency	0
Breaks <5 Years	Frequency	0

Index output: 10 (failed)

Module with maximum result: Integrity

Reason: Low remaining wall thickness

Discussion: This terracotta pipe is prone to integrity issues due to low remaining wall thickness.

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The preliminary results for gravity pipes suggest that the expected remaining life of these pipes is 75 years. Results of the time dependent performance prediction is summarized in figures G21-2 and G21-3.

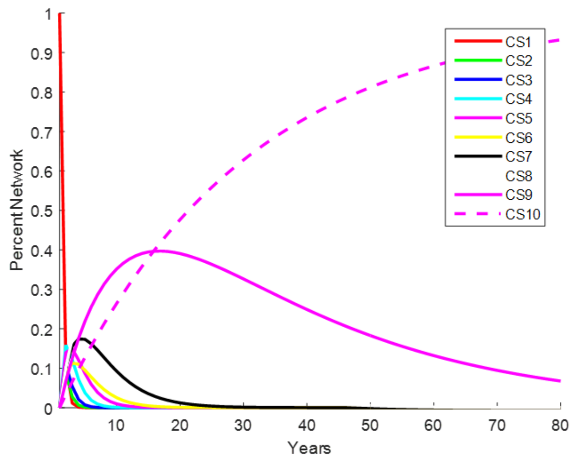

Figure G21-2. Preliminary State Dependent Performance Prediction Results

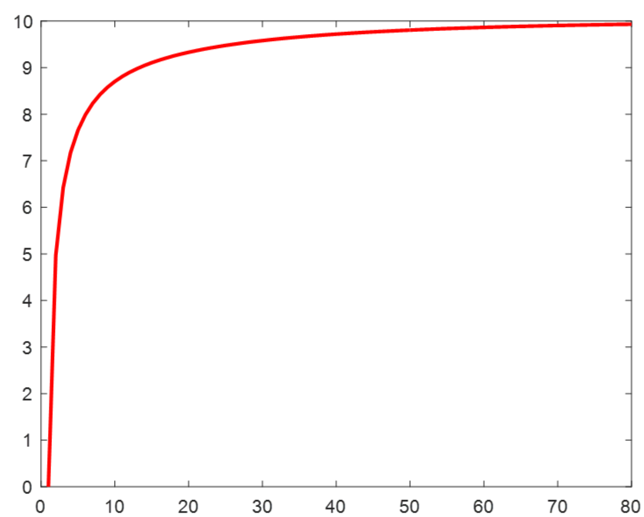

Figure G21-3. Preliminary State Dependent Performance Prediction Results

Appendix G22 – Utility #22 Force Main Piloting Results

Overview

A research team has received data from participating utility #22 in the form of Asset inventory for force mains. This database contains records for 423 pipe segments. 265 records were randomly selected, and data was extracted for these segments to pilot the performance index. Extracted data from utility records are summarized in Table G22-1.

Table G22-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe ID	Asset inventory
Pipe Material	Asset inventory
Pipe Shape	Asset inventory
Pipe Diameter	Asset inventory
Pipe Age	Asset inventory
Pipe Depth	Asset inventory
Pipe Location	Asset inventory
Pipe Length	Asset inventory
Operating Pressure	Asset inventory
Cathodic Protection	Asset inventory
Flow Velocity	Asset inventory

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset is summarized at table G22-2.

Table G22-2. Focused Calibration Dataset.

Parameter	Unit	Lower Range	Higher Range
Pipe Material	Type	AC, CI, Di, ESP, PVC, STL	
Pipe Shape	Type	Circular	
Pipe Diameter	Inches	3	48
Pipe Age	Years	3	65
Pipe Depth	Feet	12	75
Pipe Location	Type	Easement, Freeway, Highway, Local Road, Major Road	

Pipe Length	Feet	11	17909
Operating Pressure	psi	1	44
Cathodic Protection	Yes/No	No	Yes
Flow Velocity	Gal/min	1	14

After the index was run with the dataset, the outputs ranged between 1-10. Table G22-3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G22-3. Final Piloting Results

Total Number of Segments	Segments in Condition (1)	Segments in Condition (2)	Segments in Condition (3)	Segments in Condition (4)	Segments in Condition (5)	Segments in Condition (6)	Segments in Condition (7)	Segments in Condition (8)	Segments in Condition (9)	Segments in Condition (10)
265	31	29	23	19	28	30	33	54	17	1
100%	11.70%	10.94%	8.68%	7.17%	10.57%	11.32%	12.45%	20.38%	6.42%	0.38%

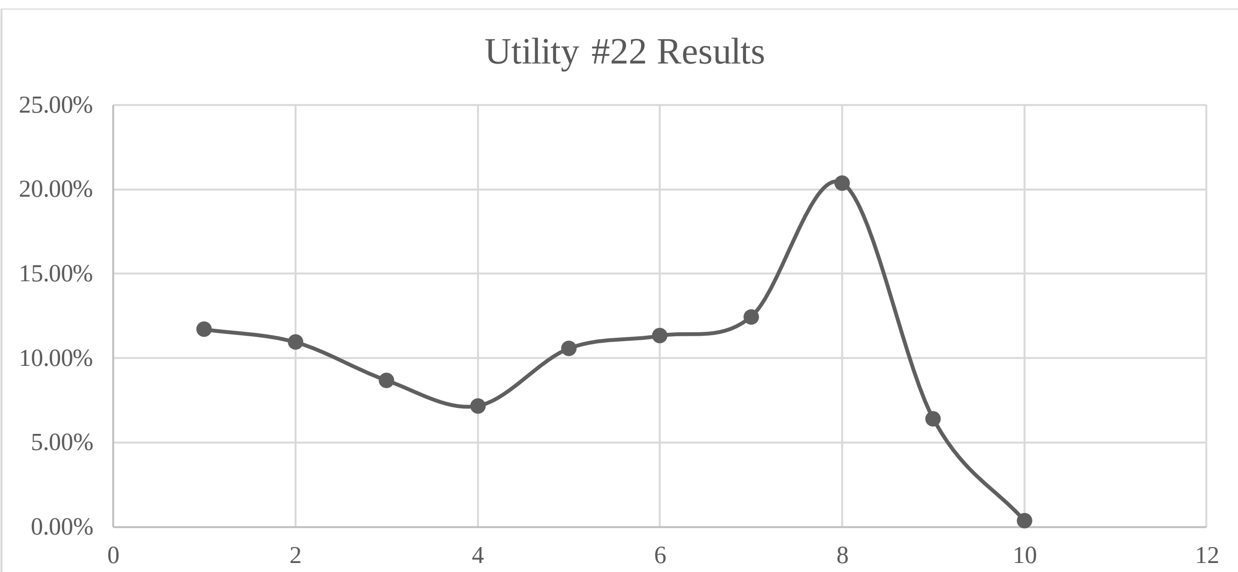

Figure G22-1. Utility #22 Results

Results with 1 (excellent) and 2 (very good) performance grades

Table G22-4 discuss summarize pipes with 1 (excellent) and 2 (very good) performance grade.

Table G22-4. Segments with 1 (excellent) and 2 (very good) performance grades

PIPEiD	Model
18016	2
18025	2
18026	2
18032	1
18034	1
18046	1
18050	1
18063	2
18065	1
18069	2
18097	1
18109	1
18110	2
18116	2
18117	2
18129	1
18130	1
18134	1
18137	1
18150	2
18153	2
18156	1
18161	1
18163	2
18184	1
18188	2
18221	1
18224	1
18227	1
18237	1
18238	1
18240	1
18276	2
18283	2
18288	2

18289	2
18292	2
18294	2
18295	2
18304	2
18309	1
18312	1
18314	1
18315	1
18316	1
18327	1
18328	1
18336	1
18340	1
18343	2
18346	1
18350	2
18353	2
18357	2
18370	2
18382	1
19244	2
19248	2
19253	2
19268	2

Results with 3 (good) and 4 (satisfactory) performance grades

Pipe segments with 3 (good) and 4 (Satisfactory) performance grade are summarized in table G22-5.

Table G22-5. Segments with 3 (good) and 4 (Satisfactory) performance grades.

PIPEiD	Model
18024	4
18029	3
18035	4
18038	4
18040	4
18054	4
18057	4

18064	3
18073	4
18076	4
18092	4
18149	3
18151	4
18154	3
18155	3
18157	3
18164	4
18171	3
18174	4
18183	3
18220	3
18222	3
18239	3
18259	3
18261	3
18263	3
18264	3
18274	3
18290	3
18317	3
18322	4
18324	4
18331	3
18339	4
18341	3
18362	3
18366	3
18372	4
18373	4
19254	4
19262	3

Results with 5 (fair) and 6 (poor) performance grades.

Pipe segments with 5 (fair) and 6 (poor) performance grades are summarized in table G22-6.

Table G22-6. Segments with 5 (fair) and 6 (poor) performance grades.

PIPEiD	Model

18009	5
18013	6
18015	5
18018	5
18020	5
18022	5
18027	6
18041	5
18044	5
18048	6
18058	6
18061	5
18068	5
18070	5
18071	5
18078	5
18084	5
18085	5
18090	5
18100	6
18101	5
18106	6
18120	6
18139	6
18141	5
18158	6
18162	5
18167	6
18170	6
18178	5
18180	6
18181	5
18182	5
18190	6
18192	6
18193	6
18200	6
18201	6
18202	6
18204	6
18207	6
18211	6

18216	6
18218	5
18229	6
18241	6
18243	6
18248	6
18249	5
18310	6
18318	5
18323	5
18329	6
18332	5
18335	6
18345	5
19243	5
19272	6

Results with 7 (serious) and 8 (critical) performance grades.

Pipe segments with 7 (serious) and 8 (critical) performance grades are summarized in table G22-7.

Table G22-7. Segments with 7 (serious) and 8 (critical) performance grades.

PIPEiD	Model
18012	8
18028	8
18043	8
18060	8
18067	8
18077	8
18079	7
18080	8
18082	8
18088	8
18095	7
18098	8
18102	7
18107	8
18111	8

18112	8
18113	7
18118	8
18121	8
18124	8
18126	7
18127	8
18128	8
18135	7
18136	7
18138	7
18140	7
18143	7
18146	7
18147	7
18152	7
18175	8
18186	8
18194	7
18205	8
18213	8
18214	7
18217	7
18219	7
18226	7
18228	8
18234	7
18235	7
18236	8
18245	7
18252	7
18255	7
18256	7
18257	7
18258	7
18265	7
18267	8
18269	8
18272	7
18273	7
18278	8
18279	8

18280	8
18282	8
18286	8
18293	8
18297	8
18307	7
18308	7
18333	7
18338	8
18348	8
18351	8
18352	8
18356	8
18358	8
18360	8
18364	8
18365	8
18367	8
18368	8
18371	8
18375	8
19240	8
19246	8
19249	8
19261	8

Results with 9 (failure) and 10 (failed) performance grades.

Pipe segments with 9 (failure) and 10 (failed) performance grade are summarized in table G22-8.

Table G22-8. Segments with 9 (failure) and 10 (failed) performance grades.

PIPEiD	Model	Module
18019	9	Integrity
18021	9	Integrity
18042	9	Integrity
18053	9	Blockage
18055	9	Integrity
18075	9	Integrity
18094	9	Integrity
18104	9	Integrity
18114	10	Blockage

18133	9	Integrity
18144	9	Integrity
18160	9	Integrity
18166	9	Integrity
18199	9	Integrity
18369	9	Integrity
18374	9	Integrity
18376	9	Integrity
18383	9	Integrity

Case Studies

Table G22-9. Pipe Segment 18199

Parameter	Unit	Value
PipeID	ID	18199
Pipe Material	Type	DI
Pipe Shape	Type	Circular
Pipe Diameter	Inches	24
Pipe Age	Years	58
Pipe Depth	Feet	33
Pipe Location	Type	Highway
Pipe Length	Feet	1818
Operating Pressure	psi	13
Cathodic Protection	Yes/No	No
Flow Velocity	Gal/min	7

Index output: 9 (failing)

Module with maximum result: Integrity

Reason: high age, under highway

Discussion: This ductile iron pipe is prone to integrity issues due to its high age (58 years) and location (under highway).

Table G22-10. Pipe Segment 18114

Parameter	Unit	Value
PipeID	ID	18114

Pipe Material	Type	CI
Pipe Shape	Type	Circular
Pipe Diameter	Inches	24
Pipe Age	Years	63
Pipe Depth	Feet	Unknown
Pipe Location	Type	Unknown
Pipe Length	Feet	8530
Operating Pressure	psi	14
Cathodic Protection	Yes/No	Yes
Flow Velocity	Gal/min	7

Index output: 10 (failed)

Module with maximum result: Blockage

Reason: high age, high length

Discussion: This cast iron pipe is prone to blockage issues due to its high age (63 years) and high length (18114 ft.)

Prediction Model Piloting and Discussion

The data received from utility #22 was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The initial results for gravity pipes suggest that the expected remaining life of these pipes is 161 years. Results of the time-dependent performance prediction are summarized in Figures G22-2 and G22-3.

