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REPLACEMENT/MAINTENANCE PRIORITIES FOR GAS DISTRIBUTION SYSTEMS

Abstract: Older portions of gas distribution piping systems in many metropolitan areas have experienced escalating maintenance/repair costs because of a greater frequency of leaks. There is also a safety concern about gas migration from a pipe leak that could result in a catastrophic incident. In spite of these problems, replacing all pipes of concern is neither practical nor economical because of the prohibitively high capital budgets required. In this paper, we describe a decision support system to evaluate replacement/preventive maintenance priorities of individual piping segments taking into account such factors as the predicted frequency of leaks, repair versus replacement costs, and risk of incidents. A statistical model is used to estimate the expected frequency of leaks and an economic model is used to calculate the expected life-cycle costs of repair versus replace options. The results of implementing the system at several gas utilities are also presented.

INTRODUCTION

Gas utilities in many metropolitan areas have experienced escalating maintenance and repair costs on older portions of their gas distribution piping systems. Of particular concern are cast iron and bare steel gas mains many of which are 50- or even 100-years old. The frequency of leaks on these mains has increased over the years. There is also a safety concern about gas migration from a pipe leak into buildings and the potential for a catastrophic incident.

In spite of these problems, replacing all cast iron and bare steel pipes is neither practical nor economical because of the prohibitively high capital budgets required. What is needed is a reliable method to identify failure-prone pipe segments and to evaluate priorities to replace or apply preventive maintenance taking into account the predicted frequency of leaks, repair versus replacement costs, and the probability and consequences of an incident following a leak. With appropriate replacement or preventive maintenance on the high-priority, failure-prone segments, the cast iron and bare steel piping systems can be maintained for many more years to provide reliable, safe, and economical service to consumers.

A review of the current industry practices indicates that maintenance decisions for gas distribution pipes are generally made using subjective judgments of experienced engineers. Some of the utilities use a "point score" method (1, pp. 17-19; 2, pp. 21-23) in which factors judged to influence the probability and consequences of failure are identified, rated on a subjective scale (such as 0 to 100) and summed to calculate a priority score. Individual segments are then ranked in a descending order of the priority score, and those ranked high are further investigated to decide whether they should be replaced.

Maintenance decisions based on subjective judgments alone may not be consistent nor cost-effective. While the point score approach enhances the subjective method, it does not explicitly evaluate the probability and consequences of failure. Furthermore, although the point score may provide a good understanding of the relative priorities of individual segments based on their current condition, it does not provide any guidance for deciding the optimal time and type of maintenance.

In this paper, we describe a decision support system to evaluate replacement/preventive maintenance priorities for individual segments of gas distributing pipes. The system uses a statistical model to predict the frequency of leaks as a function of such pipe characteristics as diameter, type and depth of cover, weather and traffic conditions, soil type, operating pressure, and repair history. An economic analysis model is then used to evaluate replacement/preventive maintenance priorities of individual pipe segments based on estimated life-cycle cost.

