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Integrated, multi-attribute decision support system for the evaluation of underground utility construction methods

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INTEGRATED, MULTI-ATTRIBUTE DECISION SUPPORT SYSTEM FOR THE EVALUATION OF UNDERGROUND UTILITY CONSTRUCTION METHODS

by

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A Dissertation Presented in Partial Fulfillment
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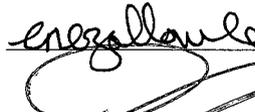
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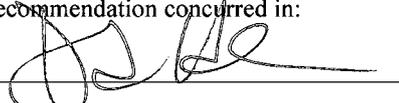
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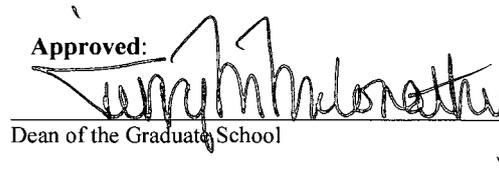
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ABSTRACT

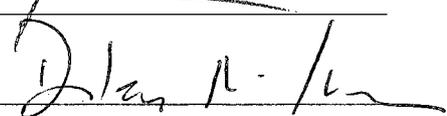The dissertation research work described herein is comprised of three primary objectives: (1) the development of a rehabilitation method selection software (TAG-R) for the National Association of Sewer Service Companies (NASSCO) and its subsequent validation and combination with TAG (a sister decision support system (DSS) software developed by the author in an earlier work); (2) the development of a social cost calculator (SCC) and its validation; and (3) the development of a proposed framework for multi-segment optimization for construction methods selection using the tools developed in the first two objectives as well as additional project related data.

The selection of a construction method involves many factors, which should be considered each time a new pipe segment needs to be addressed. This creates the need for a localized database containing technical data for the construction methods that are available for installation, replacement and rehabilitation of buried utilities. In addition to the database, a fully automated algorithm is needed for processing the project data, comparing it to the construction method databases, and identifying technically viable construction methods for the specific pipe segment under consideration. Each of these was accomplished with the developments of TAG-R, originally made commercially available through NASSCO on CD and now also being available through the TTC website in its full form, combined with TAG (a sister software developed in earlier work) at the web address <http://138.47.78.37/tagrv2/>.

The study of social costs and the benefit offered by trenchless technologies when compared with open cut construction methods has been investigated over the past 25 years by many researchers, with methodologies for estimating social cost elements and incorporating them in the bid process being examined. However, there is no algorithm that combined this work into a single, generic approach in the public domain. This created the need for a software capable of evaluating alternative construction methods based on project input and providing reliable calculations for multiple social cost categories including, (1) traffic delays and vehicle operating costs; (2) pedestrian delays; (3) noise pollution; (4) dust pollution; (5) air pollution; (6) loss of parking revenues; and, (7) pavement restoration. This was accomplished by codifying an algorithm, which uses established calculation methods, into a standalone software called Social Cost Calculator (SCC), which can evaluate up to two competing construction methods at a time.
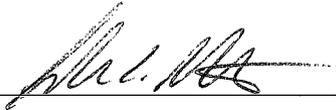
Once all methods deemed technically viable for a pipe segment were identified and their social costs determined, the most economical method can be selected by including the direct construction costs. However, there is a need to be able to evaluate multiple segments, since most utility projects involve more than a single pipe segment. This necessitated to the development of a framework for optimizing the method selection process for multiple segments. Once a method selection evaluation has been conducted for all of the segments on a given project, their direct cost and social costs are calculated for each combination of methods. The multi-segment analysis include additional parameters such as perceived risk, adjustment of the direct cost for the method service life and mobilization/demobilization cost, to determine the most economical method solution set for the project at hand.

APPROVAL FOR SCHOLARLY DISSEMINATION

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CHAPTER 1

INTRODUCTION

1.1 Background

The process of selecting construction methods for rehabilitating underground infrastructure, such as gravity sewer and drainage pipe as well as pressurized water pipes, and for prioritizing pipe segments can be a tedious one. There are numerous parameters to consider such as the host pipe dimensions, condition assessment results and access restrictions. Add to that, the need to find a cost effective solution that not only provides an economical solution in terms of direct construction costs, but also considers benefits to society (e.g. fewer traffic and pedestrian delays, business losses and parking access restrictions), which further complicates the analysis required by increasing the number of parameters that ought to be considered and the data needed for the calculations. Thus, there is a need for an easy to use software that practicing professionals can use to help them make better and more informed decisions in terms of method selection and social cost calculations. It will be shown in the literature review described in Chapter 2 that there is currently no model available for the selection of construction methods that can install, repair or rehabilitate multiple pipe segments for different utility systems (i.e. sewer, water, lateral and manholes) while considering direct construction costs and social costs. The work described in Chapters 3-7 will outline the development of a tool which

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can perform such an evaluation, making it a unique tool in area of asset and construction management.

1.2 Objective

The first objective of this dissertation is to provide the industry with a tool that can assist the construction method selection process through the implementation of a decision support system (DSS) called TAG-R or Trenchless Assessment Guide for Rehabilitation. Combined with TAG (a sister software developed by Matthews [1]), TAG-R created a comprehensive tool for the selection of a construction method for the purpose of constructing, replacing or rehabilitating a buried pipe or conduit. The next objective is to provide users with an algorithm evaluating technically viable methods based on their social aspects using a social cost calculator (SCC). Finally, this dissertation outlines a framework for integrating both elements, along with a direct cost database, into a single tool that can be used for multi-segment evaluations, a likely scenario a utility project is put out for bid. This framework allows the user to first identify technically viable methods for each segment, estimate the direct and social costs for each method based on the project specific conditions and constraints, and finally to select the overall most economic method solution set for the project. Each of these three objectives is shown in Figure 1.1, which shows the stages of pipeline asset management for prioritizing rehabilitation projects, calculating direct and social costs and selecting construction methods. While most researchers adopt a top-down approach for asset management, the author used a bottom-up approach, developing the needed databases and algorithms over the past six years, constructing a viable, complete and fully functional asset management tool for buried municipal pipeline infrastructure. Phase (5)

will be the next area to be developed as part of future work, enabling condition assessment codes to be automatically inputted from a standard asset management database for determining the structural integrity and hydraulic performance of the pipe further automating the process. The final step, which is Phase (6), is to perform a benefit/cost analysis for competing projects as part of preparing an annual and multi-year project plan.

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                    /  Cost Analysis \
                   /  of all Projects  \
                  /--------------------\
                 / (5) Condition Assessment \
                /          Data              \
               /----------------------------\
              /  (4) Multi-Segment Optimization \
             /------------------------------------\
            /  (3) Social Cost Calculator (SCC) and  \
           /         Direct Cost Databases            \
          /--------------------------------------------\
         / (2) Trenchless Assessment Guides (TAG & TAG-R) \
        /--------------------------------------------------\
       / (1) Construction Method Databases for TAG & TAG-R   \
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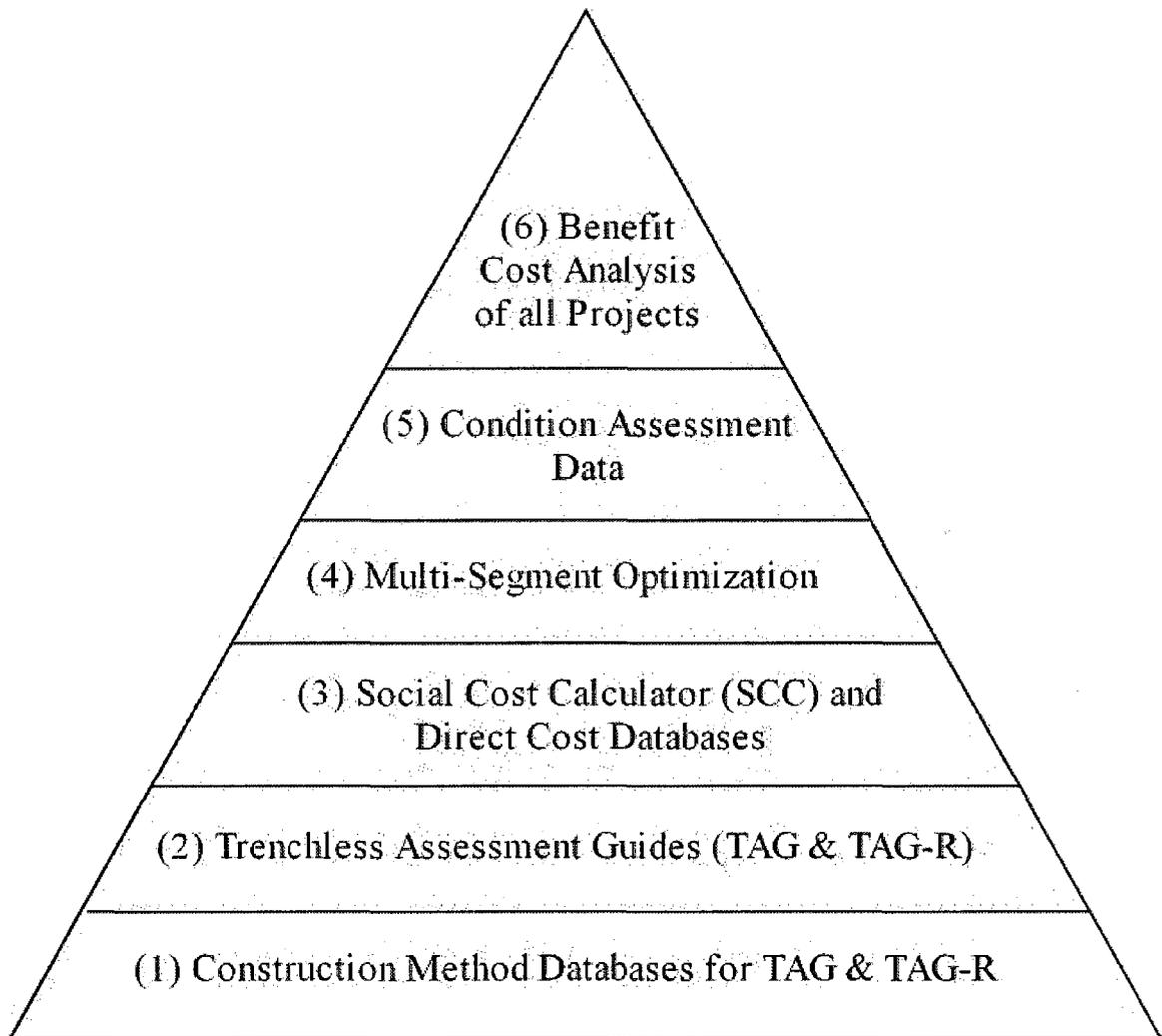
Figure 1.1 Stages of pipeline asset management.