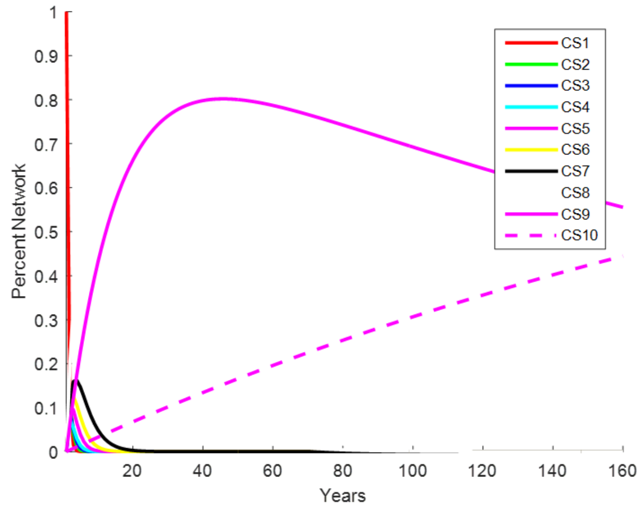

Figure G22-2. Preliminary State Dependent Performance Prediction Results

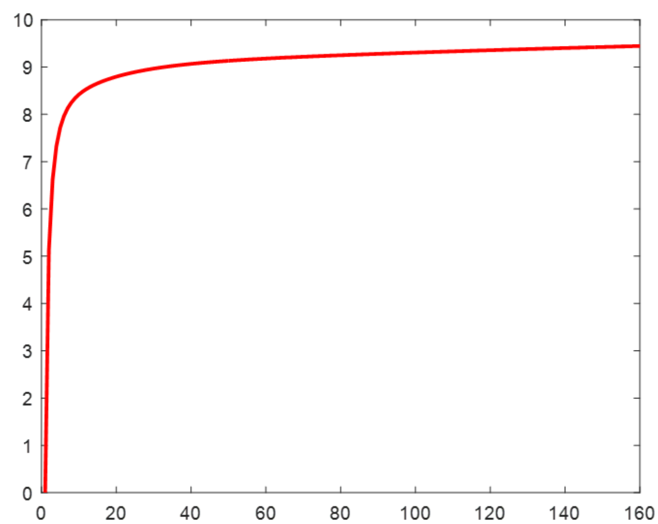

Figure G22-3. Preliminary State Dependent Performance Prediction Results

Appendix G23 – Utility #23 Force Main Piloting Results

Overview

The research team has received data from participating utility #23 in the form of;

-GIS geo-database.

-CCTV Inspections

-SSO's database

Participating utility force mains summarized in Figure G23-1.

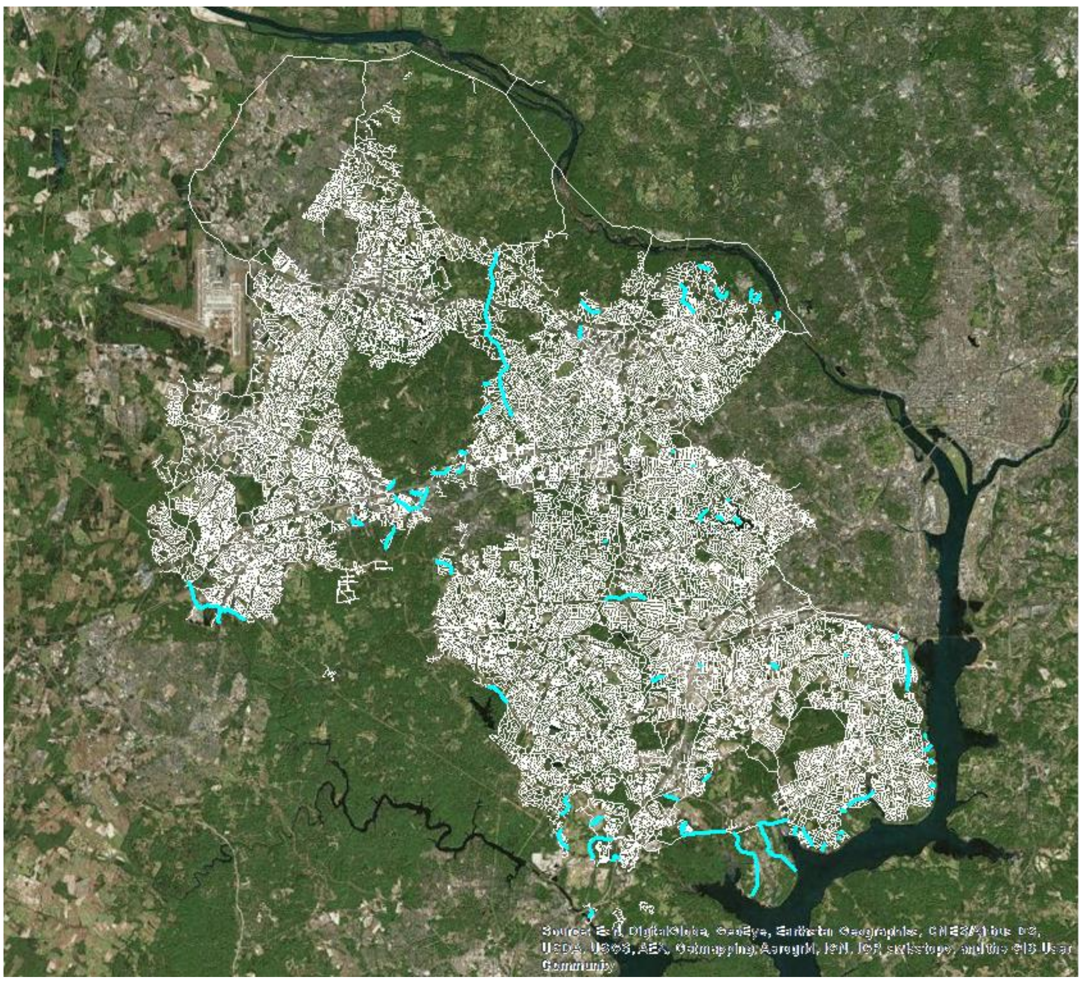

Figure G23-1. Utility #23 Force Main System (Highlighted in Blue)

Participating utility force main system consists of 111 segments totaling in 41.68 miles. Data is extracted for these 111 segments to pilot the performance index. Extracted data from utility records are summarized in Table G23-1.

Table G23-1. Parameters Extracted from Utility Data

Parameter	Source
Pipe ID	Geodatabase
Pipe Size	Geodatabase
Pipe Length	Geodatabase
Pipe Material	Geodatabase
Pipe Slope	Geodatabase
Pipe Age	Geodatabase
Pipe Location	GIS Map
Pipe Shape	Geodatabase

Performance Index Piloting Results Discussion

The ranges and the number of pipe segment parameters selected for the focused calibration dataset are summarized at Table G23-2.

Table G23-2. Focused Calibration Dataset.

Parameter	Unit	Lower Range	Higher Range
Pipe Size	Inches	5	21
Pipe Length	Feet	12	496
Pipe Material	Type	AC, CON, DIP, PVC	
Pipe Slope	%	0.15	14.07
Pipe Age	Years	15	44
Pipe Location	Type	Field, Parking Lot, Building, Road, Highway	
Pipe Shape	Type	Circular	

After the index had been run with the dataset, the outputs ranged between 0-5. Table G23-3 summarizes the overall results for the focused dataset. Following section discuss the reason for the differences.

Table G23-3 Final Piloting Results

Total Number of Segments	Segments in Condition (2)	Segments in Condition (3)	Segments in Condition (4)	Segments in Condition (5)	Segments in Condition (6)	Segments in Condition (7)	Segments in Condition (8)
141	4	72	21	36	2	5	1
100%	2.84%	51.06%	14.89%	25.53%	1.42%	3.55%	0.71%

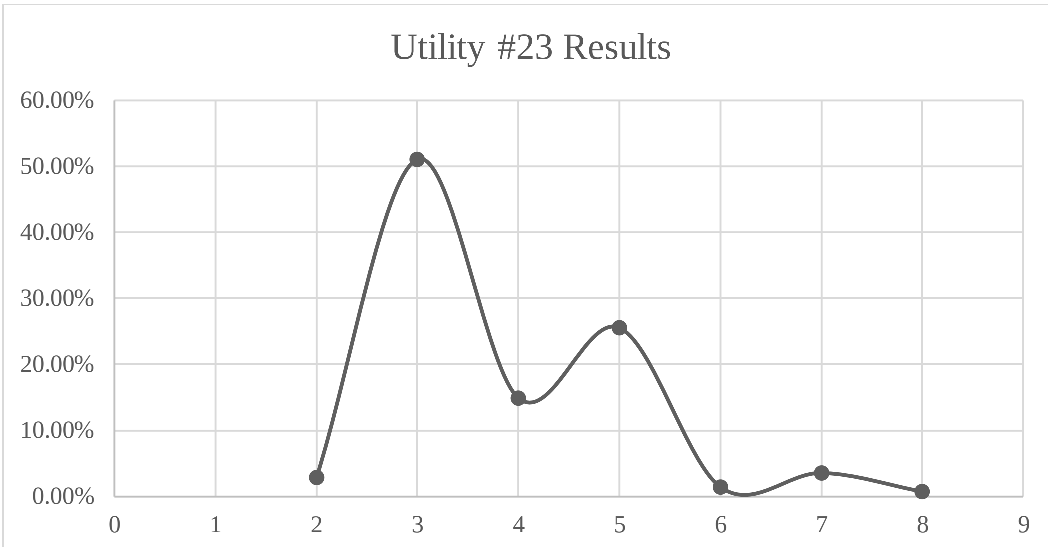

Figure G23-2. Utility #23 Results

Results with 1 (excellent) and 2 (very good) performance grades

Table G23-4 discuss summarize pipes with 1 (excellent) and 2 (very good) performance grades.

Table G23-4. Segments with 1 (excellent) and 2 (very good) performance grades

PIPEiD	Model
367	2
76668	2
4439	2
345300	2

Results with 3 (good) and 4 (satisfactory) performance grades.

Pipe segments with 3 (good) and 4 (Satisfactory) performance grades are summarized in table G23-5.

Table G23-5. Segments with 3 (good) and 4 (Satisfactory) performance grades.

PIPEiD	Model
45948	3
34420	3
68172	3
62374	3
359042	3
385361	3
345299	3
345287	3
345602	3
345285	3
15259	3
345302	3
345297	3
57410	3
243536	3
423114	3
673457	3
673456	3
68025	3
16897	3
414483	3
74701	3
414484	3
345304	3
16760	3
45877	3
345301	3
362371	3
985075	3
423115	3
435595	3
435597	3
91226	3
455762	3
91227	3
16759	3
455760	3
57480	3
35372	3

2136	3
23269	3
423117	3
455757	3
673461	3
423116	3
385650	3
673459	3
87188	3
455756	3
359043	3
41512	3
183691	3
3138	3
298944	3
35611	3
836020	3
241930	3
28672	3
737775	3
41403	3
737776	3
673460	3
673458	3
41515	3
76264	3
241929	3
356491	3
363578	3
86479	3
737774	3
52108	3
46791	3
41388	4
307858	4
241925	4
84745	4
45949	4
45416	4
296321	4
24384	4
183692	4

243841	4
41709	4
241927	4
362370	4
74347	4
2871	4
57710	4
296048	4
63093	4
935551	4
40090	4
91930	4

Results with 5 (fair) and 6 (poor) performance grades.

Pipe segments with 5 (fair) and 6 (poor) performance grade are summarized in table G23-6.

Table G23-6. Segments with 5 (fair) and 6 (poor) performance grades.

PIPEiD	Model
61602	5
15397	5
67493	5
248990	5
12592	5
27241	5
90351	5
79787	5
8497	5
74772	5
391745	5
16628	5
33881	5
14733	5
4440	5
53244	5
54415	5
298943	5
17476	5
90306	5
22869	5
51819	5

63095	5
73084	5
368	5
34368	5
48168	5
391744	5
56666	5
62360	5
79788	5
58908	5
76003	5
11656	5
74276	5
297942	5
62913	6
87075	6

Results with 7 (serious) and 8 (critical) performance grades.

Pipe segments with 7 (serious) and 8 (critical) performance grades are summarized in table G23-7.

Table G23-7. Segments with 7 (serious) and 8 (critical) performance grades.

PIPEiD	Model	Module
43323	7	Blockage
75094	7	Blockage
297943	7	Blockage
63115	7	Blockage
11951	7	Blockage
63147	8	Blockage

Case Studies

Table G23-8. PIPEiD 63147

Parameter	Unit	Value
PipeID	ID	63147
Pipe Size	Inches	6
Pipe Length	Feet	1278

Pipe Material	Type	Cast Iron
Pipe Slope	%	0
Pipe Age	Years	63
Pipe Location	Type	Building
Pipe Shape	Type	Circular

Index output: 8 (Critical)

Module with maximum result: Blockage

Reason: high age, small diameter, high length

Discussion: This high aged (63 years) Cast Iron pipe is prone to blockage issues due to its age, diameter, and length.

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The preliminary results for gravity pipes suggest that the expected remaining life of these pipes is 85 years. Results of the time-dependent performance prediction are summarized in figures G23-3 and G23-4.