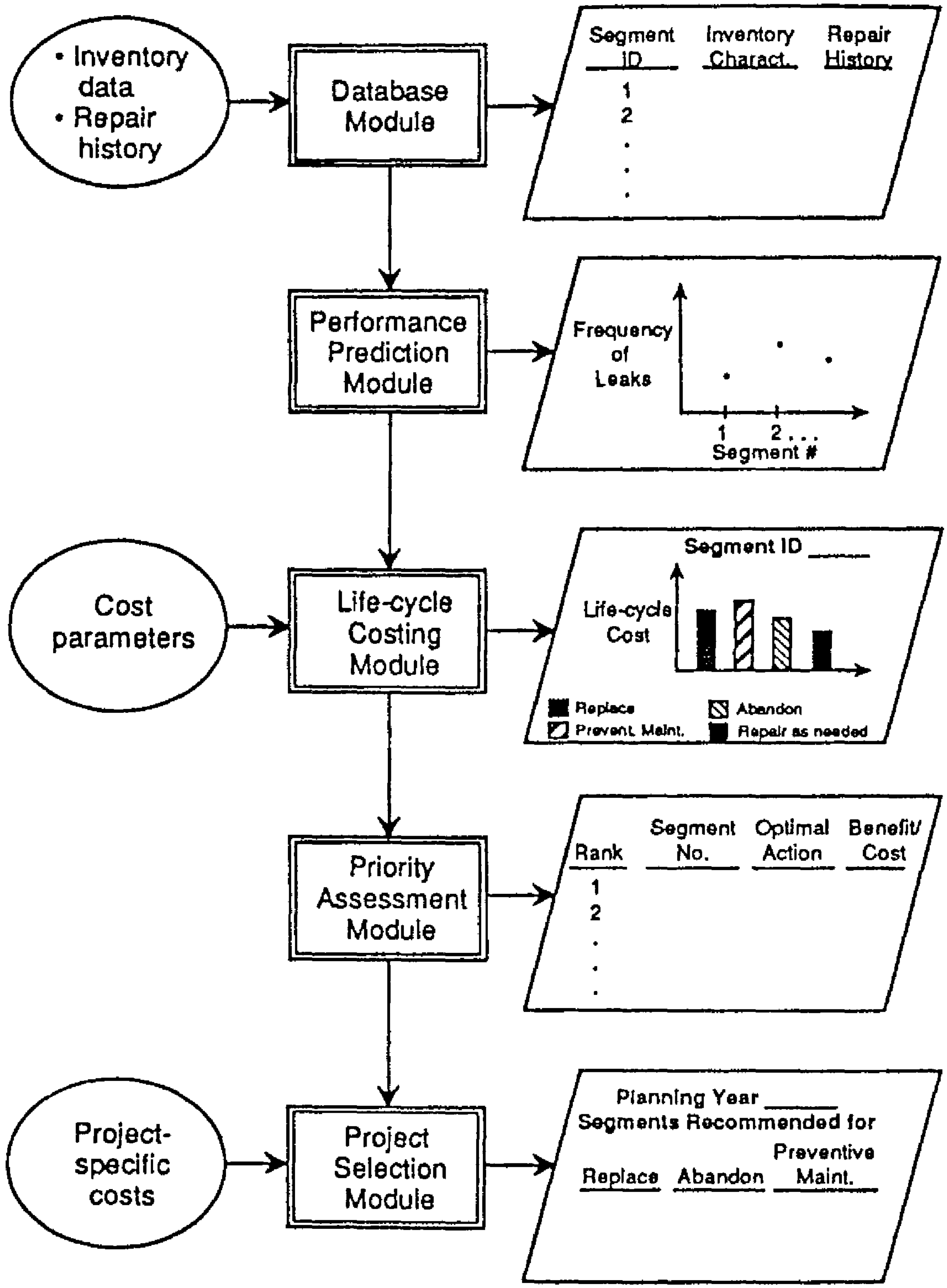
SYSTEM OVERVIEW

Figure 1 shows the major modules of the decision support system and the input-output characteristics of each module. A brief description of each module is provided below.

Database Module

This module contains information necessary to predict the frequency of leaks on individual segments. We define a segment as a continuous portion of a pipe with the same diameter and operating pressure, and with homogeneous characteristics with regard to design, construction, and past performance. Block-by-block segments are generally appropriate for a gas distribution piping system in a metropolitan area.

FIGURE 1.
MAJOR MODULES OF DECISION SUPPORT SYSTEM



Two types of data are included in this module for each segment:

- Inventory characteristics such as diameter, length, installation year, and soil type; and

- Repair history, that is, the date and type of each repair over a period of 10 years.

Relational database software is used to facilitate the input and analysis of the data collected for each segment.

Performance Prediction Module

The purpose of this module is to predict the frequency of leaks on each segment as a function of the relevant segment characteristics. Two sources of information are used in the prediction: (1) a statistical analysis of repair histories of a representative sample of segments; and (2) actual repair history of each given segment. The statistical analysis provides a model to estimate the frequency of leaks as a function of such characteristics as diameter, soil type, type and depth of cover, weather and traffic conditions, and the number of recent repairs. For a given segment, the statistical model is used to obtain a "prior" estimate of the frequency of leaks. This prior estimate is then combined statistically with the "data", i.e., the actual total number of leaks observed over the past 10 years. The combination of the prior estimate and data provides a more accurate prediction of the frequency of leaks on a given segment.