1.3 Thesis Organization

This dissertation is organized into eight chapters: (1) Introduction; (2) Literature Review; (3) Trenchless Assessment Guide for Rehabilitation; (4) Validation of TAG for Rehabilitation; (5) Social Cost Calculator for Utility Projects; (6) Validation of Social Cost Calculator; (7) Multi-Segment Optimization of Method Selection; and (8) Conclusions and Recommendations.

Chapter 2 reviews the relevant literature on decision support systems (DSS) proposed by researchers and practitioners for the selection of construction methods for utility rehabilitation, replacement and/or installation. A review of ten models is presented in the literature for evaluating competing construction technologies. More than 30 methodologies of calculating and evaluating social costs are also presented.

Chapter 3 discusses the Trenchless Assessment Guide for Rehabilitation (TAG-R) algorithm developed for NASSCO's Inspector Training Program. The model's database, graphical user interface, and technical screening process algorithm are presented in detail.

Chapter 4 describes the validation of TAG-R using four case histories. The validation of TAG-R involved using real world case histories which provides the verification needed for the program to be used by practicing engineers and contractors.

Chapter 5 discusses the Social Cost Calculator (SCC) developed for evaluating the social cost elements of utility construction projects. The program's database, graphical user interface, and calculations methods are described in detail.

Chapter 6 describes the validation of the SCC using three case histories. The validation of SCC involved using actual case histories that analyzed the social cost

aspects of various infrastructure projects. The verification is needed for the program to be used with some confidence by practicing professionals.

Chapter 7 presents the framework for an algorithm aimed at integrating the functionality of TAG, TAG-R and SCC along with existing direct cost databases into comprehensive software capable of analyzing multiple pipe segments by estimating the direct and social cost ranges for each pipe segment, and identifying the most economical solution set for the project based on labor and material costs, social impact, constructability considerations (i.e. risk and mobilization costs) and site conditions and constraints. Only a DSS algorithm that offers this level of complexity can be said to provide valuable insight to practicing professionals.

Chapter 8 presents conclusions from the research presented herein and outlines recommendations for future improvements of the software and of the methodologies presented that will enhance the tools involved in terms of functionality and ease of use.

1.4 Key Contributions

The main contributions of the work in this dissertation are described in detail below:

1. The development and validation of a comprehensive decision support system (DSS) for the selection of construction methods from a database of more than 70 technologies capable of rehabilitating sewer pipes, water systems, laterals and manholes. This is the only system to the best of the author's knowledge capable of evaluating multiple underground utility systems.

2. The development of an online DSS, which combines TAG and TAG-R into a single comprehensive web-based software, providing a dynamic decision support

system for the selection of technologies capable of installing, repairing and/or rehabilitating buried utilities, which is the only tool available for evaluating multiple pipe systems for the installation, replacement and rehabilitation of buried utilities.

3. The development and validation of a tool which can calculate the social costs for two competing construction methods at a time for up to seven separate social cost categories: (1) traffic delays and VOC, (2) pedestrian delays, (3) noise pollution, (4) dust pollution, (5) air pollution, (6) road restoration, and (7) parking revenue losses. Currently there is no model is capable of evaluating each of the seven social categories listed for multiple construction methods.

4. The development of novel framework for performing a multi-segment evaluation which uses an extensive technical feasibility evaluation, risk analysis, direct costs and social costs and identifies the most cost effective solution for numerous pipe segments.

CHAPTER 2

LITERATURE REVIEW

2.1 Background of Construction Method Selection

Decisions about how to address utility infrastructure projects require the evaluation of many factors to determine the best method to construct or repair a utility. When an experienced decision maker is called on to make a decision, a road tested approach is usually selected which has a proven track record. However, when less experienced engineers are required to undertake a detailed analysis the amount of data which must be interpreted can be overwhelming and difficult to evaluate. In addition to the magnitude of data one must consider when selecting a technology, there are economical considerations that must be taken into account, some of which are relatively complex to estimate, particularly social costs. There has been considerable work in the area of construction methods selection Decision Support Systems (DSS) [1]; however, several limitations exist which will be discussed in section 2.2 (pg. 8). Specifically, the current tools available for method selection in the area of utility construction are limited to only sewer projects and can only evaluate projects on segment-by-segment basis. In addition, most approaches disregard the social aspect of utility type projects because of the difficulty in determining the social costs of construction projects. There have been many researchers that have attempted to quantify the more elusive economical aspects of construction projects known as social costs, as shown in section 2.3, yet there is currently

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no tool available that evaluates the social cost of utility construction methods. There is also no tool that incorporates social cost accounting into the construction method selection process by combining the social costs with the anticipated direct cost of project. The tools developed in Chapters 3 and 5 bridge this gap and are combined into a framework (Chapter 7) for evaluating multiple pipe segments, while considering social and direct construction costs.

2.2 Decision Support Systems

In addition to the systems documented in Matthews [1], there have been a few new advancements in the area of DSS, particularly for utility construction methods. There have been three new advancements in the past five years which have focused on selecting a method for rehabilitating or replacing a sewer pipe [2, 3 and 4]. Each of these systems focused on the pipe condition assessment for determining the condition of the segment in question. Once the condition of each pipe is determined, the technical characteristics of the pipe are compared with the limitations of currently available rehabilitation techniques to determine which technologies are consider as viable alternatives. The primary disadvantage of each of these systems is that they only focus on the repair of sewer pipes. Baur, Hart and Kropp [5] developed a tool capable of evaluating both sewer and water pipes. While most of these systems focus on the direct cost of a construction method in their respective evaluation processes, only Halfway and Baker [2] take social cost aspects into account. Other approaches which have considered social cost in the method selection process are Diab and Morand [7], Bielecki and Stein [8] and Duggan and Doherty [10] however each of these models were only capable of evaluating pipes on a segment by segment basis as were Udaipurwala and Russell [6] and Abraham [9]. The capabilities of

each of the models is summarized in section 2.2.10 (pg. 14) with the need for a comprehensive system that can consider multiple pipe systems, social costs and direct costs being highlighted. The following sections 2.2.1 through 2.2.9 outline each of the above mentioned approaches proposed over the past five years as well as other systems not previously considered in Matthews [1] in more detail. Each of the models listed are deterministic models that can handle tangible and intangible attributes as well as multiple technologies. The reader familiar with each of these models is encouraged to turn to section 2.3 (pg. 15) where the approaches for social cost accounting are presented.

2.2.1 GIS-Based Decision Support System [2]

Halfawy and Baker (2009) developed a GIS based decision support system (DSS) prototype for evaluating alternative technologies used for sewer renewal. The prototype evaluates renewal alternatives based on their applicability to project conditions, relative costs and benefits. Applicability is evaluated based on three primary sets of criteria: sewer characteristics, site conditions and environmental factors. Sewer characteristics evaluated include among others pipe diameter, depth, and age. Some of the site conditions considered include soil types, groundwater levels and work area requirements. After the applicability stage, the costs and benefits of each renewal method are estimated and used to rank the applicable alternatives based on their cost/benefit ratio. The costs include direct and indirect costs, and the benefit are calculated in terms of service life. This prototype DSS has been used to develop renewal plans for the city of Regina, Saskatchewan, Canada.

2.2.2 Automated Decision Tool using PACP Codes [3]

Schroeder et al. (2008) developed a decision tool that extracts sewer defects from a GIS database and then identifies solutions and priorities for each pipe section. The tool stores CCTV data in a GIS map and based on this data a course of action is determined. If a pipe is set to be replaced because of hydraulic deficiencies the model is directed to do a new replacement in the short term. If not, the pipe segment is given a Structural Score (i.e. Low, Medium or High) based its condition using the Pipeline Assessment Certification Program (PACP) database. Next, a set of questions about the pipe's dimensions is answered to determine which approach is recommended. Once a recommendation is made for each pipe segment the tool prioritizes them based on a combination of each pipe segment condition and criticality.

2.2.3 Decision Support System for Rehabilitating Sewers [4]

Bairaktaris et al. (2007) developed an automated method selection system for sewers based on the processing of closed circuit television (CCTV) surveys. The system first uses a neural network classifier (NNC) to identify longitudinal cracks in the sewer from the CCTV footage. Next, based on the structural damage due to the cracks, the local and global structural integrity of the pipe is determined. Then, appropriate rehabilitation methods are chosen based on host pipe and site conditions. Finally, the residual present value of the initial cost plus a consideration of service life are taken into account to determine the most cost effective method of rehabilitation.

2.2.4 Computer Aided Rehabilitation of Sewer Networks [5]

Baur et al. (2005) helped create the Computer Aided Rehabilitation of Sewer Networks (CARE-S 2005) which was aimed at the development of software and methods that would enable engineers of sanitary sewer projects to establish and maintain effective management of their sanitary sewer and storm water systems by rehabilitating the right sewers at the correct times.

CARE-S uses multi-criteria methodologies to provide decision-support for three different types of decisions namely, developing a long-term rehabilitation strategy, selecting rehabilitation projects that are cost effective and choosing the most economical rehabilitation method. The various procedures of multi-criteria decision support that have been applied in the past to decision problems in the field of infrastructure rehabilitation were analyzed.

2.2.5 Computer-Aided Construction Methods Selection [6]

Udaipurwala and Russell (2002) developed a model for selecting forming and concrete finishing technologies for application in high-rise construction projects. The model was created and validated by working closely with industry personnel to identify project dimensions that must be evaluated when selecting a construction method and rules for assessing technical feasibility.