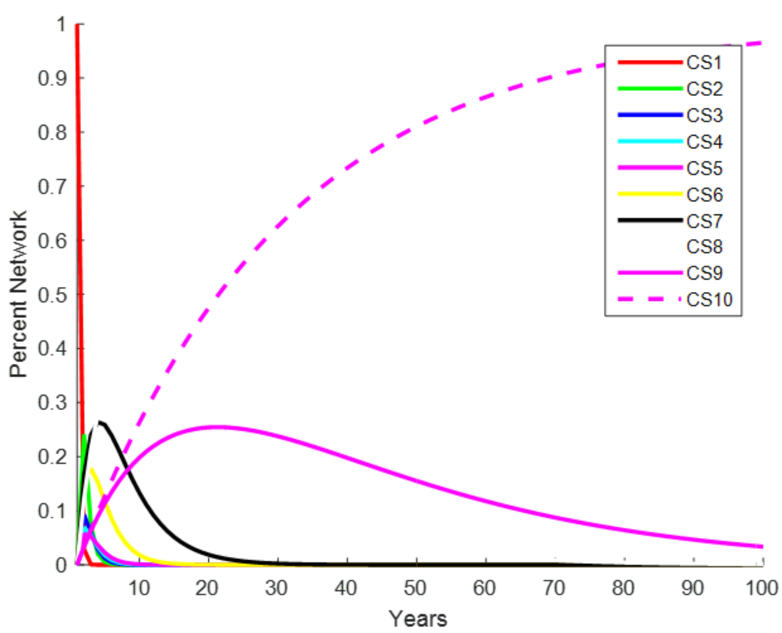

Figure G23-3. Preliminary State Dependent Performance Prediction Results

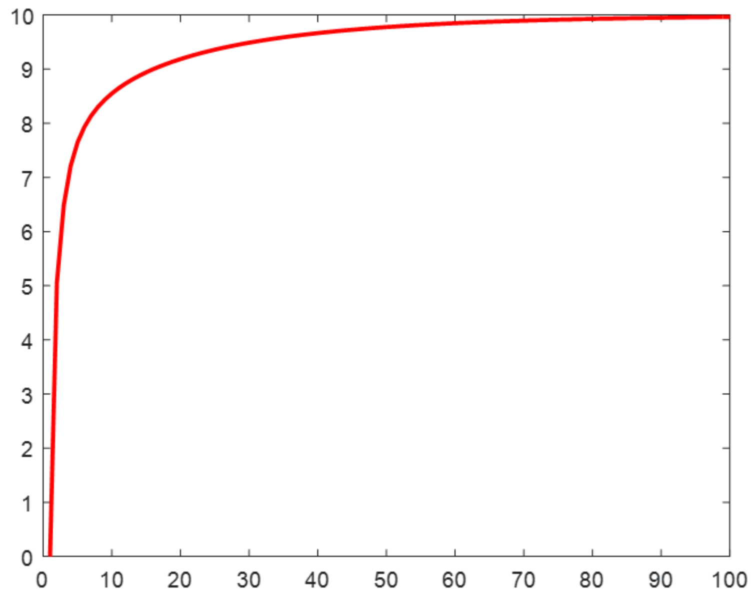

Figure G23-4. Preliminary State Dependent Performance Prediction Results

Appendix G24 – Utility #24 Force Main Piloting

The research team has been piloting the developed force main performance index with the GIS, data received from participating utility #24). These records contain data for 17031 pipe segments. 301 of this pipe were randomly selected to be evaluated. Extracted data from utility records are summarized in Table G24-1.

Table G24-1. Parameters Extracted from Utility Data

Number	Parameter	Source
1	Break <5 Years	GIS Database
2	Cathodic Protection	GIS Database
3	External Coating	GIS Database
4	Foreign Anode Distance	GIS Database
5	H2S	GIS Database
6	Node Length	GIS Database
7	Pipe Age	GIS Database
8	Pipe Depth	GIS Database
9	Pipe Diameter	GIS Database
10	Pipe Joint Type	GIS Database
11	Pipe Lining	GIS Database
12	Pipe Location	GIS Database
13	Pipe Material	GIS Database
14	Pipe Shape	GIS Database
15	Proximity to Trees	GIS Database
16	Stray Currents	GIS Database
17	Tidal Influences	GIS Database
18	Wall Thickness	GIS Database
19	Gas Pockets	GIS Database
20	Factor of Safety Left	GIS Database

Performance Index Piloting Results Discussion

A focused dataset of 301 pipes was selected to further calibrate the index this dataset includes the pipe samples with the highest and lowest ranges of the parameters and the pipe segments with the greatest results differences from the previous pass. The ranges and the number of pipe segment selected for the focused calibration dataset are summarized at Table G24-2.

Table G24-2. Focused Calibration Dataset.

Number	Parameter	Unit	Low Range	High Range
1	Break <5 Years	Yes/No	No	
2	Cathodic Protection	Yes/No	No	Yes
3	External Coating	Yes/No	No	
4	Foreign Anode Distance	Feet	0	100
5	H2S	Ppm	0	500
6	Node Length	Feet	1.3	2971
7	Pipe Age	Years	2	71
8	Pipe Depth	Feet	0	115
9	Pipe Diameter	Inches	2	48
10	Pipe Joint Type	Type	Push-On	Flanged
11	Pipe Lining	Yes/No	No	Yes
12	Pipe Location	Type	Field, Backyard, Easement, Local Road, Highway, Railroad	
13	Pipe Material	Type	AC, CAS, DIP, HDPE, PCCP, PVC, RCP,	
14	Pipe Shape	Type	Circular	
15	Proximity to Trees	Feet	1	100
16	Stray Currents	Yes/No	No	Yes
17	Tidal Influences	Yes/No	No	Yes
18	Wall Thickness	%	40	80
19	Gas Pockets	Number	0	7
20	Factor of Safety Left	%	1	12

After the model run with the dataset, the results are further investigated. Table G24-2 summarize the overall results for the focused dataset. The performance of the pipes evaluated ranges from 1 (excellent) to 4 (satisfactory). Following section discuss the results.

Table G24-2. Piloting Results

Total Number of Segments	Segments in Condition (1)	Segments in Condition (2)	Segments in Condition (3)	Segments in Condition (4)	Segments in Condition (5)	Segments in Condition (6)	Segments in Condition (7)	Segments in Condition (8)	Segments in Condition (9)	Segments in Condition (10)
301	53	13	46	118	12	8	24	22	1	3
100%	17.61	4.32%	15.28	39.20	3.99%	2.66%	7.97%	7.31%	0.33%	1.00%

	%		%	%						

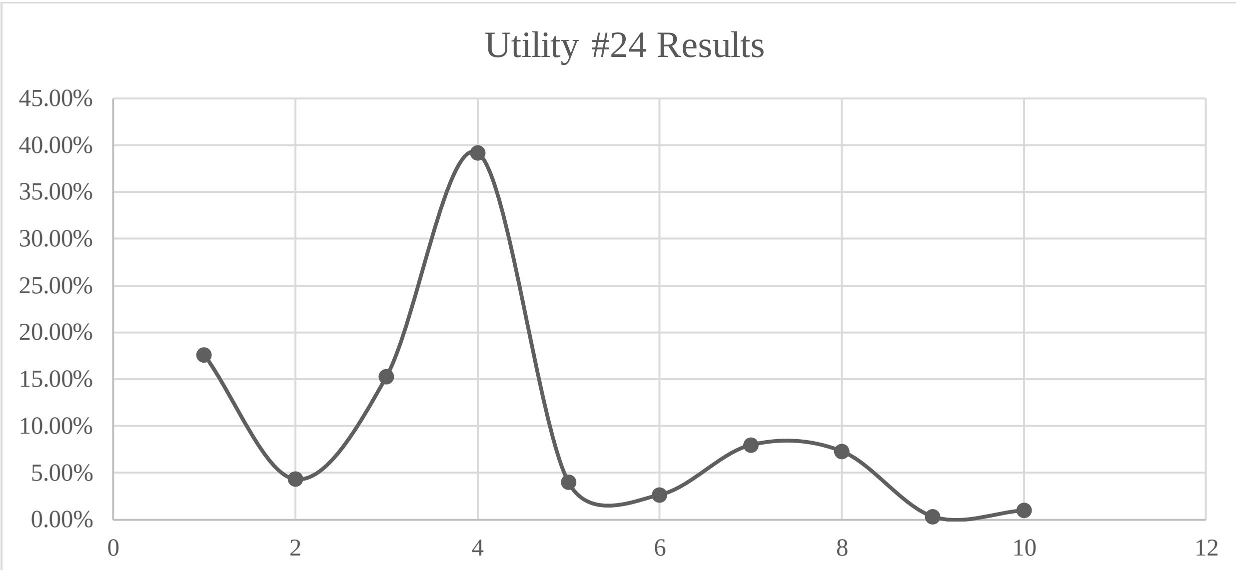

Figure G24-1. Utility #24 Results

Results with 1 (excellent) and 2 (very good) performance grade

Table G24-4 discuss summarize pipes with 1 (excellent) and 2 (very good) performance grade.

Table G24-4. Segments with 1 (excellent) and 2 (very good) performance grades

PIPEiD	Model
30601733	1
30601756	1
30601757	1
30601763	1
30601764	1
30601765	1
30601766	1
30601767	1
30601768	1
30601769	1
30601770	1
30601771	1
30601772	1
30601773	1
30601774	1

30601775	1
30601776	1
30601777	1
30601778	1
30601779	1
30601782	1
30601783	1
30602057	1
30602060	1
30602061	1
30602066	1
30602067	1
30602068	1
30602273	1
30602278	1
30602279	1
30602285	1
30602309	1
30602310	1
30602311	1
30602506	1
30602510	1
30602520	1
30602521	1
30602528	1
30602529	1
30602530	1
30602531	1
30602839	1
30602841	1
30602842	1
30602843	1
30602844	1
30602845	1
30602854	1
30602869	1
30602870	1
30602872	1
30602873	2
30602874	2
30602875	2
30602876	2

30602877	2
30602878	2
30602879	2
30602880	2
30602881	2
30602882	2
30602883	2
30602884	2
30602885	2

Results with 3 (good) and 4 (satisfactory) performance grades.

Pipe segments with 3 (good) and 4 (Satisfactory) performance grades are summarized in table G24-5.

Table G24-5. Segments with 3 (good) and 4 (Satisfactory) performance grades.

PIPEiD	Model
30601726	4
30601727	4
30601728	4
30601730	4
30601732	4
30601734	4
30601736	4
30601738	4
30601742	3
30601743	4
30601744	4
30601745	4
30601746	4
30601747	3
30601748	3
30601749	4
30601750	4
30601751	4
30601752	3
30601753	4
30601754	3
30601755	3
30601758	3

30601784	3
30601785	3
30601786	3
30601787	3
30601788	3
30601789	3
30601790	3
30601791	3
30601792	3
30601799	4
30601800	4
30602058	4
30602059	4
30602063	4
30602064	4
30602065	4
30602070	4
30602071	4
30602072	4
30602073	4
30602074	4
30602075	4
30602076	4
30602077	4
30602078	4
30602268	3
30602269	3
30602270	3
30602271	3
30602272	3
30602274	3
30602275	3
30602276	4
30602277	3
30602281	3
30602282	4
30602283	4
30602286	3
30602289	4
30602290	4
30602291	4
30602292	4

30602293	4
30602294	4
30602295	4
30602296	4
30602297	4
30602298	4
30602299	4
30602300	4
30602313	4
30602314	4
30602319	4
30602320	4
30602321	4
30602322	4
30602323	4
30602324	4
30602325	4
30602326	4
30602327	4
30602328	4
30602329	4
30602330	4
30602331	4
30602332	4
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30602335	4
30602336	4
30602337	4
30602349	4
30602351	4
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30602354	4
30602355	4
30602356	4
30602357	4
30602358	4
30602360	4
30602361	4
30602363	4
30602459	3

30602460	4
30602461	4
30602462	3
30602463	3
30602464	4
30602465	4
30602466	4
30602467	3
30602468	4
30602469	4
30602470	4
30602471	4
30602509	4
30602511	4
30602512	4
30602513	4
30602514	4
30602515	4
30602516	4
30602518	4
30602519	4
30602522	3
30602524	3
30602525	4
30602526	4
30602527	4
30602815	4
30602816	4
30602817	4
30602836	4
30602837	4
30602840	3
30602850	4
30602851	4
30602852	4
30602853	4
30602856	4
30602857	4
30602860	4
30602861	3
30602862	3
30602863	4

30602864	4
30602865	4
30602866	4
30602867	4
30602868	3
30602886	3
30602887	3
30602888	3
30602889	3
30602890	3
30602891	3
30602892	3
30602893	3
30602894	3
30602896	3

Results with 5 (fair) and 6 (poor) performance grades.

Pipe segments with 5 (fair) and 6 (poor) performance grade are summarized in table G24-6.

Table G24-6. Segments with 5 (fair) and 6 (poor) performance grades.

PIPEiD	Model
30601801	5
30601802	5
30602062	5
30602284	5
30602287	5
30602288	5
30602338	6
30602339	6
30602340	6
30602341	6
30602342	6
30602343	6
30602344	6
30602345	6
30602504	5
30602505	5
30602507	5
30602508	5
30602523	5

30602855	5

Results with 7 (serious) and 8 (critical) performance grades.

Pipe segments with 7 (serious) and 8 (critical) performance grades are summarized in table G24-7.

Table G24-7. Segments with 7 (serious) and 8 (critical) performance grades.

PIPEiD	Model
30602838	7
30602307	8
30602308	8
30601729	7
30601731	7
30601759	7
30601761	7
30601762	7
30601780	7
30601781	7
30602301	7
30602302	7
30602303	7
30602304	7
30602305	7
30602306	7
30602316	7
30602317	7
30602318	7
30602346	7
30602347	7
30602348	7
30602350	7
30602472	7
30602473	7
30602474	7
30602475	8
30602476	8
30602818	8
30602819	8
30602820	8

30602821	8
30602822	8
30602823	8
30602824	8
30602825	8
30602826	8
30602827	8
30602828	8
30602829	8
30602830	8
30602831	8
30602832	8
30602833	8
30602834	8
30602835	8

Results with 9 (failure) and 10 (failed) performance grades.