Life-Cycle Costing Module

Four maintenance options are evaluated in terms of their expected life-cycle costs. These options are:

- Continue to repair as needed
- Apply preventive maintenance
- Replace
- Abandon and transfer services

The following components of cost are analyzed in the calculation of the expected life-cycle cost:

- Cost of leak and break repairs
- Replacement cost
- Cost of preventive maintenance
- Abandonment cost
- Probability and cost of an incident
- Annual routine maintenance cost
- Interest and inflation factors

Priority Assessment Module

A benefit/cost (B/C) ratio is used to evaluate priorities of individual segments. Benefit is defined as the difference between the life-cycle costs of the "do-nothing" action (i.e. to continue to make repairs and incur incident costs due to failures) and the optimal action (i.e., the action with the least life-cycle cost). The denominator in the B/C ratio is the one-time cost of implementing the optimal action. For example, suppose a particular one block length of main has a replacement cost of $20,000 and the life-cycle cost to maintain it with failures is $25,000. The B/C ratio for that segment of main is

$$\frac{25,000 - 20,000}{20,000} = +0.25. \quad (1)$$

All mains segments are sorted in descending order of their B/C ratio. Those with positive B/C are the subset recommended for their optimal rehabilitation action. The sum of these rehabilitation action costs for the recommended segments is the budget which will prevent the overall network from falling behind in its life-cycle costs of probable repairs and incidents. However, in any year when the available budget is not adequate to handle the recommended set, the B/C order still shows the best ones to minimize long range costs. The company may prioritize segments for rehabilitations going down the B/C order until the budget is exhausted.

Project Selection Module

This module "fine tunes" the selection of segments for a maintenance action (i.e., replace, apply preventive maintenance, or abandon) based on project-specific engineering investigations and cost estimation. The priority assessment module provides an efficient screening tool to rapidly evaluate all segments in a gas piping distribution system and to identify a small number of candidate segments for which a specific maintenance action (replace, apply preventive maintenance, or abandon) is optimal.

Detailed engineering investigations of these candidate segments may be conducted to make such decisions as: (1) whether several adjacent segments should be combined to form a single replacement project; and (2) whether only a portion of a candidate segment for replacement should be replaced because of the concentration of past repairs just in that portion. Also, site-specific investigations may permit more accurate cost estimates for replacement, preventive maintenance, and abandonment.

The project selection module permits the user to force specific maintenance actions on selected segments, and to specify site-specific costs for these actions. The system makes a second pass through the priority assessment module. The recommendations from this pass can then be used to develop specific projects, and to estimate annual budget requirements, for each of the maintenance actions.

EXPERIENCE WITH SYSTEM IMPLEMENTATION

The application of this system to cast iron gas mains is described in (3). The cast iron system has been implemented at several gas utilities. The experience from these implementations suggests the following:

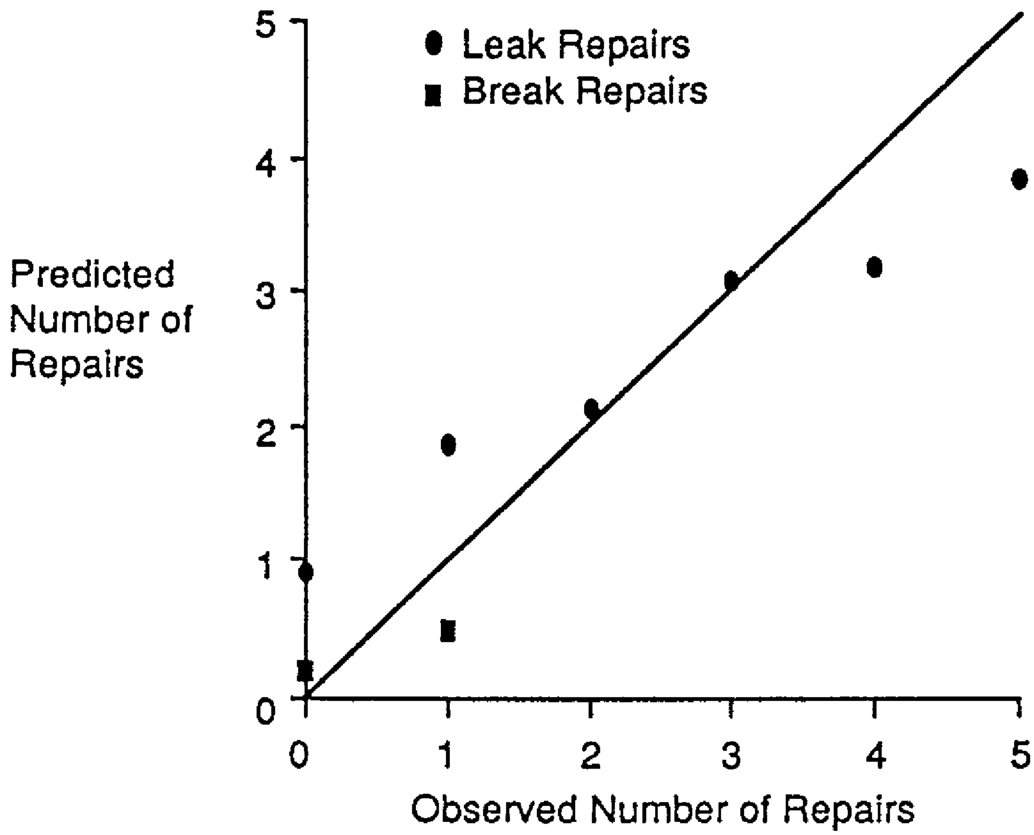
- The statistical approach to predicting the frequency of leaks identifies failure-prone segments with a high degree of reliability. The prediction models were validated by comparing the predicted and actual number of leak repairs and break repairs in a given year on individual segments. These comparisons showed a close agreement between the predicted and actual number of repairs. An example of this type of validation is shown in Figure 2. The prediction models are "dynamic", that is, the predicted number of repairs on a given segment changes with time as new information about the actual performance of the segment becomes available. For example, if leaks occur on the segment in a particular year, the subsequent predictions of how the segment would perform are revised. Thus, the models provide real-time predictions of segment performance.