2.2.6 Choosing Rehabilitation Techniques for Urban Sewers [7]

Diab and Morand (2001) proposed a multi-criteria approach for the selection of sewer rehabilitation techniques which included social cost as a criterion. The first step is an elimination phase based on the type of problem, such as structural or capacity

deficiency. The next step is a multi-criteria analysis based on the performance criteria of each method. Some of the criteria are hydraulic performance, direct cost, social cost and mechanical performance. The five social cost elements considered were noise and vibration, air pollution, pedestrian and vehicle delays, occupation of space and deviations of networks.

2.2.7 Selection Process of Sewer Rehabilitation Alternatives [8]

While discussing the major aspects of integrated management for sewer systems, Abraham et al. (1998) described a selection process for sewer rehabilitation alternatives. The model considered four alternatives for rehabilitation of large combined sewers: shotcrete, cured in place pipe (CIPP), sliplining with a fiberglass reinforced felt liner and dig and replace with reinforced concrete pipe. Shotcrete was deemed to be the low cost option, but it was only applicable in low flow pipes with no signs of corrosion. CIPP was considered an option when signs of internal corrosion existed in pipes with diameters less than 72 inches in diameters and having low flows. In pipes larger than 72 inches in diameter sliplining was seen as the best option. Dig and replace was the alternative in all other cases.

2.2.8 Multimedia Decision Support System [9]

Bielecki and Stein (1997) developed a basic guide for the selection of techniques for construction, maintenance and rehabilitation of buried pipes. The selection process begins by defining the task which includes the type, cause and extent of the damage and the physical characteristics of the host pipe (i.e. diameter, shape, depth, etc.). The next step is to narrow the down the number of methods by first identifying the needed action

as either a repair, renovation or renewal. The third step is assessing the criteria of the method sub-group which is divided into four areas: process engineering, environmental friendliness, environmental and civil law, and economic aspects. Among the economic factors considered are indirect costs such as measures to reduce emissions, traffic disturbances and damages to third part facilities. The final step is the evaluation phase which calculated the number of points each method has accrued during the previous three steps. The method with the highest number of points and lowest cost is considered best suited for the job.

2.2.9 Selection Guide for Trenchless Technologies [10]

Duggan and Doherty (1995) developed a guide for the selection of methods to be used for sewer system replacement and rehabilitation. The guide outlines technologies available for rehabilitation and replacement of sewer systems and provides criteria for selection of suitable methods. The two types of criteria used are the screening criteria, which are yes/no questions, and the evaluation criteria. For a method to be selected it needs to meet the following criteria: (1) must be applicable to the existing conditions, (2) must reduce or eliminate groundwater infiltration, (3) must not allow surcharge in the system, (4) should improve the hydraulic characteristics of the system, (5) should minimize social and economic impacts, (6) should be cost effective, and (7) should provide long-term maintenance improvements.

All methods meeting the criteria will then be ranked based on the weight given to the criteria for a particular method. The method that is able to accomplish all of the criteria the best will be selected as the best alternative. After the methodology is

explained a detailed description of each technology is given, listing the advantages and disadvantages of each.

2.2.10 Discussion of Decision Support Systems

The models referenced above along with the models previously identified in Matthews [1] can be used for the selection of methods for construction projects, however there is no model currently available which considers the direct cost, social cost, multiple utility systems and which can account for multiple pipe segments. The tools developed in Chapters 3 and 5 are combined into a framework for multi-segment optimization of construction method selection as presented in Chapter 7 and the capabilities of this novel methodology are highlighted in Table 2.1.

Table 2.1 Comparison of decision support models for method selection.

Model	Handle Multiple Technologies	Tangible and Intangible Attributes	Handle Multiple Pipe Systems	Fully Automated	Considers Direct Cost	Allows for Demobilization Adjustment	Considers Service Life of Pipe Material	Considers Social Cost	Considers Multiple Pipe Segments
Halfawy and Baker [2]	Yes	Yes	X	Yes	Yes	Yes	Yes	Yes	X
Schroeder et al. [3]	Yes	Yes	X	Yes	X	X	X	X	Yes
Bairaktaris et al. [4]	Yes	Yes	X	Yes	Yes	X	Yes	X	X
Baur et al. [5]	Yes	Yes	Yes	Yes	Yes	X	Yes	X	X
Udaipurwala and Russell [6]	Yes	Yes	X	Yes	Yes	X	X	X	X
Diab and Morand [7]	Yes	Yes	X	X	Yes	Yes	X	Yes	X
Abraham et al. [8]	Yes	Yes	X	Yes	Yes	Yes	X	X	X
Bielecki and Stein [9]	Yes	Yes	Yes	X	Yes	X	Yes	Yes	X
Duggan and Doherty [10]	Yes	Yes	X	Yes	Yes	X	Yes	Yes	X
Matthews Methodology, 2010	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

The framework highlighted above (as described in Chapter 7) is the only model available capable of evaluating multiple pipe segments of different types of systems (i.e. sewer, water, lateral and manhole) while considering both direct cost and social cost. The next section will describe the methodologies currently available for estimating social costs, which is the basis for the calculator (as described in Chapter 5) used for determining the social cost parameter included in the framework highlighted above.

2.3 Social Cost Considerations

Social costs, as described here, are costs not assumed by parties involved in the contractual agreement. These costs are typically assumed by society as a whole in the form of lost time and revenue. There has been much debate about how social costs should be analyzed and if they should be considered during the planning phase of a construction project. Three models which have attempted to incorporate social cost into the construction bid process will now be discussed in detail providing frameworks for incorporating social costs into the construction bid process which is currently not a common practice in the construction bid estimating process [11]. Allen and Ocenosak [11], Xueqing et al. [12] and Chen and Ding [13] all provide approaches for trying to include social cost in the construction bid process however none of the proposed methodologies focuses on the calculation of the actual social costs. As in section 2.2, the reader who is familiar with these methodologies may turn to section 2.4 (pg. 17) for the methodologies available for calculating individual social cost aspects.

2.3.1 Method for Analyzing Costs and Risks of a Tunnel Project [11]

Allen and Ocenosak (2008) describe method of asset management called a Business Case Evaluation (BCE) that takes into account indirect costs and risks associated with different construction alternatives. A BCE typically includes the background of the project, expected benefits to the business, construction alternatives, expected risks and expected costs, both direct and indirect. There is also consideration given to the do nothing approach, where the costs and risks of maintaining the status quo are taken into account. The information is evaluated in the form of a net present value

(NPV) analysis for the project life cycle. Describing costs and risks in monetary terms allow for the alternative with the lowest NPV to be identified and used.

2.3.2 Bid Method for Considering Social Costs [12]

Xueqing et al. (2008) proposed a new bid evaluation process that takes into account social costs. The authors applied the order method and experts' opinion for determining which social costs should be evaluated. Since there was not a simple way of combining the cost and time of a project, a fuzzy evaluation method was used to perform a multi-target decision making process. The direct construction costs, social costs and construction time were considered jointly and the best construction alternative was chosen using the fuzzy evaluation method.

2.3.3 Social Benefits-Cost Analysis Model [13]

Chen and Ding (2007) proposed a model for evaluating social benefits and costs to help decision-makers in China make choices based on benefits to society. The model uses a four-stage process for evaluating proposed construction projects. The first stage is the project benefit-cost analysis which is obtained by calculating investment and output by market price. The second stage is the enterprise benefit-cost analysis which deducts taxpaying, interest and capital return from the project benefit-cost analysis. The third stage is the efficiency benefit-cost analysis which is similar to stage one, but the prices used for project investment and output are imaginary prices and not actual market prices. The final stage is the social benefit-cost analysis which can be determined by two different methods. The direct method quantifies the benefits and costs encountered by members of the referent group (e.g. society as a whole). However, this approach was

proven to be very difficult to execute. The indirect method eliminates the net benefit of the non-referent group in stage three.

2.4 Methodologies for Calculating Social Costs Parameters

The following section describes the various methodologies currently available for calculating the most common aspects of social costs as they relate to underground utility projects. Currently, no methodology is available for evaluating the seven social cost categories considered in this work for multiple construction methods.

The primary focus of social costs as they relate to utility construction projects, which was first studied in the 1980's, was the delay caused to traffic users due to road closures. Researchers focused on the benefits that trenchless technologies offered to road users in the form of fewer delays, yet estimating methods were lacking in the area [40, 41, 42, 43 and 44]. Some researchers proposed to charge contractors road rental fees for causing traffic delays to road users which was one of the earliest forms of social cost estimating [36, 37, 38 and 39]. Subsequently, traffic delay studies were carried out using highway capacity procedures, where traffic delays were determined using established equations [23 and 25] rather than being estimated by visual inspections [33, 34 and 35].

Eventually, other aspects of social cost accounting began to be explored. Pedestrian delays were examined by very few researchers with these based primarily on the visual inspection of delay times and conservative estimates for value of time [24, 33, 34 and 37]. Lost revenue due to fewer available parking spaces was also considered a cost to society, since lost revenue would result in lower local revenues that could be used for community budgets [16, 28, 29, 33, 34 and 37]. Other social cost studies suggested that the service life of pavements was reduced once the pavement was cut into for utility

replacements [15, 27, 28, 34, 35 and 37] and that the maintenance would increase over the remaining service life [23].

Environmental factors, such as noise, air and dust pollution, were considered important in the study of social cost factors for utility projects. The benefits through the use of trenchless technologies was assumed, however there were no reliable calculation methods development for estimating these costs [35, 37, 38 and 41]. Noise pollution was estimated using williness-to-pay studies as well as noise depreciation studies. The noise depreciation studies determined the social cost factor as a reduction of property values based on permanent noise, such as airport or traffic noise [14, 19, 20, 24, 28, 30, 31, 32, 33, 38 and 41]. Air pollution is considered to be lower when using trenchless methods [16, 22, 24, 28 and 35], but there were no attempts to calculate or quantify it in any of the social cost studies. Dust pollution is the final environmental factor, which was first calculated in Boyce and Bried [33 and 34] and the basis for subsequent studies which examined dust pollution [15 and 17].