Pipe segments with 9 (failure) and 10 (failed) performance grades are summarized in table G24-8.

Table G24-8. Segments with 9 (failure) and 10 (failed) performance grades.

PIPEiD	Model
30602858	9
30602846	10
30602847	10
30602859	10

Table G24-9. Pipe Segment SF-031-4972

Number	Parameter	Value	Unit
1	PIPEiD	SF-031-4972	ID
2	Break <5 Years	No	Yes/No
3	Cathodic Protection	No	Yes/No
4	External Coating	No	Yes/No
5	Flow Velocity	Unknown	Ft/Sec
6	Foreign Anode Distance	33	Ft.
7	Ground Cover	Gravel	Type
8	H2S	Unknown	ppm

9	Live Load	High	Type
10	Node Length	356.32	Feet
11	Operating Pressure	Unknown	PSI
12	Pipe Age	36	Years
13	Pipe Break	No	Yes/No
14	Pipe Depth	10	Feet
15	Pipe Diameter	8	Inch
16	Pipe Joint Type	Unknown	Type
17	Pipe Lining	No	Yes/No
18	Pipe Location	Railroad	Type
19	Pipe Material	Ductile Iron	Type
20	Pipe Renewal	No	Yes/No
21	Pipe Shape	Circular	Type
22	Pipe Slope	Unknown	%
23	Proximity to Trees	30	Feet
24	Stray Currents	Yes	Yes/No
25	Tidal Influences	No	Yes/No
26	Wall Thickness	Unknown	%
27	Gas Pockets	Unknown	Number
28	Factor of Safety Left	Unknown	Factor

Index output: 10 (failed)

Module with maximum result: External Corrosion

Reason: Moderate age, under railroad, and possible stray current

Discussion: This ductile iron pipe is prone to external corrosion issues due to its moderate age (36 years) and location (under railroad).

Table G24-10. Pipe Segment NF-153-291

Number	Parameter	Value	Unit
1	Break <5 Years	No	Yes/No
2	Cathodic Protection	No	Yes/No
3	External Coating	No	Yes/No
4	Flow Velocity	Unknown	Ft/Sec
5	Foreign Anode Distance	0	Ft.
6	Ground Cover	Gravel	Type
7	H2S	Unknown	ppm
8	Live Load	Low	Type

9	Node Length	36.5	Feet
10	Operating Pressure	Unknown	PSI
11	Pipe Age	6	Years
12	Pipe Break	No	Yes/No
13	Pipe Depth	3	Feet
14	Pipe Diameter	24	Inch
15	Pipe Joint Type	Unknown	Type
16	PIPEiD	NF-153-291	ID
17	Pipe Lining	No	Yes/No
18	Pipe Location	Right of Way	Type
19	Pipe Material	Ductile Iron	Type
20	Pipe Renewal	No	Yes/No
21	Pipe Shape	Circular	Type
22	Pipe Slope	Unknown	%
23	Proximity to Trees	150	Feet
24	Stray Currents	No	Yes/No
25	Tidal Influences	No	Yes/No
26	Wall Thickness	Unknown	%
27	Gas Pockets	17	Number
28	Factor of Safety Left	5.28	Factor

Index output: 10 (failed)

Module with maximum result: Blockage

Reason: high age, high length

Discussion: This ductile iron pipe is prone to internal corrosion due to high number of gas pockets.

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The preliminary results for gravity pipes suggest that the expected remaining life of these pipes is 98 years. Results of the time-dependent performance prediction are summarized in figures G24-2 and G24-3.

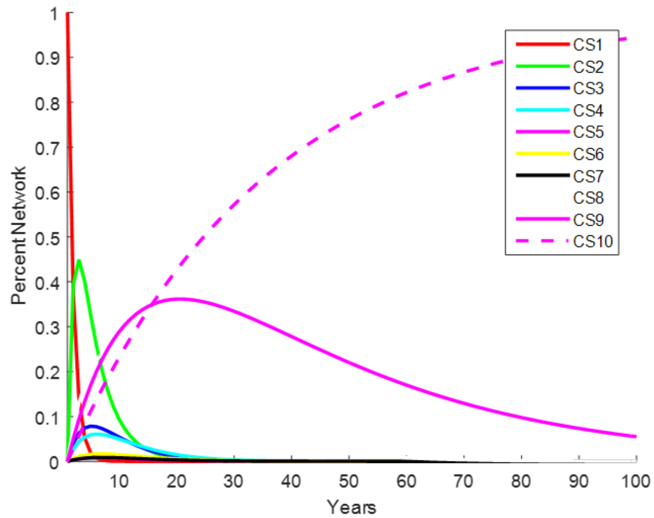

Figure G24-2. Preliminary State Dependent Performance Prediction Results

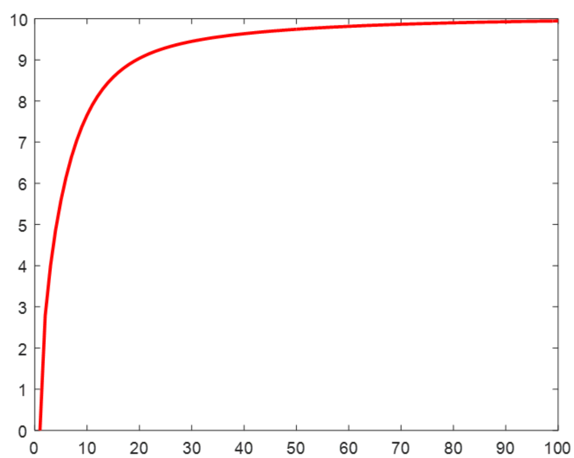

Figure G24-3. Preliminary State Dependent Performance Prediction Results

Appendix G25 – Utility #25 Force Main Piloting Results

The research team has been piloting the developed force main performance index with the data received from participating utility #25. These records contain data for 175 force main pipe segments. All of these pipes was selected to be evaluated. Extracted data from utility records are summarized in Table G25-3.

Table G25-3. Parameters Extracted from Utility Data

Parameter	Source
Pipe Age	Geodatabase
Pipe Diameter	Geodatabase
Pipe Length	Geodatabase
Pipe Location	Geodatabase
Pipe Slope	Geodatabase
Pipe Shape	Geodatabase
Pipe Material	Geodatabase

Performance Index Piloting Results Discussion

The ranges of the parameters for the piloting input dataset is summarized at table G25-4.

Table G25-4. Piloting Dataset.

	Low Range	High Range	Unit
Pipe Age	5.95	61.91	Years
Pipe Diameter	2	54	Inches
Pipe Length	10.99	10773.87	Feet
Pipe Location	Back yard/Front yard	NA	Type
Pipe Slope	0	97	% Grade
Pipe Shape	Circular		Type
Pipe Material	CI, DI, RCP, PVC, Variable		Type

After the index was run with the dataset, the results are further investigated. Table G25-5 summarizes the overall results for the focused dataset. The performance of the pipes evaluated ranges from 1 (excellent) to 4 (satisfactory). Following section discuss the results.

Table G25-5. Piloting Results

Total Number of Segments	Segments in Condition (1)	Segments in Condition (2)	Segments in Condition (3)	Segments in Condition (4)	Segments in Condition (5)	Segments in Condition (6)	Segments in Condition (7)	Segments in Condition (8)	Segments in Condition (9)	Segments in Condition (10)
175	15	25	27	21	18	10	13	16	19	11
100%	8.57%	14.29 %	15.43 %	12.00 %	10.29 %	5.71%	7.43%	9.14%	10.86 %	6.29%

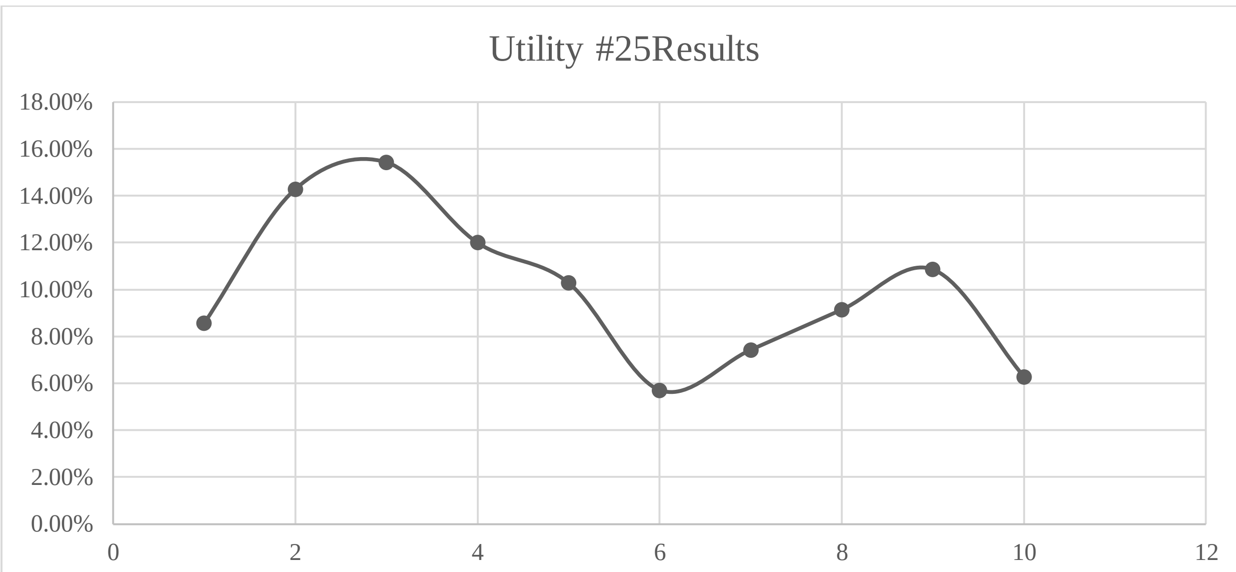

Figure G25-1. Utility #25 Results

Results with 1 (excellent) and 2 (very good) performance grades

Table G25-4 discuss summarize pipes with 1 (excellent) and 2 (very good) performance grades.

Table G25-4. Segments with 1 (excellent) and 2 (very good) performance grades

PIPEiD	Model
62887	2
62888	2
62889	2
62890	2

62916	2
62917	2
62990	2
62991	2
63538	2
63717	2
63840	2
64230	2
64297	2
64301	2
64302	2
64303	2
64304	2
64305	2
64306	2
64359	2
64364	2
64365	2
64367	2
64368	2
64369	2
64371	1
64375	1
64376	1
64377	1
64380	1
64381	1
64388	1
64412	1
65075	1
65391	1
65649	1
65862	1
66682	1
66683	1
72606	1

Results with 3 (good) and 4 (satisfactory) performance grades.

Pipe segments with 3 (good) and 4 (Satisfactory) performance grades are summarized in table G25-5.

Table G25-5. Segments with 3 (good) and 4 (Satisfactory) performance grades.

PIPEiD	Model
59780	4
59783	4
59784	3
59823	4
59824	3
60113	4
60245	4
60585	4
60586	4
60587	4
60588	4
60589	4
60590	3
60604	4
60606	4
60614	4
60616	4
60777	3
60778	4
60817	4
60818	4
60819	3
60820	3
60821	3
61449	3
61451	3
61462	4
61960	3
62134	3
62144	3
62146	3
62190	4
62193	3
62194	3

62195	3
62779	3
62780	4
62781	3
62785	3
62786	4
62787	3
62788	3
62789	3
62790	3
62837	3
62882	3
62883	3
62884	3

Results with 5 (fair) and 6 (poor) performance grades.

Pipe segments with 5 (fair) and 6 (poor) performance grades are summarized in table G25-6.

Table G25-6. Segments with 5 (fair) and 6 (poor) performance grades.

PIPEiD	Model
55830	6
56641	5
56642	5
58383	5
59717	5
59732	5
59733	6
59734	5
59735	5
59736	5
59737	6
59775	5
59779	5
59781	6
59785	5
59786	5
59787	5
59788	5
59789	5
59790	5

60615	6
61481	5
62143	6
64271	6
64385	6
66545	5
66546	6
72607	6

Results with 7 (serious) and 8 (critical) performance grades.

Pipe segments with 7 (serious) and 8 (critical) performance grades are summarized in table G25-7.

Table G25-7. Segments with 7 (serious) and 8 (critical) performance grades.

PIPEiD	Model
59776	8
60608	8
62836	7
62878	8
62886	8
64363	7
64373	8
64374	8
64384	8
64802	7
65034	8
65035	8
65071	7
65072	8
65073	8
65076	8
65077	7
65078	7
65080	7
65081	8
65082	7
65141	7
65248	8
65249	7

65250	7
65650	8
65863	8
65864	7
66238	7

Results with 9 (failure) and 10 (failed) performance grades.

Pipe segments with 9 (failure) and 10 (failed) performance grade are summarized in table G25-8.

Table G25-8. Segments with 9 (failure) and 10 (failed) performance grades.