- Replacement priorities identified by the system maximize the cost-effectiveness of limited replacement dollars. That is, the replacement of the identified segments would achieve the greatest reduction in maintenance costs and in the risk of leaks and breaks for each capital dollar spent. The demonstration of these benefits for one gas utility is presented in (3, pp. 34-39). The use of the decision support system by this company reduced the frequency of breaks by 30 percent; maintenance and repair costs were reduced by about two million dollars; and capital replacement cost was also reduced by about two million dollars.

- Although many similar factors affect the frequency of leaks in different gas distribution piping systems, the relative weights of individual factors vary significantly from one system to another. For this reason, the prediction models need to be calibrated with system-specific inventory data and repair histories. The statistical analysis has identified the following factors as having an important effect on the frequency of leaks:

    - Diameter
    - Length
    - Installation year
    - Soil type

FIGURE 2.
VALIDATION OF STATISTICAL PREDICTION MODELS



- Type and depth of cover
- Traffic density
- City or state construction
- Cumulative number of break repairs
- Cumulative number of leak repairs
- Operating pressure
- Density of preventive clamps

Not all of the factors have turned out to be important for each given piping system. The process of calibrating the prediction models with system-specific data identifies not only the important factors, but also the relative weights of these factors which are determined from statistical correlations.

- The statistical prediction models require a database consisting of inventory data and repair histories of individual segments. The magnitude of the effort needed to develop such as a database varies widely from utility to utility. A small number of utilities have computerized databases both for inventory data and repair histories. For these utilities, the development of the necessary database will be a relatively small effort. Many utilities have computerized repair histories, but not inventory data. The inventory characteristics of individual segments (such as diameter, length and installation year) are maintained on hard copies of maps. For these utilities, the development of the database will require a moderate amount of effort to prepare a computerized database of inventory characteristics. For a system of say, 1000 miles of pipes, the database effort probably would be one to two man-years. If neither inventory data nor repair histories are computerized and the available hard-copy information is decentralized (for example, located in different district offices), the development of the database is likely to require a substantial effort (3 to 5 man-years).

- The system-recommended rate of replacement for cast iron gas piping systems at different utilities varies over one-half of one percent to about two percent. This suggests that, for many utilities, cast iron gas piping systems will continue to be in place for several decades.

EVALUATION OF SYSTEM BENEFITS

The primary benefits of the decision support system is the identification of "right" (the most failure-prone) segments. The replacement of these segments in a descending order of the benefit/cost ratio will result in the greatest reduction in the frequency of leaks for a fixed capital replacement budget. In this section, we compare the reduction in the frequency of leaks using the decision support system versus using a point score method.

Segments in a cast iron gas piping system were ranked in a descending order of replacement priority using each of the two decision methods. A fixed replacement rate of 4 miles/year was assumed and segments for replacement were identified using the prioritized list from each of the two methods. The number of leaks that actually did occur on each set of segments recommended for replacement was determined from repair records. By replacing these segments, the associated number of leaks would have been avoided. Figure 3 shows a plot of the number of leaks avoided versus years for each decision method. The use of the decision support system would have consistently avoided a greater number of leaks in each year of analysis. This result suggests that the decision support system is more reliable than a point score method in identifying failure-prone segments.