Pucker [14] was the first author to attempt to validate social cost methodologies by comparing the results of five case histories to the most widely accepted estimating procedures. Pucker presented five case histories from North America and Europe that compared the social costs of trenchless alternative versus open cut ones. The findings showed that traffic delays were the dominant factor in urban areas, accounting for as much as 60% of the total sum of all social costs. A rule of thumb proposed was that if the traffic delay costs were calculated to be less than 10% of the direct contract cost, then social costs could be neglected. However if they were more than 25% of the direct cost,

they were significant and should be taken into account during the planning stages of the project.

This work, along with each of these studies mentioned below led to the development of the Social Cost Calculator (SCC), one of the main results of this dissertation research, described in Chapter 5. SCC is the only known tool available for the estimation of the seven social cost categories. Table 2.2 summarizes the capabilities of each methodology presented and the novel aspect of SCC described in Chapter 5 which addresses each social cost category while providing a methodology for incorporating social cost into the construction bid process. Appendix F contains detailed descriptions of each of these methodologies. The social costs methodologies described in Appendix F do not address each of the seven categories mentioned earlier (i.e. traffic delay, pedestrian delay, parking loss, pavement restoration, noise, air and dust pollution) while providing a methodology for incorporating the costs into the construction bid process. This highlights the need for a single tool capable of evaluating each of the seven social cost categories, which led to the development of SCC, and a process for incorporating them into the bid process, as described in Chapter 7.

Table 2.2 Summary of Social Cost Methodologies.

References	Traffic Delay	Pedestrian Delay	Parking Space Loss	Decreased Pavement Service Life	Noise Pollution	Air Pollution	Dust Pollution	Method for Incorporating Into Bid Process
Allen and Ocenosak [11]	X	X	X	X	X	X	X	Yes
Xueing et al. [12]	X	X	X	X	X	X	X	Yes
Chen and Ding [13]	X	X	X	X	X	X	X	Yes
Pucker [14]	Yes	X	Yes	Yes	Yes	X	Yes	Yes
Michielsen [15]	Yes	X	X	X	X	X	X	Yes
Allouche and Gilchrist [16]	Yes	X	Yes	X	Yes	Yes	Yes	Yes
Perrin and Jhaveri [17]	Yes	X	X	X	X	X	X	Yes
Gangavarapu et al. [18]	Yes	X	X	X	X	X	X	Yes
Jung and Sinha [19]	Yes	X	X	X	Yes	X	X	Yes
Gilchrist et al. [20]	X	X	X	X	Yes	X	X	Yes
Tighe et al. [21]	Yes	X	X	Yes	X	X	X	Yes
Fea et al. [22]	Yes	X	X	X	X	Yes	X	X
Tighe et al. [23]	Yes	X	X	X	X	X	X	Yes
Lonardo et al. [24]	Yes	X	X	X	Yes	Yes	X	Yes
McKim [25]	Yes	X	X	X	X	X	X	Yes
Bried and Boyce [26]	Yes	X	X	X	X	X	X	Yes
Grunwald [27]	Yes	X	X	Yes	Yes	Yes	X	X
Kolator [28]	Yes	X	Yes	Yes	Yes	X	Yes	Yes
McKim [29]	Yes	Yes	Yes	X	X	X	X	Yes
Hsu and Jiang [30]	Yes	X	X	X	Yes	Yes	X	Yes
Hsieh et al. [31]	Yes	X	X	X	Yes	Yes	X	X
Voorhoeve [32]	Yes	X	X	X	Yes	Yes	X	X
Boyce and Bried [33]	Yes	Yes	Yes	X	Yes	X	Yes	Yes
Boyce and Bried [34]	Yes	Yes	Yes	Yes	X	X	Yes	Yes
Budhu and Iseley [35]	Yes	X	X	Yes	X	Yes	X	Yes
Thomson [36]	Yes	X	X	X	X	X	X	X
Berosch and Angot [37]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	X
Vickridge et al. [38]	Yes	X	X	X	Yes	X	Yes	Yes
Daley [39]	Yes	X	X	X	X	X	X	Yes
Norgrove and O'Reilly [40]	Yes	X	X	X	X	X	X	X
Bristow et al. [41]	Yes	X	X	X	Yes	Yes	X	Yes
Green and Wood [42]	Yes	X	X	X	X	X	X	Yes
Noden [43]	Yes	X	X	X	X	X	X	X
Glennie and Reed [44]	Yes	X	X	X	X	X	X	X
Matthews SCC, 2010	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

2.5 Summary

There have been many attempts to develop DSS for infrastructure applications and to establish methodologies for estimating social costs. The work described in this dissertation provides a novel comprehensive methodology and tool for selecting a group of technically viable construction methods, determining their associated social costs and then performing a multi-segment analysis to select the best solution set (or group of

technologies) that can complete the project at hand in the most cost effective and least

risky manner.

CHAPTER 3

TRENCHLESS ASSESSMENT GUIDE FOR REHABILATION

3.1 Background

The research leading to the creation of this evaluation tool was commissioned by the National Association of Sewer Service Companies (NASSCO) and was intended to be used as part of their Inspector Training and Certification Program (ITCP) which provides field construction professionals the tools they need to understand and inspect trenchless pipeline renewal technologies [45]. The tool, called the Trenchless Assessment Guide for Rehabilitation (TAG-R), was created as a stand-alone program to assist consulting and municipal engineers as well as contractors in the evaluation of trenchless technologies used for the rehabilitation of utilities (i.e. sanitary sewers, potable water, etc.). The tool does not evaluate trenchless technologies for installing new alignments or for performing inline replacements, because those methods were addresses in a previous software program named TAG [1]. The two software packages were to be combined, creating an integrated, comprehensive decision support environment covering all existing trenchless construction methods used for the installation, replacement and rehabilitation of buried utilities. TAG-R, which was codified using Microsoft Visual Studio .NET 2003, is compatible with standard Microsoft operating systems Windows XP and Vista. The tool includes specific technical data for more than 65 construction technologies used for the rehabilitation of utility pipelines and manholes [46].

The primary objective of this research was to collect the needed data to develop and implement databases and algorithms that perform the following goals. First, the software needed to store, manage, retrieve and present extensive technical data for a large number of construction methods in an organized and user friendly manner. Next, the program would need to perform a comprehensive evaluation of each method's technical information by comparing it to the user's project specific information. Finally, TAG-R would need to provide the user with a list of technically viable methods and their technical information in a user friendly environment for review and additional evaluation. By identifying the technically viable technologies, the program educates the user as to the methods capable of performing the job, while providing guidance to the use of trenchless technologies that might not have been considered otherwise.

The parameters needed to evaluate the various utility systems were based on a list of host pipe conditions from the knowledge of the author and his supervisor. The list of parameters was complied and submitted to NASSCO's committee of industry experts for approval of inclusion or not in the evaluation process which followed. The technical committee was led by Gerry Muenchmeyer, NASSCO Technical director, and made up of the more ten members. The members involved most closely with review of the technical parameters were: Lynn Osborn, Insituform; Grant Whittle, Ultraliner; Rick Turkopp, Hobas; Ed Kampbell, NASSCO; and, Irene McSweeney, City of Boston. Once the parameters were approved for inclusion into the software, the question of how to evaluate each parameter was determined by researchers at the TTC and given to each of the members of the technical committee for approval. Once the parameters were tentatively agreed upon, it was determined that each member would run common

scenarios that they encountered against the evaluation parameters to see if the model was providing valid results. Many of the parameters were considered obvious (i.e. length, diameter, deterioration and allowable capacity reduction) however there were a few parameters considered to be necessary in the beginning that became obsolete upon further study. Once such parameter was product manufacture (i.e. whether the product was manufactured in the field or factory), which the committee determined was actually a constructability issue that did not belong in the method selection process. During the committee's evaluation process it was also determined that the need for bypass pumping was too difficult to define and it was therefore left out of the evaluation process. Although some technologies required full bypass pumping of a pipe to be installed correctly, all methods require some form of bypass pumping. The level of bypass required was considered to be a constructability issues as well and therefore eliminated from further inclusion in the method selection process. The definitions for all of the parameters used in the evaluation process and the parameters which were excluded are described in section 3.2 and the algorithm used for evaluating each method category is outlined in the flowcharts at the end of each method category section.

3.2 Method Database

The core of the program is an extensive method database which contains detailed information for each of the trenchless technologies. The methods are divided into the following main categories: gravity (sanitary/storm/combined) sewers, pressure (potable/non-potable) water pipes, laterals and connection seals and manholes.

A detailed description and a color image are provided for each construction method. Some of the technical parameters, such as length and diameter, are applicable for

all of the pipe replacement categories. The length parameter is the maximum length of any host pipeline or lateral section on a project that can be renewed in a single drive. The diameter is the inside diameter of the host pipe.

The extent of deterioration of a buried pipe is commonly classified as either partially deteriorated or fully deteriorated. Partially deteriorated pipes require only non-structural solutions, meaning the host pipe can support the soil and surcharge loads throughout the expected design life of the rehabilitation system, and the soil adjacent to the existing pipe provides adequate side support. The pipe may have longitudinal cracks and exhibit up to 10% distortion or ovality compared with the original diameter. Fully deteriorated pipes need a fully structural solution because the host pipe is not structurally sound and cannot support soil and/or live loads over the design life of the rehabilitation system.

Cross-section reduction refers to the amount of reduced flow capacity allowed by the host pipe once it has been renewed. No allowable reduction refers to materials, that when installed, penetrate the pipe joint and do not leave a lining in place (i.e. chemical grouting). Pipes allowing only a small amount of cross-sectional reduction require a tight-fit, field manufactured renewal system with no annular space between the host pipe and the new liner system, such as a cured-in-place pipe (CIPP) liner. In cases where an intermediate reduction in capacity is allowed, a loose fitting factory manufactured pipe inserted into the host, which can be designed with or without the use of annular grout (e.g. spiral wound liner), can also be considered. A larger allowable reduction would enable the insertion of a smaller pipe into the host pipe with the annulus being grouted, resulting in a noticeable reduction in cross-sectional area. Such methods include some

types of sliplining. It is important to note that reduction in cross-sectional area does not necessarily mean a reduction in flow capacity. It is common for the Manning's roughness coefficient, n, to typically be reduced substantially, compensating partially or fully, for the loss in the pipe's cross-sectional area.