PIPEiD	Model
59825	10
60593	9
60594	9
60595	9
60596	10
60600	10
60601	9
60605	10
60609	10
60611	9
60612	10
60613	9
60617	10
60618	9
60619	9
60816	9
61446	10
61447	9
61959	9
62147	9
62161	10
62186	9
62778	9
62784	9
62791	10
62832	9
62833	9
62834	9
62835	9

64298	10

Table G25-9. Pipe Segment #64385

Parameter	Value	Unit
PIPEiD	64385	ID
Pipe Age	24.46	Year
Pipe Diameter	4	Inches
Pipe Length	441.24	Feet
Pipe Location	Back Yard	Type
Pipe Slope	1.7	% Grade
Pipe Shape	Unknown	Type
Pipe Material	Unknown	Type

Index output: 6 (bad)

Module with maximum result: Blockage

Reason: Small diameter, moderate length, moderate slope

Discussion: This moderate aged, pipe with small diameter, moderate length, and moderate slope scored 3 (good). The parameters indicate that there might be some blockage issues.

Table G25-10. Pipe Segments # 59776

Parameter	Value	Unit
PIPEiD	59776	ID
Pipe Age	47.71	Year
Pipe Diameter	24	Inches
Pipe Length	539.99	Feet
Pipe Location	Back Yard	Type
Pipe Slope	1.5	% Grade
Pipe Shape	Circular	Type
Pipe Material	Cast Iron	Type

Index output: 8 (v.poor)

Module with maximum result: Blockage

Reason: moderate diameter, high length

Table G25-11. Pipe Segments # 64298

Parameter	Value	Unit
PIPEiD	64298	ID
Pipe Age	61.91	Year
Pipe Diameter	16	Inches
Pipe Length	4251.73	Feet
Pipe Location	Back Yard	Type
Pipe Slope	0	% Grade
Pipe Shape	Circular	Type
Pipe Material	Cast Iron	Type

Index output: 10 (failed)

Module with maximum result: Integrity

Reason: High age.

Discussion: This cast iron pipe with high age scored 10 (failed). The fact that this pipe has a higher age indicates there might be integrity issues. Another module which scored high is the blockage module due to a high length of the pipe segment.

Prediction Model Piloting and Discussion

The data received from participating utility was utilized to illustrate the implementation of the performance prediction model and present preliminary results. The preliminary results for gravity pipes suggest that the expected remaining life of these pipes is 58 years. Results of the time dependent performance prediction is summarized in figures 2 and 3.

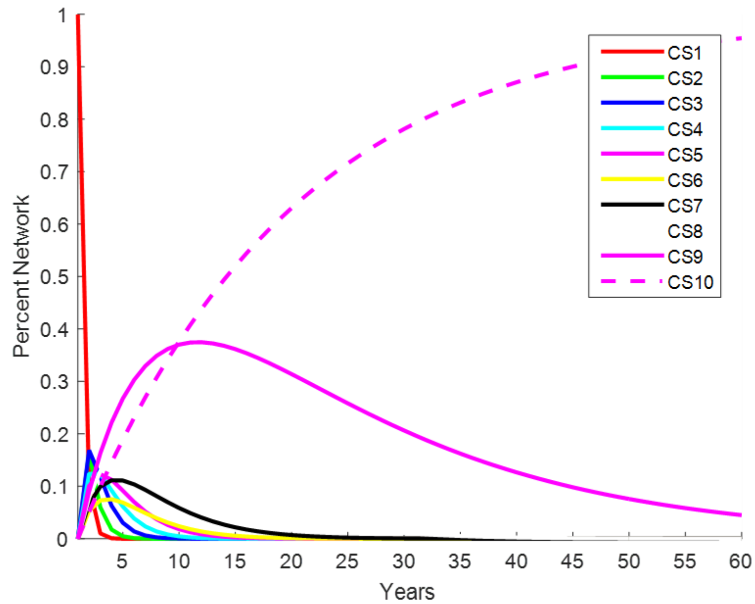

Figure G25-2. Preliminary State Dependent Performance Prediction Results

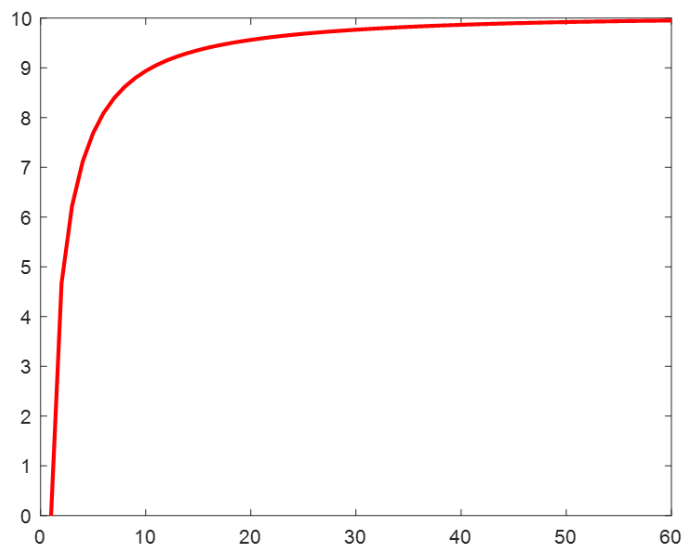

Figure G25-3. Preliminary State Dependent Performance Prediction Results

Appendix H – Pipe Classes

Table H1. Pipe Classes According to Construction Era

	Material	Era 1	Era 2	Era 3	Era 4	Era 5	Era 6
1	Asbestos Cement	Pre 1978	1978 to 2002	2002 to present			
2	Bolted NR Concrete	Pre 1904	1904 to 1930	1930 to 1970	1970 to 1980	1980 to present	
3	Cast Iron	1804 to 1925	1926 to 1949	1949 to 1957	1958 to 1978		
4	Corrugated Metal	1896 to 1900	1901 to 1920	1921 to 1947	1947 to 1956	1957 to 1976	1976 to present
5	Ductile Iron	1948 to 1958	1959 to 1978	1979 to 2004	2004 to present		
6	Fiber Glass	Pre 1959	1960 to 1968	1969 to 1996	1996 to present		
7	Glass Reinforcement	Pre 1959	1960 to 1968	1969 to 1996	1996 to present		
8	HDPE	pre 1950	1951 to 1960	1961 to 1980	1981 to 1990	1990 to 2002	2002 to present
9	Orangeburg	Pre 1948	post 1948				
10	PCCP	1942 to 1955	1955 to 1963	1963 to 1970	1971 to 1980	1981 to 1991	1991 to present
11	PE	pre 1950	1951 to 1960	1961 to 1980	1981 to 1990	1990 to 2002	2002 to present
12	PP						
13	PVC	1952 to 1972	1972 to 1985	1985 to 1997	1997 to present		
14	Reinforced Concrete	Pre 1904	1904 to 1930	1930 to 1970	1970 to 1980	1980 to present	
15	Steel	1896 to 1900	1901 to 1920	1921 to 1947	1947 to 1956	1957 to 1976	1976 to present
16	Truss Pipe						

17	Unbolted NR Concrete	Pre 1904	1904 to 1930	1930 to 1970	1970 to 1980	1980 to present	
18	Vitrified Clay	Pre 1915	1915 to 1955	1955 to 1975	1975 to 1983	1983 to present	
19	Brick	Pre 1973	1973 to 1999	1999 to present			

Table H2. Pipe Classes According to Size

	Material	Size 1	Size 2	Size 3	Size 4
1	Asbestos Cement	4 to 16	16 to 42		
2	Bolted NR Concrete	4 to 12	15 to 36		
3	Cast Iron	3 to 12	14 to 30	36 and above	
4	Corrugated Metal	4 to 12	18 to 36	36 to 84	84 to 144
5	Ductile Iron	3 to 12	14 to 30	36 and above	
6	Fiber Glass	8 to 27	30 to 156		
7	Glass Reinforcement	54 to 144			
8	HDPE	4 to 12	15 to 24	24 to 60	60 to 72
9	Orangeburg	4 to 16	16 to 42		
10	PCCP	16 to 30	36 to 66	72 and above	
11	PE	4 to 12	15 to 24	24 to 60	60 to 72
12	PP				
13	PVC	2 to 15	18 to 36	36 and above	
14	Reinforced Concrete	12 to 30	36 to 108	108 to 180	
15	Steel	4 to 12	18 to 36	36 to 84	84 to 144
16	Truss Pipe				
17	Unbolted NR Concrete	4 to 12	15 to 36		
18	Vitrified Clay	4 to 24	27 to 42		

19	Brick	8 to 40	above 40		

Table H3. Pipe Classes According to Shape

	Material	Shape 1	Shape 2	Shape 3	Shape 4	Shape 5	Shape 6	Shape 7	Shape 8	Shape 9
1	Asbestos Cement	Circular	horizontal elliptical	vertical elliptical	arch	rectangular				
2	Bolted NR Concrete	Circular	horizontal elliptical	vertical elliptical	arch	rectangular				
3	Cast Iron	Circular								
4	Corrugated Metal	Circular								
5	Ductile Iron	Circular								
6	Fiber Glass	Circular	horizontal elliptical	vertical elliptical	arch	rectangular				
7	Glass Reinforcement	Circular	Arched with flat bottom	Barrel	Egg Shaped	Horseshoe	Oval or Elliptical	Rectangle	Trapezoidal	U shaped
8	HDPE	Circular								
9	Orangeburg	Circular								
10	PCCP	Circular	horizontal elliptical	vertical elliptical	arch	rectangular				
11	PE	Circular								
12	PP	Circular								
13	PVC	Circular								
14	Reinforced Concrete	Circular	horizontal elliptical	vertical elliptical	arch	rectangular				
15	Steel	Circular								
16	Truss Pipe	Circular								
17	Unbolted NR Concrete	Circular	horizontal elliptical	vertical elliptical	arch	rectangular				
18	Vitrified Clay	Circular								

19	Brick	Circular	Arched with flat bottom	Barrel	Egg Shaped	Horseshoe	Oval or Elliptical	Rectangle	Trapezoidal	U shaped

Appendix I – MHA Algorithm

```
x= 5000;
aa= 23;
% generate initial values of Pij
data = [7   529 0   1
9   378 0   1660
11  493 0   0
12  978 0   0
15  0   0   665
16  1759    0   228
18  533 0   550
20  2667    677 760
22  319 611 0
23  1948    289 281
24  1606    0   0
25  477 0   0
27  745 262 0
28  851 0   0
29  810 216 0
30  1356    0   0
32  2062    0   442
33  962 0   111
35  1286    0   0
42  273 0   246
46  244 113 0
48  66  0   0
51  1216    180 0
];
count=0;
cpos=1;
% data matrix setup
[nrows,ncols]=size(data);
age=data(:,1);
number_pjt=data(:,2:ncols);
sumrow=data(:,ncols);
% assign initial value to Pij from random number generator.
%Sum of Pij must be equal 1 and each Pij must be in the range [0,1]
N11=rand(1);
N12=0.1+0.8*rand(1); %rand(1);
temp12=1-(exp(N12)/(1+exp(N12)));
N13=-1*log(1/temp12-1)*(1+rand(1));
N23=randn(1);
p12=exp(N12)/(1+exp(N12))
p13=exp(N13)/(1+exp(N13))
p23=exp(N23)/(1+exp(N23))
p11=1-(p12+p13); p22=1-p23;
%Initiate variance-covariance matrix with arbitrary values
cova1=[0.2 0 0;0 0.5 0;0 0 0.15];
cova=cova1;
%Initiate iteration start value
ite=2;
while ite<=x
if ite>(x-aa)
%cova=cova2;
end
```

```
% record old values of Pij
oldN11=N11;
oldN12=N12;
oldN13=N13;
oldN23=N23;
oldp11=p11;
oldp12=p12;
oldp13=p13;
oldp22=p22;
oldp23=p23;
% generate new values of Pij
NN=randn(3);
NN=NN(1,:);
N12=oldN12+cova(1,:)*NN';
N13=oldN13+cova(2,:)*NN';
N23=oldN23+cova(3,:)*NN';
p12=exp(N12)/(1+exp(N12));
p13=exp(N13)/(1+exp(N13));
p23=exp(N23)/(1+exp(N23));
p11=1-(p12+p13);
p22=1-p23;
% check that sum of Pij must be 1
if p11<0
prob_value=0; %reject new sample
else
%r_new=logpost2(nrows,age,number_pjt,p11,p12,p13,p22,p23);
p33=1;
for i=1:nrows %nrows
    p1t(i,1)=1;
    p2t(i,1)=0.0;
    p3t(i,1)=0.0;
for j=1:(age(i))
    p1t(i,j+1)=p11*p1t(i,j);
p2t(i,j+1)=p12*p1t(i,j)+p22*p2t(i,j);
p3t(i,j+1)=p13*p1t(i,j)+p23*p2t(i,j)+p33*p3t(i,j);
end % j
log_pjt(i,1)=log(p1t(i,age(i)+1));
log_pjt(i,2)=log(p2t(i,age(i)+1));
log_pjt(i,3)=log(p3t(i,age(i)+1));
loglike(i)=number_pjt(i,:)*log_pjt(i,:)';
end % i,nrows
y=sum(loglike);
%r_old=logpost2(nrows,age,number_pjt,oldp11,oldp12,oldp13,oldp22,oldp23);
oldp33=1;
for i=1:nrows %nrows
    oldp1t(i,1)=1;
    oldp2t(i,1)=0.0;
    oldp3t(i,1)=0.0;
for j=1:(age(i))
    oldp1t(i,j+1)=oldp11*oldp1t(i,j);
oldp2t(i,j+1)=oldp12*oldp1t(i,j)+oldp22*oldp2t(i,j);
oldp3t(i,j+1)=oldp13*oldp1t(i,j)+oldp23*p2t(i,j)+oldp33*oldp3t(i,j);
end % j
oldlog_pjt(i,1)=log(oldp1t(i,age(i)+1));
oldlog_pjt(i,2)=log(oldp2t(i,age(i)+1));
oldlog_pjt(i,3)=log(oldp3t(i,age(i)+1));
oldloglike(i)=number_pjt(i,:)*oldlog_pjt(i,:)';
```

```
end
yold=sum(oldloglike);
prob_value=exp(y-yold);
end
%Generate a random uniform number in [0,1] to check the new Pij
Ucheck=rand(1);
if (prob_value > 1)||(prob_value>Ucheck) % accepted
    count=count+1;
last_accept=ite;
if (count/x)>0.234
% stoploop=ite
ite=x;
end
else % Not accepted and return to old values Pij
N11=oldN11;
N12=oldN12;
N13=oldN13;
N23=oldN23;
p11=oldp11;
p12=oldp12;
p13=oldp13;
p22=oldp22;
p23=oldp23;
end
if ite>(x-aa)
pp11(cpos)=p11;
pp12(cpos)=p12;
pp13(cpos)=p13;
pp22(cpos)=p22;
pp23(cpos)=p23;

cpos=cpos+1;
end %if ite
ite=ite+1;

end % while ite
if p22>=0.99;
    p22=.099;
    p23=1-p22;
end
yy=[pp11' pp12' pp13' pp22' pp23'];
[row_y,col_y]=size(yy);
number_of_acceptance=count
acceptance_rate=count/x
disp('the last accepted is: ')
disp(last_accept);
%kk=yy(row_y-5:row_y,:)
for kk=1:col_y % compute mean value
    y(kk)=sum(yy(:,kk))/(row_y);
end % for kk
disp(y);
y=yy;%(row_y-100:row_y,:);
```