A similar comparison of the replacement effectiveness of the decision support system and the use of subjective judgments alone is described in (4, pp. 40-41). The results of this comparison also show a substantially higher reduction in the number of leaks if the replacement priorities from the decision support system (rather than those based on subjective judgment alone) are used to select segments for replacement.

SUMMARY AND CONCLUSIONS

The repair histories of individual segments of a gas distribution piping system provide a wealth of information that can be used in a formal statistical analysis. The decision support system described in this paper incorporates: (1) statistical models to predict the frequency of leaks; (2) economic analysis to identify the maintenance action with the least life-cycle cost; and (3) benefit/cost evaluations to identify replacement priorities. The implementation of the system at several gas utilities demonstrate that the system is much more reliable in identifying failure-prone segments than either subjective judgments alone or a point-score method. The main expected benefits of using the system are a lower frequency of leaks, reduced maintenance and repair costs, and a lower-risk of incidents from gas pipe leaks.

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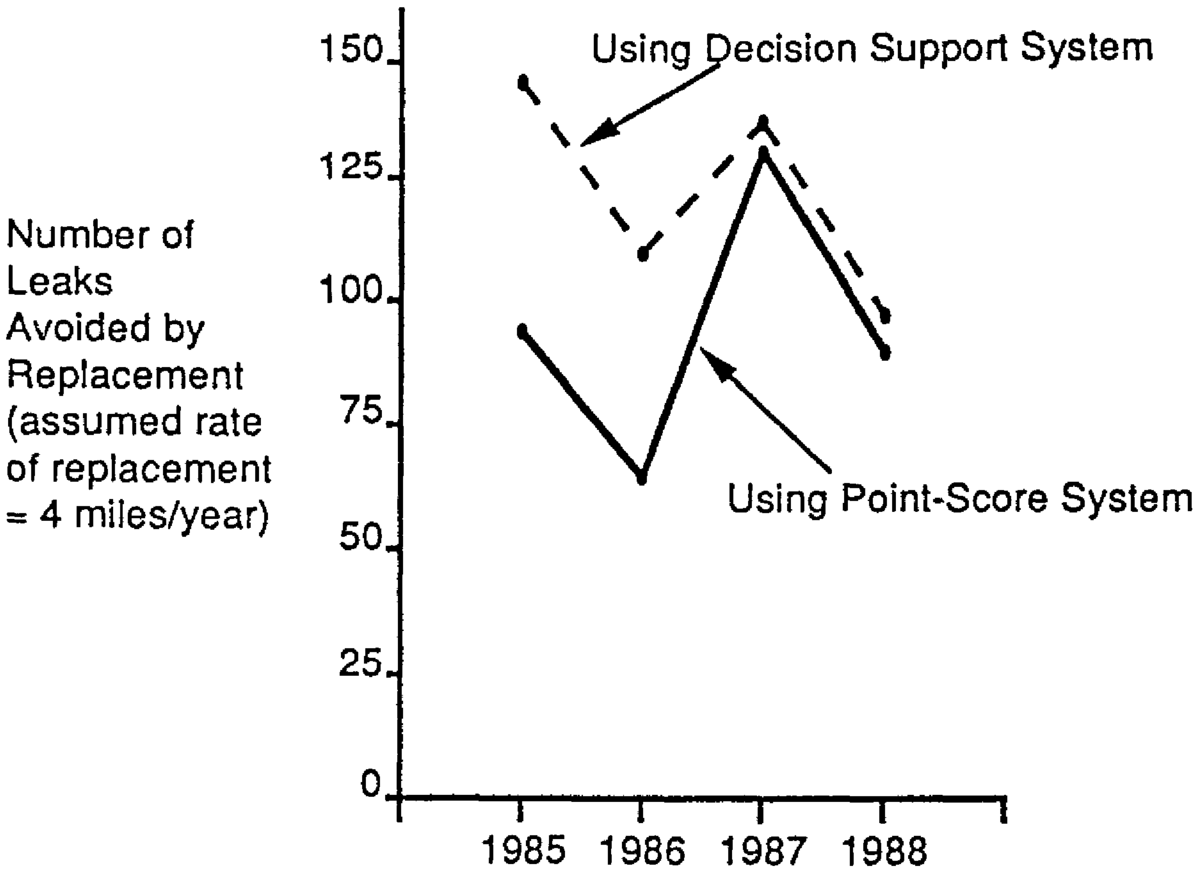
FIGURE 3.
EVALUATION OF BENEFITS OF DECISION SUPPORT SYSTEM



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