Bends refer to horizontal as well as vertical bends in the host pipe that some methods may not be able to maneuver due limited flexibility and material make-up. The four degrees of bend considered are $11.25°$, $22.5°$, $45°$ and $90°$. If the actual degree of the bend is different from the four values given the next highest degree bends is selected. For straight pipes, the option called "No Bends" would be selected and therefore not used as evaluation parameter the method selection process, since all technologies can rehabilitate straight pipes.

Two parameters included in the databases, but not used during the technical evaluation, are traffic impact and product manufacture. Traffic impact refers to the general level of disturbance (i.e. low, moderate or high) created by a particular method. Product manufacture indicates whether the liner is made in the factory (i.e. fold-and-form pipe) and then shipped to the site or whether it is made in the field (i.e. CIPP or grout-in-place liners). Neither of these parameters are used during the selection process (since they were deemed as constructability issues that should be considered after method selection is made), but they are simply given as additional information.

3.2.1 Sanitary, Storm and Combined Sewer

Gravity driven sanitary sewer mains carry wastewater from entry points to sewer treatment plants. The flow is moved by gravity; therefore the mains must be installed on grade. In some gravity systems lift stations have to be installed to raise the flow up so that

the sewer pipes don't become too deep, making them difficult to inspect and repair. Storm sewers carry rainwater run-off to a body of surface water and they are gravity driven pipes as well. The flow is collected in storm drains and catch basins and then sent to its end location. There are also combined sewers that collect sanitary and storm flow and carry it to treatments plants that are equipped to handle both types of flow. Table 3.1 lists the 23 technologies that can be used for full line rehabilitation or spot repair of sanitary, storm and combined gravity sewers.

Table 3.1 Sanitary, storm and combined sewer rehabilitation methods.

No.	Method	Category
1	CIPP Inversion (Structural)	Full Line Rehabilitation
2	CIPP Inversion (Non-Structural)	Full Line Rehabilitation
3	CIPP Pulled In (Structural)	Full Line Rehabilitation
4	CIPP Pulled In (Non-Structural)	Full Line Rehabilitation
5	Folded Pipe (Structural)	Full Line Rehabilitation
6	Folded Pipe (Non-Structural)	Full Line Rehabilitation
7	Sectional Sliplining	Full Line Rehabilitation
8	Segmental Sliplining	Full Line Rehabilitation
9	Continuous Sliplining	Full Line Rehabilitation
10	Spiral Wound (Not Grouted)	Full Line Rehabilitation
11	Grout in Place Liners (PVC)	Full Line Rehabilitation
12	Grout in Place Pipe (HDPE)	Full Line Rehabilitation
13	Structural Panel Lining	Full Line Rehabilitation
14	Concrete Spray-On Coating (Man Entry)	Full Line Rehabilitation
15	Polymer Coating (Man Entry)	Full Line Rehabilitation
16	Polymer Coating (Non-Man Entry)	Full Line Rehabilitation
17	Flood Grouting	Full Line Rehabilitation
18	CIPP Sleeves	Spot Repair
19	Mechanical Sleeves	Spot Repair
20	Mechanical Joint Seals	Spot Repair
21	Chemical Grouting	Spot Repair
22	Robotic Injection	Spot Repair
23	Rerounding	Spot Repair

These methods may differ in the material(s) used, method of construction or application, functionality, and intended use (i.e. local defect versus access point to access point).

In addition to the parameters described earlier there are also several other technical parameters which need to be considered to help properly evaluate technologies, some of which are specific to only gravity driven sewer pipes. One of those parameters is flow control or bypass pumping which is required when using most of the technologies, but some, such as sliplining, only require limited flow control and sometimes can be installed in full live flows (which could be very significant in large diameter interceptors that have too much flow to bypass pump).

The pipe shape refers to the geometry of the original host pipe. The two primary shapes considered are circular and box-shaped. Egg-shaped is also common pipe geometry, but the methods that apply for circular pipes can also accomplish the rehabilitation of egg-shaped host pipes as well.

Reverse crown occurs when the crown of the host pipe begins to collapse and forms a reverse crown curvature. This typically occurs in arch brick pipes. Technologies that rely on arch design are no longer applicable as structural rehabilitation solutions in this case. A reverse crown configuration can only be lined with a smaller round pipe and then grouted to provide structural support.

Allowable pipe access includes both manholes and access pits. Methods that, due to their size and material make-up, can be installed directly through a manholes opening would be considered manhole accessible, such as folded pipes. Technologies that cannot be installed directly through a manhole opening due to their size and material make-up

require that an access pit be dug out for the installation process (i.e. continuous sliplining).

Cross-section transitions refer to host pipes that change diameter at least once between existing manholes. This could be due to point repairs which used a different pipe size than the original or to accommodate changes in the required capacity based on the hydraulic design. Some technologies are able handle a size transition while others require a relatively constant diameter to function as intended.

Another parameter included in the database, but not used in the technical evaluation, is annular grout. Annular grout informs the user whether or not grout must be pumped into the annulus (i.e. as a function of the space between the host pipe and the new liner) for completing the installation process using a particular technology. This parameter serves as addition information that can be considered during the design stage of the project, but should not be considered during method selection.

Figure 3.1 shows a sample method database form for sanitary, storm and combined sewers (CIPP Inversion-Structural). Some methods had to be split into several subcategories due to length-to-diameter ratio considerations. For example, a host pipe between 4 and 15 inches in diameter could be rehabilitated using a CIPP inversion process up to 1000 feet in length. However, if the host pipe is between 16 and 42 inches a single drive of up to 2500 feet could be accomplished.

Figure 3.1 Database form for CIPP Inversion-Structural.

The algorithm for evaluating sewer rehabilitation methods is presented as a flowchart in Figure 3.2.

Figure 3.2 Sewer evaluation flowchart.

3.2.2 Potable and Non-Potable Water

Non-potable water refers to sanitary sewer force mains which carry wastewater from the user to the sewer treatment plant while under pressure. Other applications include 'gray' water and processing water used in agricultural and industrial applications, respectively. These lines do not have to be installed on grade as their contents are forced by pressure to move through the pipe. Potable water lines distribute drinking water to homes and businesses. These pipes also operate under pressure that carries the flow

through the lines. Table 3.2 lists 13 methods that are available for the rehabilitation of potable and non-potable water pressure pipes.

Table 3.2 Potable and non-potable water rehabilitation methods.

No.	Method	Category	M-28 Class
1	CIPP Inversion* (Structural)	Non-Potable Water	Class II or III
2	CIPP Inversion* (Non-Structural)	Potable & Non-Potable Water	Class II or III
3	Folded Pipe (Mechanical)	Potable & Non-Potable Water	Class III or IV
4	Folded Pipe (PVC)	Potable & Non-Potable Water	Class III or IV
5	Reduced Diameter Pipe (PE)	Potable & Non-Potable Water	Class III or IV
6	Hose Liners	Potable & Non-Potable Water	Class II or III
7	Continuous Sliplining	Potable & Non-Potable Water	Class III or IV
8	Segmental Sliplining	Potable & Non-Potable Water	Class III or IV
9	Concrete Spray-On Liner (Man Entry)	Potable & Non-Potable Water	Class II or III
10	Cement Coating (Non-Man Entry)	Potable & Non-Potable Water	Class I or II
11	Polymer Coating (Man Entry)	Potable & Non-Potable Water	Class I or II
12	Polymer Coating (Non-Man Entry)	Potable & Non-Potable Water	Class I
13	Mechanical Seal	Potable & Non-Potable Water	Class IV

*Fiber-reinforced CIPP

The M-28 classes are defined by AWWA as a liner's capacity to handle internal pressure loads. Class I liners primarily only protect the inner surface of the pipe from corrosion, with minimal ability to bridge discontinuities such as holes or gaps. Class II liners have a long term internal burst strength that is less than the maximum allowable operating pressure of the host pipe; are designed to bridge specified size holes and gaps; and depend on adhesion to the host pipe wall to prevent collapse when the pipe becomes depressurized. Class III liners also have a long term internal burst strength that is less than the maximum allowable operating pressure of the host pipe; and are designed to bridge specified size holes and gaps; but have sufficient inherent ring stiffness to be self-supporting in the event of depressurization. Class III liners may also be designed to withstand specified external hydrostatic or vacuum forces. The final class of liner, Class IV, has a long term internal burst strength that is greater than the maximum allowable

operating pressure of the host pipe and the liner must be capable of surviving possible failure of the host pipe [47].

There are several parameters that are specific to pressure pipes in addition to the general parameters mentioned in Section 3.2. Pressure rating refers to the operating pressure that the flow in the force main or water line operates under. The pressure rating was subdivided into the following three sub-classes. Low pressure systems are those which operate a pressure below 60 psi, and they can be repaired by all of the above mentioned technologies. Standard operating conditions are defined as pipes operating between 60 and 150 psi, and many of the technologies listed in Table 3.2 can rehabilitate these lines for diameters up to 12 inches. High pressure systems that operate above 150 psi and larger diameter pipes that operate above 100 psi can only be renewed with slipliners or mechanical seals.

Another parameter concerns the method for reconnecting the services which can help determine which rehabilitation method might be most suitable. If the host pipe has no domestic or commercial connections, no method should be excluded as a viable option. If "Internally" is selected then services can be renewed only from inside the newly rehabilitated pipe. Alternatively, if "Externally" is chosen an excavation will be needed at each service location for reestablishing the connection. If either method is permissible than this parameter is no longer used to eliminate candidate methods.