Appendix J- Ordered Logit Algorithm

Script to run the functions

```
clear
clc
load('trinkercreek2.mat');
perf = ordinal(Integrity);
X=[age, depth]
 [B,dev,stats] =
mnrfit(X,perf,'model','ordinal','Interactions','off','Link','logit');
[pihat,dlow,dhi] = mnrval(B,a,stats,'model','ordinal','type','cumulative');
```

Functions

```
function [b,dev,stats] = mnrfit2(x,y,varargin)
%MNRFIT Fit a nominal or ordinal multinomial regression model.
%   B = MNRFIT(X,Y) fits a nominal multinomial logistic regression model for
%   the response Y and predictor matrix X.  X is an N-by-P design matrix with
%   N observations on P predictor variables.  Y is an N-by-K matrix, where
%   Y(I,J) is the number of outcomes of the multinomial category J for the
%   predictor combinations given by X(I,:).  The sample sizes for each
%   observation (rows of X and Y) are given by the row sums SUM(Y,2).
%   Alternatively, Y can be an N element column vector of scalar integers
from
%   1 to K indicating the value of the response for each observation, and all
%   sample sizes are taken to be 1.  MNRFIT automatically includes intercept
%   (constant) terms; do not enter a column of ones directly into X.
%
%   The result B is a (P+1)-by-(K-1) matrix of estimates, where each column
%   corresponds to the estimated intercept term and predictor coefficients,
%   one for each of the first (K-1) multinomial categories.  The estimates
for
%   the K-th category are taken to be zero.
%
%   MNRFIT treats NaNs in X and Y as missing data, and removes the
%   corresponding observations.
%
%   B = MMNRFIT(X,Y,'PARAM1',val1,'PARAM2',val2,...) allows you to
%   specify optional parameter name/value pairs to control the model fit.
%   Parameters are:
%
%      'model' - the type of model to fit, one of the text strings 'nominal'
%         (the default), 'ordinal', or 'hierarchical'.
%
%      'interactions' - determines whether the model includes an interaction
%         between the multinomial categories and the coefficients.  Specify
as
%         'off' to fit a model with a common set of coefficients for the
%         predictor variables, across all multinomial categories.  This is
%         often described as "parallel regression".  Specify as 'on' to fit a
%         model with different coefficients across categories.  In all cases,
%         the model has different intercepts across categories.  Thus, B is a
%         vector containing K-1+P coefficient estimates when 'interaction' is
```

```
%         'off', and a (P+1)-by-(K-1) matrix when it is 'on'. The default is
%         'off' for ordinal models, and 'on' for nominal and hierarchical
%         models.
%
%      'link' - the link function to use for ordinal and hierarchical models.
%         The link function defines the relationship g(mu_ij) = x_i*b_j
%         between the mean response for the i-th observation in the j-th
%         category, mu_ij, and the linear combination of predictors x_i*b_j.
%         Specify the link parameter value as one of the text strings 'logit'
%         (the default), 'probit', 'comploglog', or 'loglog'.  You may not
%         specify the 'link' parameter for nominal models; these always use a
%         multivariate logistic link.
%
%      'estdisp' - specify as 'on' to estimate a dispersion parameter for
%         the multinomial distribution in computing standard errors, or 'off'
%         (the default) to use the theoretical dispersion value of 1.
%
%   [B,DEV] = MNRFIT(...) returns the deviance of the fit.
%
%   [B,DEV,STATS] = MNRFIT(...) returns a structure that contains the
%   following fields:
%       'dfe'       degrees of freedom for error
%       's'         theoretical or estimated dispersion parameter
%       'sfit'      estimated dispersion parameter
%       'se'        standard errors of coefficient estimates B
%       'coeffcorr' correlation matrix for B
%       'covb'      estimated covariance matrix for B
%       't'         t statistics for B
%       'p'         p-values for B
%       'resid'     residuals
%       'residp'    Pearson residuals
%       'residd'    deviance residuals
%
%   See also MNRVAL, GLMFIT, GLMVAL, REGRESS, REGSTATS.

%   References:
%      [1] McCullagh, P., and J.A. Nelder (1990) Generalized Linear
%          Models, 2nd edition, Chapman&Hall/CRC Press.


if nargin < 2
    error('stats:mnrfit:TooFewInputs', ...
          'Requires at least two input arguments.');
end

pnames = { 'model' 'interactions' 'link' 'estdisp'};
dflts =  {'nominal'             []      []      'off'};
[eid,errmsg,model,interactions,link,estdisp] = statgetargs(pnames, dflts,
varargin{:});
if ~isempty(eid)
    error(sprintf('stats:mnrfit:%s',eid),errmsg);
end

if ischar(model)
    modelNames = {'nominal','ordinal','hierarchical'};
    i = strmatch(lower(model), modelNames);
```

```
    if isempty(i)
    error('stats:mnrfit:BadModel', ...
          'The value of the ''model'' parameter must be ''nominal'',
''ordinal'', or ''hierarchical''.');
    end
    model = modelNames{i};
else
    error('stats:mnrfit:BadModel', ...
          'The value of the ''model'' parameter must be ''nominal'',
''ordinal'', or ''hierarchical''.');
end

if isempty(interactions)
    % Default is 'off' for ordinal models, 'on' for nominal or hierarchical
    parallel = strcmp(model,'ordinal');
elseif isequal(interactions,'on')
    parallel = false;
elseif isequal(interactions,'off')
    parallel = true;
elseif islogical(interactions)
    parallel = ~interactions;
else % ~islogical(interactions)
    error('stats:mnrfit:BadInteractions', ...
          'The value of the ''interactions'' parameter must be ''on'' or
''off''.');
end
if parallel && strcmp(model,'nominal')
    % A nominal model with no interactions is the same as having no
predictors.
    warning('stats:mnrfit:NominalNoInteractions', ...
            'A nominal model with no category interactions is equivalent\nto
a model with no predictor variables.');
    x = zeros(size(x,1),0,class(x));
end

dataClass = superiorfloat(x,y);

if isempty(link)
    link = 'logit';
elseif ~isempty(link) && strcmp(model,'nominal')
    error('stats:mnrfit:LinkNotAllowed', ...
          'You may not specify the ''link'' parameter for a nominal model.');
end
if ischar(link) && ismember(link, {'logit' 'probit' 'comploglog' 'loglog'})
    [emsg,flink,dlink,ilink] = stattestlink(link,dataClass);
else
    error('stats:mnrfit:BadLink', ...
          'The value of the ''link'' parameter must be ''logit'', ''probit'',
''comploglog'', or ''loglog''.');
end

if isequal(estdisp,'on')
    estdisp = true;
elseif isequal(estdisp,'off')
    estdisp = false;
elseif ~islogical(estdisp)
```

```
    error('stats:mnrfit:BadEstDisp', ...
          'The value of the ''estdisp'' parameter must be ''on'' or
''off''.');
end

% Remove missing values from the data.  Also turns row vectors into columns.
[anybad,wasnan,y,x] = statremovenan(y,x);
if anybad
    error('stats:mnrfit:InputSizeMismatch', ...
          'X and Y must have the same number of rows.');
end
p = size(x,2);
[n,k] = size(y);
if n == 0
    error('stats:mnrfit:NoData', ...
          'X and Y must contain at least one valid observation.');
end

if k == 1
    if min(y) < 1 || any(y ~= floor(y))
        error('stats:mnrfit:BadY', ...
             'If Y is a column vector, it must contain positive integer
category numbers.');
    end
    y = accumarray({(1:n)' y},ones(dataClass));
    k = size(y,2);
    m = ones(n,1,dataClass);
else
    m = sum(y,2);
end
if parallel
    pstar = k - 1 + p;
    dfe = n * (k-1) - pstar;
else
    pstar = p + 1;
    dfe = (n-pstar) * (k-1);
end

if strcmp(model,'hierarchical')
    if nargout < 3
        [b,dev] = hierarchicalFit(x,y,m,link,n,k,p,pstar,parallel,estdisp);
    else
        [b,dev,stats] = ...
            hierarchicalFit(x,y,m,link,n,k,p,pstar,parallel,estdisp);
    end
else
    % Set up initial estimates from the data themselves
    pi = y ./ repmat(m,1,k); % the raw percentages
    pi = pi + (1/k - pi) ./ repmat(m,1,k); % shrink towards equal
probabilities
    if strcmp(model,'nominal')
        [b,hess,pi] = nominalFit(x,y,m,pi,n,k,p,pstar,parallel);
    else % 'ordinal'
        z = cumsum(y(:,1:(k-1)),2);
        [b,hess,pi,gam] = ...
            ordinalFit(x,z,m,pi,flink,ilink,dlink,n,k,p,pstar,parallel);
```

```
    end

    % Deviance residuals - one for each vector observation of cell counts
    mu = pi .* repmat(m,1,k);
    D = zeros(size(y),dataClass);
    t = (y > 0); % avoid 0*log(0), but let (pi==0) & (y>0) happen
    D(t) = 2 * y(t) .* log(y(t) ./ mu(t));
    rd = sum(D,2);
    dev = sum(rd);

    if nargout > 2
        % The Pearson residuals in terms of y and pi are not equivalent to
        % those computed using z and gamma.  Use the appropriate version to
        % estimate dispersion.
        if strcmp(model,'nominal')
            r = y - pi .* repmat(m,1,k);
            rp = r ./ sqrt(pi .* (1 - pi) .* repmat(m,1,k));
            sigsq = ((k-1)/k) * sum(sum(rp .* rp)) ./ dfe; % bias corrected
        elseif strcmp(model,'ordinal')
            r = z - gam .* repmat(m,1,k-1);
            rp = r ./ sqrt(gam .* (1 - gam) .* repmat(m,1,k-1));
            sigsq = sum(sum(rp .* rp)) ./ dfe;
        end
        stats.beta = b;
        stats.dfe = dfe;
        if dfe > 0
            stats.sfit = sqrt(sigsq);
        else
            stats.sfit = NaN;
        end
        if estdisp
            stats.s = stats.sfit;
            rp = rp ./ stats.sfit;
        else
            stats.s = ones(dataClass);
        end
        stats.estdisp = estdisp;

        if ~isnan(stats.s) % dfe > 0 or estdisp == 'off'
            % bcov = inv(hess); bcov = (bcov + bcov')/2;
            bcov =
linsolve(hess,eye(size(hess)),struct('SYM',true,'POSDEF',true));
            if estdisp
                bcov = bcov * sigsq;
            end
            se = sqrt(diag(bcov));
            stats.covb = bcov;
            stats.coeffcorr = bcov ./ (se*se');
            if ~parallel
                se = reshape(se,pstar,k-1);
            end
            stats.se = se;
            stats.t = b ./ se;
            if estdisp
                stats.p = 2 * tcdf(-abs(stats.t), dfe);
            else
```

```
                stats.p = 2 * normcdf(-abs(stats.t));
            end
        else
            stats.se = NaN(size(b),dataClass);
            stats.coeffcorr = NaN(numel(b),dataClass);
            stats.t = NaN(size(b),dataClass);
            stats.p = NaN(size(b),dataClass);
        end
        stats.resid = r;
        stats.residp = rp;
        stats.residd = rd;
    end
end
if nargout > 2 && any(wasnan)
    stats.resid  = statinsertnan(wasnan, stats.resid);
    stats.residp = statinsertnan(wasnan, stats.residp);
    stats.residd = statinsertnan(wasnan, stats.residd);
end


%-----------------------------------------------------------------------
function [b,XWX,pi,gam] =
ordinalFit(x,z,m,pi,flink,ilink,dlink,n,k,p,pstar,parallel)

kron1 = repmat(1:k-1,pstar,1);
kron2 = repmat((1:pstar)',1,k-1);

gam = cumsum(pi(:,1:(k-1)),2);
eta = flink(gam);

% Main IRLS loop
iter = 0;
iterLim = 100;
tolpos = eps(class(pi))^(3/4);
seps = sqrt(eps); % don't depend on class
convcrit = 1e-6;
b = 0;
while iter <= iterLim
    iter = iter + 1;

    % d.gamma(i,)/d.eta(i,) is actually (k-1) by (k-1) but diagonal,
    % so can store d.mu/d.eta as n by (k-1) even though it is really
    % n by (k-1) by (k-1)
    mu = repmat(m,1,k-1) .* gam;
    deta = dlink(gam) ./ repmat(m,1,k-1); % d(eta)/d(mu)
    dmu = 1 ./ deta;  % d(mu)/d(eta)

    % Adjusted dependent variate
    Z = eta + deta.*(z - mu);

    % Tridiagonal symmetric weight matrix (scaled by m)
    diagW = dmu .* dmu .* (1./pi(:,1:(k-1)) + 1./pi(:,2:k));
    offdiagW = -(dmu(:,1:(k-2)) .* dmu(:,2:k-1)) ./ pi(:,2:(k-1));