Also, when rehabilitating potable water lines, the product usually has to be ANSI/NSF 61 certified. This certification is done to ensure that the drinking water is not being contaminated by the carrier pipes. Therefore, any method or material which has not been certified will be eliminated from further consideration, which is the case for folded

pipe (PVC) which has yet to receive such certification. Figure 3.3 shows a sample

method database form for potable and non-potable water line rehabilitation methods.

Figure 3.3 Database form for Hose Liners.

The algorithm for evaluating water rehabilitation methods is presented as a
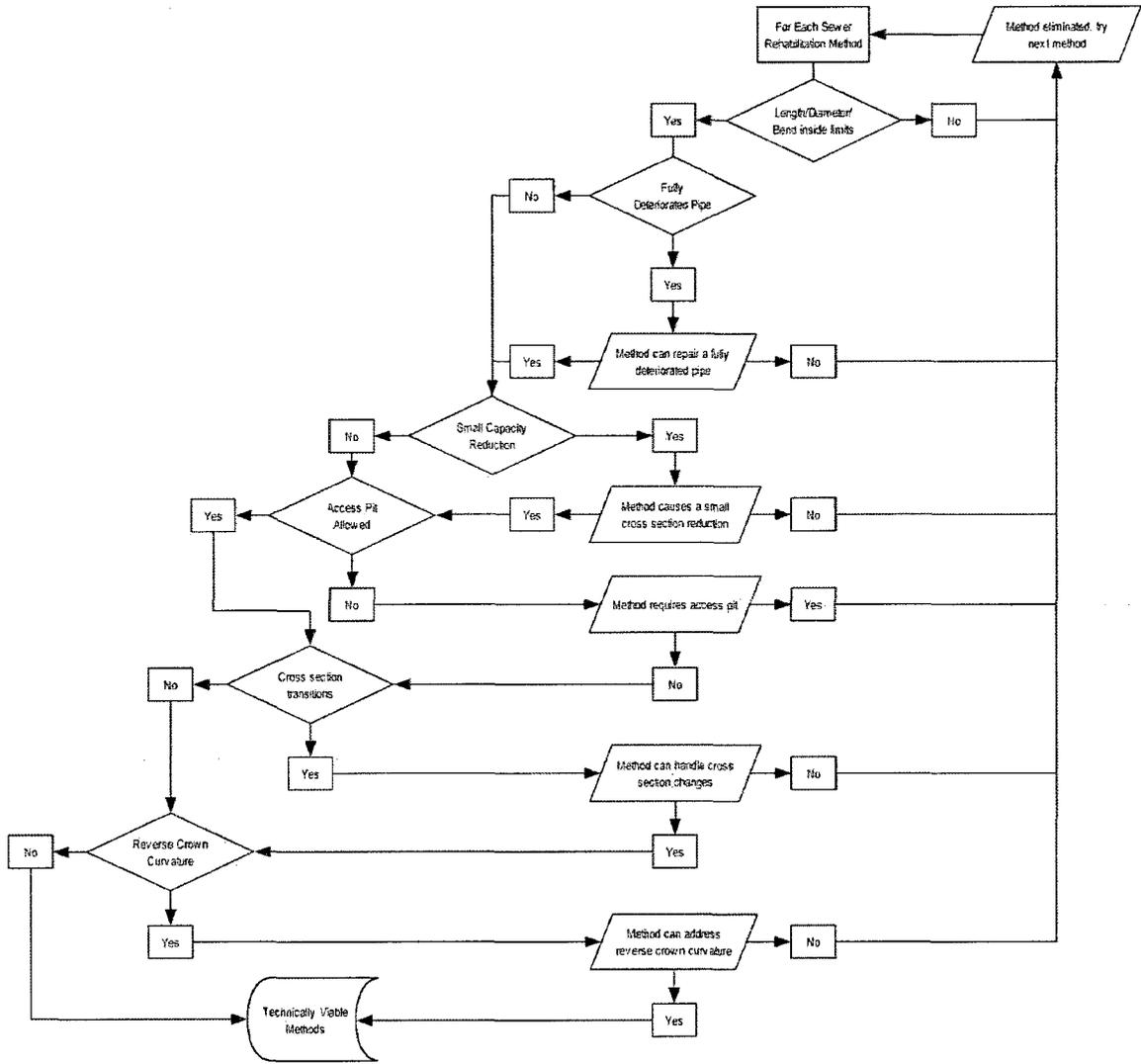
flowchart in Figure 3.4.

For Each Water Rehabilitation Method

Method eliminated, try next method

Length/Diameter/Bend /Pressure inside limits — Yes / No

Fully Deteriorated Pipe — No / Yes

Method can repair a fully deteriorated pipe — Yes / No

NSF Certification Required — No / Yes

Method uses NSF certified materials — Yes / No

Access Pit Allowed — Yes / No

Method requires access pit to reinstall services — Yes / No

Cross section transitions — No / Yes

Method can handle cross section changes — Yes / No

Technically Viable Methods

Figure 3.4 Water evaluation flowchart.

3.2.3 Lateral and Connection Seal

Sewer laterals carry wastewater away from homes and businesses by gravity to the sewer main lines, which may be gravity driven or force mains. These pipes are typically between 4 and 8 inches in diameter and less than 100 feet long. Connection seals are used to renew or repair the location where a lateral or service line connects to the main line. Table 3.3 lists 11 methods used for the renewal and reconnection of laterals and services.

Table 3.3 Lateral and connection seal rehabilitations methods.

No.	Method	Category
1	CIPP Inversion-Inside Out (Main to Cleanout)	Laterals
2	CIPP Inversion-Outside In (Cleanout to Main)	Laterals
3	CIPP Pulled-In-Outside In (Cleanout to Main)	Laterals
4	Chemical Grouting	Laterals
5	Continuous Sliplining	Laterals
6	Folded Pipe	Laterals
7	Full Wrap Tee	Connection Seals
8	Resin Hat Connections	Connection Seals
9	Fused Hat Connections	Connection Seals
10	Grouted	Connection Seals
11	Robotic	Connection Seals

Lateral and connection seal parameters include many of the previously mentioned attributes; however, the access parameter has different values depending on the configuration of the lateral. Some technologies are able to be installed from the lateral cleanout, such as an outside-in CIPP inversion. A technology might be able to be installed from the mainline (i.e. inside-out CIPP inversion), and in that case access to the main is needed. If access to the lateral is not restricted, access pit, cleanout or mainline could all be selected as the type of access to the host lateral. Figure 3.5 shows a sample lateral method database form for a CIPP inversion-inside out (main to cleanout) which is launched from inside the main line.

Figure 3.5 Database form for CIPP Inversion-Inside Out (Main to Cleanout).

The algorithm for evaluating lateral rehabilitation methods is presented as a flowchart in Figure 3.6.
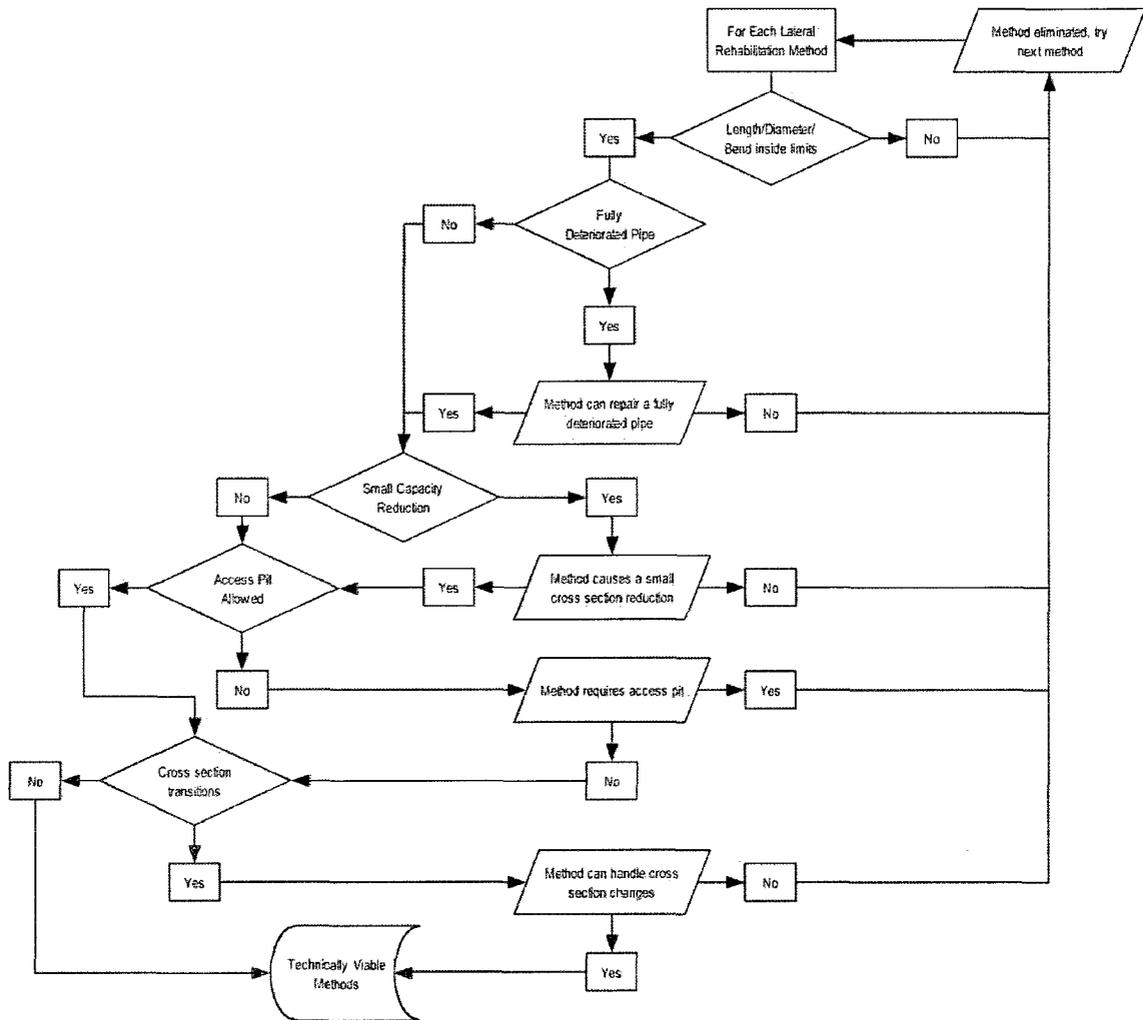
Figure 3.6 Lateral evaluation flowchart.

3.2.4 Manhole

Manhole structures provide access to sewer and drainage pipes for maintenance and inspection. They can become corroded and degraded over time, which leads to infiltration of groundwater and contribute to infiltration. Table 3.4 lists 14 methods that can be used for the maintenance and restoration of manhole structures or some of their components.

Table 3.4 Manhole maintenance and rehabilitation methods.

No.	Method	Category
1	Chemical Grout	Maintenance
2	Cementitious Repair	Maintenance
3	Channel Inserts	Maintenance
4	Chimney Seals (Mechanical, Polymer or CIPP)	Maintenance
5	Barrel Joint Seal (Mechanical or Polymer)	Maintenance
6	Inflow Dish	Maintenance
7	Cementitious Coating	Coating
8	Epoxy Coating	Coating
9	Polyurethane Coating	Coating
10	Protective Liner (HDPE or PVC)	Corrosion Protection
11	Modified Polymer Skin Panel	Corrosion Protection
12	Cementitious Cast in Place	Structural
13	Cured-in-Place Liner	Structural
14	FRP Inserts	Structural

The three primary reasons for rehabilitating manholes are: general maintenance for controlling infiltration/inflow, applying a corrosion resistant barrier or a structural renewal. If the manhole is considered structurally sound with little indication of settlement, cracking or was determined to have signs of structural fatigue (e.g. minor corrosion, infiltration/inflow through precast joints, mortar joints or around the pipe connections), then general maintenance is all that is required. When the manhole is exhibiting early signs of moderate structural distress (e.g. minor cracks, loss of mortar or bricks, corrosion less than ½ inch in depth, or minor cross-sectional distortion less than 10%), but is still supporting the soils and live loads a semi-structural coating is required. If the manhole is exhibiting signs of severe structural distress and/or collapse is eminent, a fully structural renewal is required. Conditions that indicate this degree of deterioration would be distortion greater than 10% of the manhole diameter; severe corrosion exposing the reinforcement steel or large sections of the structure being collapsed or missing altogether.

Infiltration in a manhole is typically caused by groundwater that flows in through joints, cracks, the bench, the invert or near pipe connections. Inflow is typically runoff of water during a rainfall event that flows in through the manhole cover holes and/or between the casting and the chimney.

The corrosion level of a manhole can be minimal, light wall or heavy wall. If the manhole is in very good condition with some of the brick mortar or concrete surface in a solid hard condition, then no corrosion has occurred. Light wall corrosion is when the brick mortar is deteriorated and missing or concrete surfaces are soft and flaking in spots. Heavy wall corrosion is evident when bricks and mortar are missing in a number of areas, several inches of soft concrete exposed or sections of the wall surface are missing.

Brick manholes lacking structural integrity have bricks missing in a number of areas with distortion in the wall. In concrete manholes, portions of the wall will be missing, with reinforcement bars exposed or missing. A manhole with a wall that has partially collapsed would require a structural reconstruction with a structurally sound lining system or a completely new structure.

Bench repairs are required when the bench is cracked and deteriorated with sections missing, no bench currently exists, or groundwater is infiltrating at the bench. An invert repair is needed if the invert is missing or eroded, the pipe running through the invert is fractured or dislodged, or the elevation does not match the elevations of the incoming and outgoing pipes. Figure 3.7 shows a sample method database form for the manhole rehabilitation methods.

Figure 3.7 Database form for Epoxy Coating.

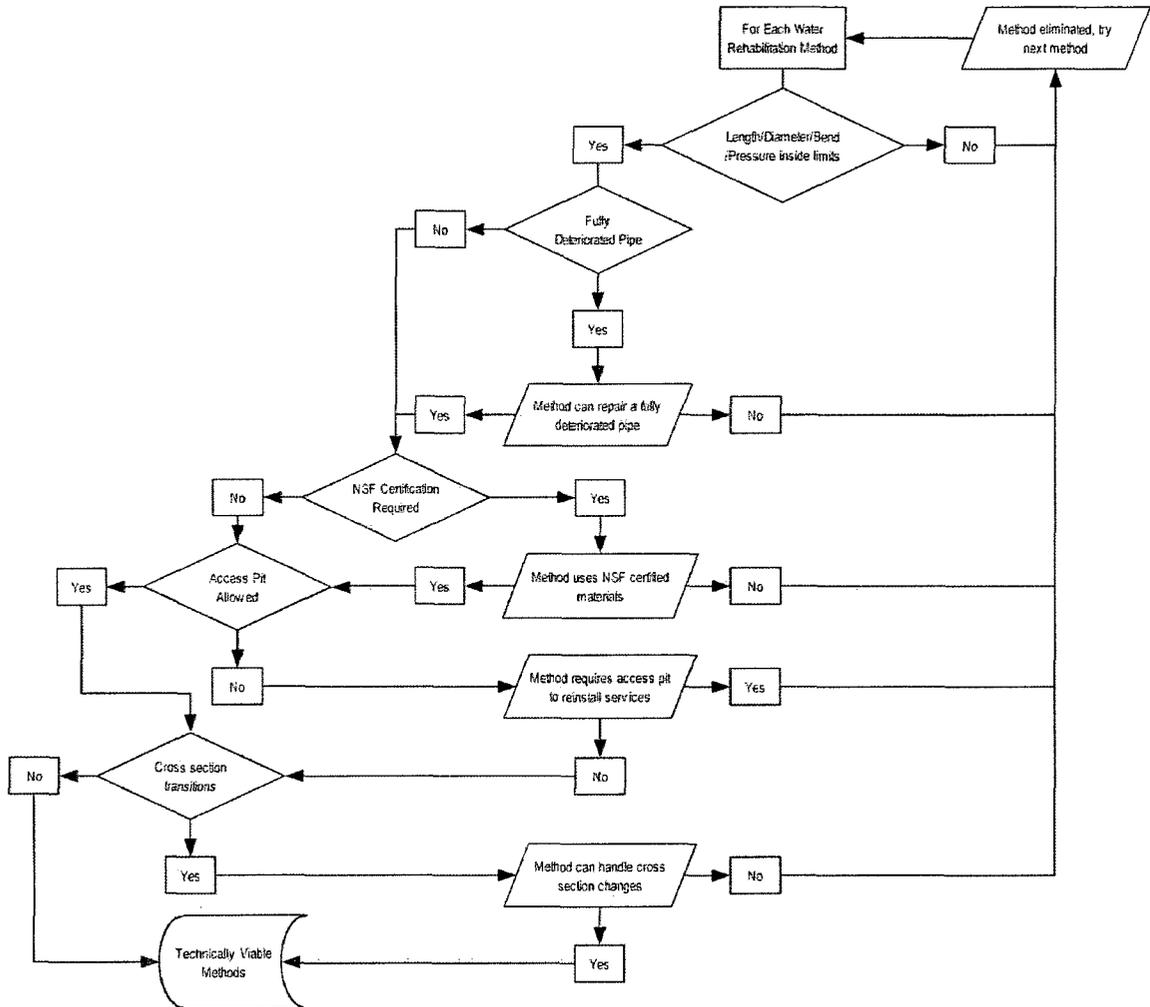The algorithm for evaluating manhole rehabilitation methods is presented as a flowchart in Figure 3.8.
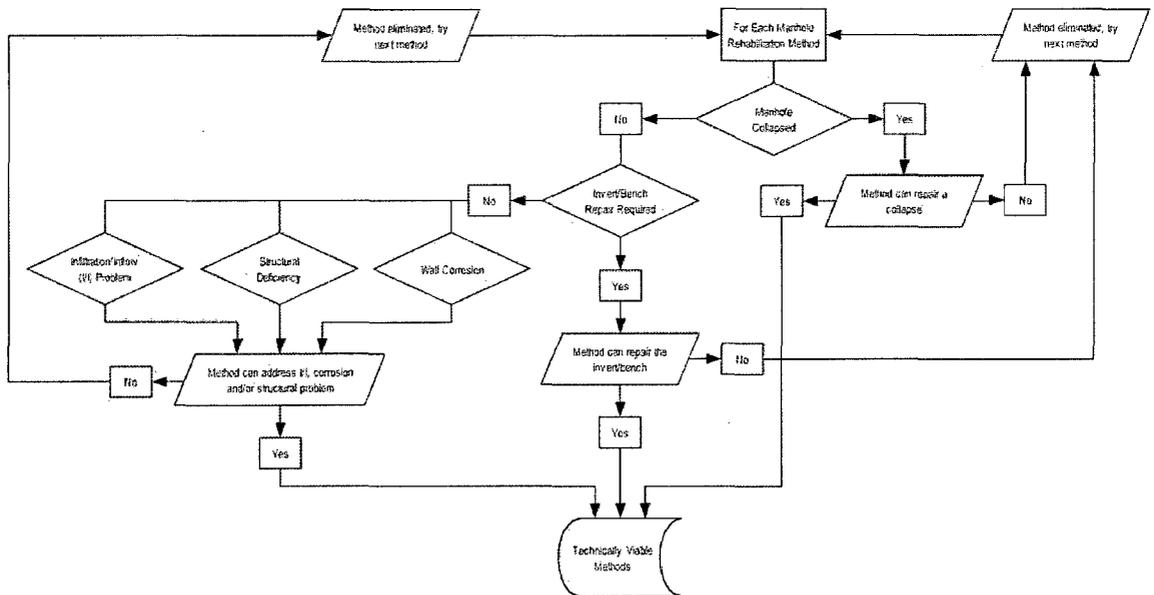
Figure 3.8 Manhole evaluation flowchart.