    % Update the coefficient estimates.
```

```
    b_old = b;
    XWX = 0;
    XWZ = 0;
    for i = 1:n
        W = (1./m(i)) .* (diag(diagW(i,:)) + ...
                          diag(offdiagW(i,:),1) + diag(offdiagW(i,:),-1));
        if p > 0
            % The first step for a nonparallel model can be wild, so fit
            % a parallel model for the first iteration, regardless
            if parallel || (iter==1)
                % Do these computations, but more efficiently
                % Xstar = [eye(k-1) repmat(x(i,:),k-1,1)];
                % XWX = XWX + Xstar'*W*Xstar;
                % XWZ = XWZ + Xstar'*W*Z(i,:)';
                xi = x(i,:);
                OneW = sum(W,1);
                xOneW = xi'*OneW;
                XWX = XWX + [W      xOneW'; ...
                             xOneW  sum(OneW)*(xi'*xi)];
                XWZ = XWZ + [W; xOneW] * Z(i,:)';
            else
                xstar = [1 x(i,:)];
                % Do these computations, but more efficiently
                % XWX = XWX + kron(W, xstar'*xstar);
                % XWZ = XWZ + kron(W*Z(i,:)', xstar');
                XWX = XWX + W(kron1,kron1) .*
(xstar(1,kron2)'*xstar(1,kron2));
                WZ = Z(i,:)*W;
                XWZ = XWZ + WZ(1,kron1)' .* xstar(1,kron2)';
            end
        else
            XWX = XWX + W;
            XWZ = XWZ + W * Z(i,:)';
        end
    end
    b = XWX \ XWZ;

    % Update the linear predictors.
    eta_old = eta;
    if parallel
        if p > 0
            eta = repmat(b(1:(k-1))',n,1) + repmat(x*b(k:pstar),1,k-1);
        else
            eta = repmat(b',n,1);
        end
    else
        if iter == 1
            % the first iteration was a parallel fit, transform those
            % estimates to the equivalent non-parallel format.
            b = [b(1:k-1)'; repmat(b(k:end),1,k-1)];
        else
            % Convert from vector to the matrix format.
            b = reshape(b,pstar,k-1);
        end
        if p > 0
            eta = repmat(b(1,:),n,1) + x*b(2:pstar,:);
        else
```

```
            eta = repmat(b,n,1);
        end
    end

    % Update the predicted cumulative and category probabilities.
    for backstep = 0:10
        gam = ilink(eta);
        diffgam = diff(gam,[],2);
        pi = [gam(:,1) diffgam 1-gam(:,k-1)];

        % If all observations have positive category probabilities,
        % we can take the step as is.
        if all(pi(:) > tolpos)
            break;

        % Otherwise try a shorter step in the same direction.  eta_old is
        % feasible, even on the first iteration.
        elseif backstep < 10
            eta = eta_old + (eta - eta_old)/5;

        % If the step direction just isn't working out, force the
        % category probabilities to be positive, and make the cumulative
        % probabilities and linear predictors compatible with that.
        else
            pi = max(pi,tolpos);
            pi = pi ./ repmat(sum(pi,2),1,k);
            gam = cumsum(pi(:,1:k-1),2);
            eta = flink(gam);
            break;
        end
    end

    % Check stopping conditions.
    cvgTest = abs(b-b_old) > convcrit * max(seps, abs(b_old));
    if (~any(cvgTest(:))), break; end
end
if iter > iterLim
    warning('stats:mnrfit:IterOrEvalLimit', ...
            ['Maximum likelihood estimation did not converge.  Iteration
limit\n' ...
             'exceeded.  You may need to merge categories to increase
observed counts.']);
end


%----------------------------------------------------------------------
function [b,XWX,pi] = nominalFit(x,y,m,pi,n,k,p,pstar,parallel)

kron1 = repmat(1:k-1,pstar,1);
kron2 = repmat((1:pstar)',1,k-1);

eta = log(pi);

% Main IRLS loop
iter = 0;
```

```
iterLim = 100;
tolpos = eps(class(pi))^(3/4);
seps = sqrt(eps); % don't depend on class
convcrit = 1e-6;
b = 0;
while iter <= iterLim
    iter = iter + 1;

    mu = repmat(m,1,k) .* pi;

    % Updated the coefficient estimates.
    b_old = b;
    XWX = 0;
    XWZ = 0;
    for i = 1:n
        W = diag(mu(i,:)) - mu(i,:)'*pi(i,:);

        % Adjusted dependent variate
        Z = eta(i,:)*W + (y(i,:) - mu(i,:));

        if p > 0 % parallel models with p>0 have been weeded out
            xstar = [1 x(i,:)];
            % Do these computations, but more efficiently
            % XWX = XWX + kron(W(1:k-1,1:k-1), xstar'*xstar);
            % XWZ = XWZ + kron(Z(1:k-1)', xstar');
            XWX = XWX + W(kron1,kron1) .* (xstar(1,kron2)'*xstar(1,kron2));
            XWZ = XWZ + Z(1,kron1)' .* xstar(1,kron2)';
        else
            XWX = XWX + W(1:k-1,1:k-1);
            XWZ = XWZ + Z(1:k-1)';
        end
    end
    b = XWX \ XWZ;

    % Update the linear predictors.
    eta_old = eta;
    if parallel % parallel models with p>0 have been simplified already
        eta = repmat(b',n,1);
    else
        b = reshape(b,pstar,k-1);
        if p > 0
            eta = repmat(b(1,:),n,1) + x*b(2:pstar,:);
        else
            eta = repmat(b,n,1);
        end
    end
    eta = [eta zeros(n,1,class(eta))];

    % Update the predicted category probabilities.
    for backstep = 0:10
        pi = exp(eta);
        pi = pi ./ repmat(sum(pi,2),1,k);

        % If all observations have positive category probabilities,
        % we can take the step as is.
```

```
        if all(pi(:) > tolpos)
            break;

        % Otherwise try a shorter step in the same direction.  eta_old is
        % feasible, even on the first iteration.
        elseif backstep < 10
            eta = eta_old + (eta - eta_old)/5;

        % If the step direction just isn't working out, force the
        % category probabilities to be positive, and make the linear
        % predictors compatible with that.
        else
            pi = max(pi,tolpos);
            pi = pi ./ repmat(sum(pi,2),1,k);
            eta = log(pi);
            break;
        end
    end

    % Check stopping conditions
    cvgTest = abs(b-b_old) > convcrit * max(seps, abs(b_old));
    if (~any(cvgTest(:))), break; end
end
if iter > iterLim
    warning('stats:mnrfit:IterOrEvalLimit', ...
            ['Maximum likelihood estimation did not converge.  Iteration
limit\n' ...
             'exceeded.  You may need to merge categories to increase
observed counts.']);
end


%-------------------------------------------------------------------------
function [b,dev,stats] =
hierarchicalFit(x,y,m,link,n,k,p,pstar,parallel,estdisp)

dataClass = superiorfloat(x,y);

% Compute the sample sizes for the conditional binomial observations.  Some
% might be zero, rely on glmfit to ignore those, tell us the right dfe, and
% return NaN residuals there.
m = [m repmat(m,1,k-2)-cumsum(y(:,1:(k-2)),2)];

warnStateSaved = warning('off','stats:glmfit:IterationLimit');
[wmsgSaved,widSaved] = lastwarn;
lastwarn(''); % clear this so we can look for a new iter limit warning
needToWarn = false;
try
    if parallel
        % Same slopes for the categories, fit a single binomial model by
        % transforming the multinomial observations into conditional binomial
        % observations.
        ii = repmat(1:n,1,k-1);
        jj = repmat(1:k-1,n,1);
        dummyvars = eye(k-1,k-1,dataClass);
```

```
        xstar = [dummyvars(jj,:) x(ii,:)];
        ystar = y(:,1:k-1);
        if estdisp, estdisp = 'on'; else estdisp = 'off'; end
        if nargout < 3
            [b,dev] = glmfit(xstar,[ystar(:) m(:)],'binomial',...
                'link',link,'constant','off','estdisp',estdisp);
            needToWarn = checkForIterWarn(needToWarn);
        else
            [b,dev,stats] = glmfit(xstar,[ystar(:) m(:)],'binomial', ...
                'link',link,'constant','off','estdisp',estdisp);
            needToWarn = checkForIterWarn(needToWarn);
            stats.resid = reshape(stats.resid,n,k-1);
            stats.residp = reshape(stats.residp,n,k-1);
            stats.residd = sum(reshape(stats.residd,n,k-1),2);
            stats = rmfield(stats,'resida');
        end

    else % ~parallel
        % Separate slopes for the categories, fit a sequence of conditional
        % binomial models
        b = zeros(pstar,k-1,dataClass);
        dev = zeros(dataClass);
        if nargout < 3
            for j = 1:k-1
                [b(:,j),d] = glmfit(x,[y(:,j) m(:,j)],
'binomial','link',link);
                needToWarn = checkForIterWarn(needToWarn);
                dev = dev + d;
            end
        else
            stats = struct('beta',zeros(pstar,k-1,dataClass), ...
                           'dfe',zeros(dataClass), ...
                           'sfit',NaN(dataClass), ...
                           's',ones(dataClass), ...
                           'estdisp',estdisp, ...
                           'se',zeros(pstar,k-1,dataClass), ...
                           'coeffcorr',zeros(pstar*(k-1),dataClass), ...
                           't',zeros(pstar,k-1,dataClass), ...
                           'p',zeros(pstar,k-1,dataClass), ...
                           'resid',zeros(n,k-1,dataClass), ...
                           'residp',zeros(n,k-1,dataClass), ...
                           'residd',zeros(n,1,dataClass));
            for j = 1:k-1
                [b(:,j),d,s] = glmfit(x,[y(:,j) m(:,j)],
'binomial','link',link);
                needToWarn = checkForIterWarn(needToWarn);
                dev = dev + d;
                stats.beta(:,j) = b(:,j);
                stats.dfe = stats.dfe + s.dfe; % not n-pstar if some m's are
zero
                stats.se(:,j) = s.se;
                jj = (j-1)*pstar + (1:pstar);
                stats.coeffcorr(jj,jj) = s.coeffcorr;
                stats.p(:,j) = s.p;
                stats.t(:,j) = s.t;
                stats.resid(:,j)  = s.resid;
                stats.residp(:,j) = s.residp;
```

```
                stats.residd = stats.residd + s.residd;
            end
            if stats.dfe > 0
                % Weed out the NaN residuals caused by zero conditional sizes
                % when computing dispersion.
                t = ~isnan(stats.residp(:));
                sigsq = sum(stats.residp(t) .* stats.residp(t)) ./ stats.dfe;
                stats.sfit = sqrt(sigsq);
            else
                % stats.sfit already NaN
            end
            if estdisp
                sigma = stats.sfit;
                stats.s = sigma;
                stats.residp = stats.residp ./ sigma;
                stats.se = stats.se .* sigma;
                stats.t = stats.t ./ sigma;
                stats.p = 2 * tcdf(-abs(stats.t), stats.dfe);
            else
                % stats.s already 1
            end
        end
    end
catch
    warning(warnStateSaved);
    rethrow(lasterror);
end
[wmsg,wid] = lastwarn;
if needToWarn
    warning('stats:mnrfit:IterOrEvalLimit', ...
            ['Maximum likelihood estimation did not converge.  Iteration
limit\n' ...
             'exceeded.  You may need to merge categories to increase
observed counts.']);
elseif ~isempty(widSaved) && isempty(wid)
    % Restore any pre-existing warning if there was not a new one.
    lastwarn(wmsgSaved,widSaved);
end
warning(warnStateSaved);

function needToWarn = checkForIterWarn(needToWarn)
[wmsg,wid] = lastwarn;
needToWarn = needToWarn || strcmp(wid,'stats:glmfit:IterationLimit');
```

Appendix K – K-M Method Algorithm

Script to run the function

```
clear
clc
data=xlsread('dataset.xlsx', '10state', 'B7:N29');
[obs1,obs2]= size(data);
age=data(1:obs1)';
counter=0;
xtotal=[];
for n=1:obs1;
    counter=counter+1;
    [number]=data(1,2)
    [agen]=age(counter,1);
    x = ones(number,1)*agen;
    xtotal=cat(1,xtotal,x)
end
[lenght1,lenght2]=size(xtotal)
censor=zeros(lenght1,1);
final=cat(2,xtotal,censor);
alpha=0.5;
kmplot(xtotal,alpha,0);
```

Function

```
function varargout=kmplot(varargin)
% KMPLOT Plot the Kaplan-Meier estimation of the survival function
% Survival times are data that measure follow-up time from a defined
% starting point to the occurrence of a given event, for example the time
% from the beginning to the end of a remission period or the time from the
% diagnosis of a disease to death. Standard statistical techniques cannot
% usually be applied because the underlying distribution is rarely Normal
% and the data are often "censored". A survival time is described as
% censored when there is a follow-up time but the event has not yet
% occurred or is not known to have occurred. For example, if remission time
% is being studied and the patient is still in remission at the end of the
% study, then that patientï¿½s remission time would be censored. If a patient
% for some reason drops out of a study before the end of the study period,
% then that patientï¿½s follow-up time would also be considered to be
% censored. The survival function S(t) is defined as the probability of
% surviving at least to time t. The graph of S(t) against t is called the
% survival curve. The Kaplanï¿½Meier method can be used to estimate this
% curve from the observed survival times without the assumption of an
% underlying probability distribution.
%
% Syntax:   kmplot(x,alpha,censflag)
%
%     Inputs:
%           X (mandatory)- Nx2 data matrix:
%                          (X:,1) = survival time of the i-th subject
%                          (X:,2) = censored flag
%                                   (0 if not censored; 1 if censored)
%           note that if X is a vector, all the flags of the second column
%           will be set to 0 (all data are not censored).
```

```
%           ALPHA (optional) - significance level (default 0.05)
%           CENSFLAG (optional) - Censored Plot flag (default 0). If 0
%           censored data will be plotted spreaded on the horizontal
%           segment; if 1 they will be plotted at the given time of
censoring.
%     Outputs:
%           Kaplan-Meier plot
%
%      Example: (+ indicate that patient is censored)
%
%                   ---------------------
%                   Patient     Survival
%                               time
%                   ---------------------
%                      1        7
%                      2        12
%                      3        7+
%                      4        12+
%                      5        11+
%                      6        8
%                      7        9
%                      8        6
%                      9        7+
%                     10        2
%                   ----------------------
%    X=[7 0; 12 0; 7 1; 12 1; 11 1; 8 0; 9 0; 6 0; 7 1; 2 0];
%
%    Calling on Matlab the function: kmplot(X) the function will plot the
%    Kaplan-Meier estimation of the survival function
%
%           Created by Giuseppe Cardillo
%           giuseppe.cardillo-edta@poste.it
%
% To cite this file, this would be an appropriate format:Curve
% Cardillo G. (2008). KMPLOT: Kaplan-Meier estimation of the survival
% function.
% http://www.mathworks.com/matlabcentral/fileexchange/22293

%Input Error handling
args=cell(varargin);
nu=numel(args);
if isempty(nu)
    error('Warning: Data vectors are required')
elseif nu>3
    if nu>4
        error('Warning: Max two input data are required')
    end
end
default.values = {[7 0; 12 0; 7 1; 12 1; 11 1; 8 0; 9 0; 6 0; 7 1; 2
0],0.05,0,1};
default.values(1:nu) = args;
[x alpha cflag flag] = deal(default.values{:});
if ~all(isfinite(x(:))) || ~all(isnumeric(x(:)))
    error('Warning: all X values must be numeric and finite')
end
if isvector(x)
    x(:,2)=0;
```

```
else
    if ~isequal(size(x,2),2)
        error('KMPLOT requires Nx2 matrix data.');
    end
    if ~all(x(:,2)==0 | x(:,2)==1)
        error('Warning: all X(:,2) values must be 0 or 1')
    end
end
if nu>1
    if isempty(alpha)
        alpha=0.05;
    else
        if ~isscalar(alpha) || ~isnumeric(alpha) || ~isfinite(alpha)
            error('Warning: it is required a numeric, finite and scalar ALPHA
value.');
        end
        if alpha <= 0 || alpha >= 1 %check if alpha is between 0 and 1
            error('Warning: ALPHA must be comprised between 0 and 1.')
        end
    end
end
if nu==3
    if isempty(cflag)
        cflag=0;
    else
        if ~isscalar(cflag) || ~isnumeric(cflag) || ~isfinite(cflag)
            error('Warning: it is required a numeric, finite and scalar
CENSFLAG value.');
        end
        if cflag~=0 && cflag~=1
            error('Warning: CENSFLAG value must be 0 or 1')
        end
    end
end
clear args default nu
%string for LEGEND function
str1=[num2str((1-alpha)*100) '% confidence interval'];

%sort data by survival time
x=sortrows(x,1);
%table of patients observed for each survival time
%the TABULATE function sets up this matrix:
%table1=[time count percent(on total)]
table1=[0 size(x,1) 1; tabulate(x(:,1))];
%if all observed time are integers remove not observed time added by
%TABULATE function
table1(table1(:,3)==0,:)=[];

%Table of censored data
table12=tabulate(x(x(:,2)==1));
if ~isempty(table12)
    % remove not observed time added by TABULATE function
    table12(table12(:,3)==0,:)=[];
    % setup the vector of the censored data
    [cens,loc]=ismember(table1(:,1),table12(:,1)); %find censored data
end
```

```
%the percents stored in the the third column are unuseful;
%so, place in the third column how many subjects are still alive at the
%beginning of the i-th interval.
a1=[table1(1,2); -1.*table1(2:end,2)];
table1(:,3)=cumsum(a1); table1(2:end,3)=table1(1:end-1,3);
%number of deaths in the intervals (don't take in account the censored
%data)
if ~isempty(table12)
    table1(cens,2)=table1(cens,2)-table12(loc(cens),2);
end
%finally, delete the first row that is now useless
table1(1,:)=[];

t1=[0;table1(:,1)]; %this is the x variable (time);
%this is the y variable (survival function)
T1=[1;cumprod(1-(table1(:,2)./table1(:,3)))];
if flag %if this function was not called by LOGRANK function
    %compute the standard error of the survival function
    SE=[0;T1(2:end).*sqrt(cumsum(table1(:,2)./(table1(:,3).* ...
        (table1(:,3)-table1(:,2)))))];
end

%censored data plotting
if ~isempty(table12)
    %if there are censored data after max(t1), add a new cell into the t1,
    %T1 and SE arrays
    if table12(end,1)>=t1(end,1)
        t1(end+1,1)=table12(end,1)+1;
        T1(end+1,1)=T1(end,1);
        if flag %if this function was not called by LOGRANK function
            SE(end+1,1)=SE(end,1);
        end
    end
    if ~cflag
        %vectors preallocation
        xcg=zeros(1,sum(table12(:,2))); ycg=xcg; J=1;
        %for each censored data into the i-th time interval...
        for I=1:size(table12,1)
            %compute how many position into the array they must occupy
            JJ=J+table12(I,2)-1;
            %find the correct time interval in which censored data must be
            %placed
            A=find(t1<=table12(I,1),1,'last');
            B=find(t1>table12(I,1),1,'first');
            %equally divide this interval
            int=linspace(table12(I,1),t1(B,1),table12(I,2)+2);
            %put all in the vectors of the plotting variables
            xcg(J:JJ)=int(2:end-1);
            ycg(J:JJ)=T1(A);
            %update the counter
            J=JJ+1;
        end
    else
        xcg=table1(table1(:,2)==0,1);
        ycg=T1(table1(:,2)==0);
```

```
    end
else
    if ~flag %if this function was called by LOGRANK function
        xcg=[]; ycg=[];
    end
end
%compute the hazard rate
c1=T1.*numel(x);
c2=-(diff(log(c1(1:end-1)))./diff(t1(1:end-1)));
lambda=mean(c2(c2~=0));

if flag %if this function was not called by LOGRANK function
    %compute the (1-alpha)*100% confidence interval curves
    cv=realsqrt(2)*erfcinv(alpha); %critical value
    %lower curve (remember that: the lower curve values can't be negative)
    lowc=max(0,T1-SE.*cv);
    %if the lower curve reaches the 0 earlier than survival function, trim
the
    %data.
    if isequal(lowc(end-1:end),[0; 0])
        lowcend=find(lowc==0,1,'first');
    else
        lowcend=length(lowc);
    end
    %upper curve (remember that the upper curve values can't be >1)
    upc=min(1,T1+SE.*cv);
    %eventually, correct the data.
    if isequal(upc(end),1)
        cupend=find(upc<1,1,'last');
        upc(cupend:end)=upc(cupend);
    end

    %compute the median survival time (if exist...)
    if isempty(T1(T1==0.5)) %if there is not a point where T=0.5...
        I=find(T1>0.5,1,'last'); %find the first point where T>0.5
        J=find(T1<0.5,1,'first'); %find the first point where T<0.5
        if isempty(J) %if all points are >0.5...
            mt=0; %...there is no median time
        else
            %compute the median time by linear interpolation.
            p=polyfit([t1(I) t1(J)],[T1(I) T1(J)],1);
            mt=(0.5-p(2))/p(1);
            str2=['Median time ' num2str(mt)]; %string for LEGEND function
        end
    else
        mt=t1(T1==0.5);
        str2=['Median time ' num2str(mt)]; %string for LEGEND function
    end

    %plot all the data
    clf
    hold on
    S2=stairs(t1(1:lowcend),lowc(1:lowcend),'g--'); %lower confidence
interval curve
    stairs(t1,upc,'g--'); %upper confidence interval curve
    S1=stairs(t1,T1,'b'); %Kaplan-Meier survival function
```

```
    if mt>0 %if exist a median time...
        S3=plot([0 mt mt],[0.5 0.5 0],'k:');
    end
    if ~isempty(table12) %if there are censored data...
        S4=plot(xcg,ycg,'r+');
    else
        S4=[];
    end
    hold off

    %set the axis properly
    xmax=max(t1)+1;
    axis([0 xmax 0 1.2]);
    axis square
    %add labels and legend
    txt=sprintf('Kaplan-Meier estimate of survival function (hazard rate:
%0.4f)\n',lambda);
    title(txt,'FontName','Arial','FontSize',14,'FontWeight','Bold');
    ylabel('Transition Probability (From PS1 to
Worst)','FontName','Arial','FontSize',14,'FontWeight','Bold');
    xlabel('Time in State
(Years)','FontName','Arial','FontSize',14,'FontWeight','Bold');
    if mt
        if isempty(S4)
            legend([S1 S2 S3],'Data',str1,str2)
        else
            legend([S1 S2 S3 S4],'Data',str1,str2,'Censored')
        end
    else
        if isempty(S4)
            legend([S1 S2],'Data',str1)
        else
            legend([S1 S2 S4],'Data',str1,'Censored')
        end
    end
end
if nargout
    varargout(1)={table1};
    varargout(2)={table12};
    varargout(3)={t1};
    varargout(4)={T1};
    varargout(5)={xcg};
    varargout(6)={ycg};
    varargout(7)={lambda};
end
```

Appendix L – Code to Create Deterioration Curves from Transition Matrices

```
% FINITE STATE-SPACE MARKOV CHAIN
 clear
 clc
% TRANSITION OPERATOR
P=[0.7338   0.1109  0.0049  0.0244  0.0144  0.0048  0.0093  0.0090  0.0045
0.0840
0.0000  0.8447  0.0049  0.0244  0.0144  0.0048  0.0093  0.0090  0.0045
0.0840
0.0000  0.0000  0.8496  0.0244  0.0144  0.0048  0.0093  0.0090  0.0045
0.0840
0.0000  0.0000  0.0000  0.8740  0.0144  0.0048  0.0093  0.0090  0.0045
0.0840
0.0000  0.0000  0.0000  0.0000  0.8884  0.0048  0.0093  0.0090  0.0045
0.0840
0.0000  0.0000  0.0000  0.0000  0.0000  0.8932  0.0093  0.0090  0.0045
0.0840
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.9025  0.0090  0.0045
0.0840
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.9115  0.0045
0.0840
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.9160
0.0840
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000
1.0000
];
nYears = 80

% INITIAL STATE IS Excellent
X(1,:) = [1 0 0 0 0 0 0 0 0 0];

% RUN MARKOV CHAIN
for iB = 2:nYears
    X(iB,:) = X(iB-1,:)*P; % TRANSITION
end
% DISPLAY
figure; hold on
h(1) = plot(1:nYears,X(:,1),'r','Linewidth',2);
h(2) = plot(1:nYears,X(:,2),'g','Linewidth',2);
h(3) = plot(1:nYears,X(:,3),'b','Linewidth',2);
h(4) = plot(1:nYears,X(:,4),'c','Linewidth',2);
h(5) = plot(1:nYears,X(:,5),'m','Linewidth',2);
h(6) = plot(1:nYears,X(:,6),'y','Linewidth',2);
h(7) = plot(1:nYears,X(:,7),'k','Linewidth',2);
h(8) = plot(1:nYears,X(:,8),'w','Linewidth',2);
h(9) = plot(1:nYears,X(:,9),'m','Linewidth',2);
h(10) = plot(1:nYears,X(:,10),'m--','Linewidth',2);
h(11) = plot([80 80],[0 1],'g--','Linewidth',2);
hold off
legend(h, {'CS1','CS2','CS3','CS4','CS5','CS6','CS7','CS8','CS9','CS10'});
xlabel('Years')
ylabel('Percent Network')
xlim([1,nYears]);
ylim([0 1]);
```