3.3 Technical Evaluation

TAG-R performs a sound technical evaluation by comparing the project's specifications with the technical limitations of the construction methods. The technical evaluation begins by selecting the type of system which needs rehabilitation. Available system types include sanitary sewer (force mains and gravity flow), storm and combined sewers, potable water (pressure), sewer laterals and manholes. A screen capture of the system selection form is shown in Figure 3.9.

Figure 3.9 System selection form.

The next step is to input the project specific technical parameters, which include construction parameters and host pipe details. Construction parameters include the length and diameter of the pipe section that needs to be renewed. The deterioration level of the host pipe is input next as either partially deteriorated (non-structural) or fully deteriorated (structural). The allowable cross-section reduction of the pipe and the types of permissible access to the pipe are the final two construction parameters. Figure 3.10 shows the construction parameters input form for a storm sewer system.

Figure 3.10 Construction parameters for a Storm Sewer.

Some of the parameters are intuitive and can easily be input by the user, whereas

others might not be instinctively clear such as the cross-section reduction. In those cases

the user can select the "Need Help" option which is a pop up that provides further

information concerning available options, as shown in Figure 3.11.

Figure 3.11 Cross-section reduction help section.

In addition to the construction parameters mentioned above, the operating pressure of the system (psi) should be specified for sewer force mains and potable water pressure mains. The construction parameters form for these types of systems is shown in Figure 3.12.

Figure 3.12 Construction parameters for Potable Water.

The host pipe details are input next and include the maximum degree of bend in the host pipe, which can be None, 11.25°, 22.5°, 45° or 90°. Other details include the host pipe shape (i.e. circular or box-shaped) and if any diameter transition sections or reverse crown curvatures exist between the access points. Figure 3.13 displays the host pipe details input form for a storm sewer system.

Figure 3.13 Host pipe details for a Storm Sewer.

Alternate host pipe details for potable water pressure and sewer force mains include the method for reconnecting the services or laterals. Also, for potable water the need for NSF certified materials is evaluated to ensure that a method complies with federal regulations. The form for host pipe details associated with potable water systems is shown in Figure 3.14.

Figure 3.14 Host pipe details for Potable Water.

Inquiries regarding the conditions of manhole structures are made for three categories: general, invert/bench repairs and manhole collapse. General questions allow TAG-R to determine if the manhole has infiltration and/or inflow problems due to groundwater and surface water, the level of corrosion of the manhole wall and if the manhole has structural deficiencies. The next section asks two specific questions concerning the condition of the manhole bench and invert, respectively. The final question determines if the manhole is suffering from a complete collapse, thus requiring a complete replacement. Figure 3.15 shows the manhole question form for a manhole structure determined to suffer from infiltration, light wall corrosion and requiring a bench repair.

Figure 3.15 Manhole conditions input form.

3.4 Screening Process & Implementation

The screening process begins by focusing on a single database using the DSS selection functions. The algorithm processes the users input, "Storm Sewer" for example, and queries the gravity sewer database while taking the user to the relevant input screen. The first sections of data to be processed are the construction parameters length and diameter. The screening process requires that the input value be within the maximum and minimum values for each field in the database. For example, if the diameter of sewer needing to be repaired was 36 inches, only the methods that have a value greater than 36 inches as their maximum viable diameter and less than 36 inches as their minimum viable diameter are considered technically viable and passed to the next stage of the evaluation. A method such as grout in place liners (PVC), which has a maximum diameter of 180 inches and minimum diameter of 25 inches, would be consider viable for this particular example, whereas spiral wound (non-grout) liners would be eliminated since it has maximum and minimum diameters of 24 and 6 inches, respectively.

There are several factors that compare the user inputs to the values in the database directly for compatibility. Lack of compatibility could result in the elimination of the method under consideration. These parameters include the deterioration level of the host pipe (fully deteriorated or partially deteriorated). If only a partial deterioration has occurred in the host pipe then it will not be an eliminating factor, however if a fully deteriorated pipe is being considered only methods which provide fully structural rehabilitations will be permitted to the next step of the evaluation process. For example, if the user selects fully deteriorated as the condition of the pipe in question, a method like polymer coating would be eliminated because it is not capable of providing a structural

rehabilitation, whereas continuous sliplining can provide a structural rehabilitation. The process of coding this parameter, shown in Figure 3.16, involves comparing the users input only if it is "Fully Deteriorated (Structural)" to the column in the database named "FullDet". If the value in the database is "No", that means that the method is not capable of performing structural renewals, and therefore is deleted from the list of technically viable methods.

```
Private Sub fulldeteval()
    Dim fulldet As String
    Dim dr As DataRow

    Try
        fulldet = Me.cbFullDet.SelectedItem
    Catch
    End Try

    For Each dr In DsAccess.Tables("FullRehabMethod").Rows
        If CStr(dr("FullDet")) = "No" And fulldet = "Fully Deteriorated (Structural)" Then
            dr.Delete()
            GoTo line3
        End If
line3:
    Next dr
    For Each dr In DsAccess.Tables("SpotRehabMethod").Rows
        If CStr(dr("FullDet")) = "No" And fulldet = "Fully Deteriorated (Structural)" Then
            dr.Delete()
            GoTo line4
        End If
line4:
    Next dr
    Me.DsAccess.AcceptChanges()
End Sub
```

Figure 3.16 Code sample of deterioration evaluation.

Degree of allowable cross-section reduction, utility access, bends, pipe geometry, diameter transitions and reverse curvatures are all screened in a similar manner.

Potable water and force mains have a separate set of parameters which need to be evaluated such as operating pressure, lateral/service reconnection method and NSF certification. Lateral or service reconnection can be chosen from a drop-down menu as either: no service connections, externally, internally or either. The algorithm for analyzing this parameter compares the user's input to the value in the column named

"LatRec". If the user's input was either "No Service Connections" or "Either" then no elimination process is performed. If the user selects "Internally", meaning lateral services must be reconnected from inside of the host pipe, and a method has "Externally" as its value for this parameter, then the construction method under consideration will be deleted, as shown in Figure 3.17.

```
Private Sub latreceval()
    Dim latrec As String
    Dim dr As DataRow

    Try
        latrec = Me.cbLatRec.SelectedItem
    Catch
    End Try

    For Each dr In DsAccess.Tables("PotableWater").Rows
        If CStr(dr("LatRec")) = "External" And latrec = "Internally" Then
            dr.Delete()
            GoTo line8
        End If

        If dr.RowState <> DataRowState.Deleted And CStr(dr("LatRec")) = "Internal" And latrec = "Externally" Then
            dr.Delete()
            GoTo line8
        End If
line8:
    Next dr
    Me.DsAccess.AcceptChanges()
End Sub
```

Figure 3.17 Code sample for lateral reconnection evaluation.

Manhole methods have a different set of parameters, all of which are evaluated by a "Yes" or "No" comparison. There are three levels of evaluation: A) overall condition of the manhole; B) does the manhole have an invert and/or bench problem; and, C) does the manhole experience a complete collapse. Figure 3.18 outlines how the algorithm deals with the complete collapse of a manhole. If the user has selected "Yes" for a manhole collapse, then a global parameter called "HasCollapsed" is activated, which supersedes the prior steps in the evaluation process and limits the evaluation process to the remaining lines of code in the sub function. The remaining evaluation eliminates all methods which do not have a "Yes" as a value in the column named "TotColl" in the database. This narrows the results to only methods that are capable of full manhole replacement.

```
       Private Sub colleval()
            Dim coll As String
            Dim dr As DataRow

            Try
                 coll = Me.cbColl.SelectedItem
            Catch
            End Try

            If coll = "Yes" Then
                 HasCollapsed = True
            Else
                 HasCollapsed = False
            End If

          For Each dr In DsAccess.Tables("Manhole4").Rows
                 If CStr(dr("TotColl")) = "No" And coll = "Yes" Then
                      dr.Delete()
                      GoTo line7
                 End If
                 If CStr(dr("TotColl")) = "No" And coll = "No" Then
                      dr.Delete()
                      GoTo line7
                 End If
                 If CStr(dr("TotColl")) = "Yes" And coll = "No" Then
                      dr.Delete()
                      GoTo line7
                 End If
line7:
            Next dr
            Me.DsAccess.AcceptChanges()
       End Sub
```

Figure 3.18 Code sample for manhole collapse evaluation.

3.5 Results

Once the technical evaluation is completed by the algorithms outlined above, the results are displayed in a format similar to the original database, with only the technically viable methods being shown in the list box. The results form for the storm sewer section, which has been used for describing the technical evaluation above, is shown in Figure 3.19. For this particular example only three methods were considered technically viable, namely: CIPP Inversion (Structural), CIPP Pulled In (Structural) and Grout in Place Pipe (HDPE).

Figure 3.19 Results for Storm Sewer example.

3.6 Discussion

The decision support system developed in this work is the only system developed capable of evaluating multiple pipe systems including, sanitary sewer (gravity driven), storm drains, combined sewers, sanitary sewer force mains, water distribution pipes, sewer laterals and manholes. The previous works described earlier in the literature review were only capable of evaluating one category of piping systems, namely sanitary sewer pipes as outlined in Table 2.1 based on the host characteristics and condition. Although TAG-R is capable of evaluating multiple pipe systems, there is still a need to be able to evaluate construction methods based on their associated social costs as well as direct costs. This led to the development of the social cost calculator described in Chapter 5.

CHAPTER 4

VALIDATION OF TAG FOR REHABILIATION

4.1 Validation

An automated decision support system, such as TAG for Rehabilitation (TAG-R), must be extensively validated using real world case histories of construction projects, which considered multiple technologies as viable options during their planning phases. This allows for comparison of not only the outcomes of the selection processes, but also validation of the steps needed to make an informed decision when selecting a construction method. The validation of TAG-R involved running more than 12 case studies through the model to verify the selection process and results with actual projects that have published. Summaries of the case histories, a project description, the methods used for the project and the recommendations of TAG-R can be found in Tables A.1 and A.2 located in Appendix A. Four sample case histories are provided below in detail.

4.2 Case Study #1: Sewer Rehabilitation, Minneapolis, Minnesota [48]

A sewer line designated 1-MN-320 constructed in 1889 from limestone and brick, had performed well over its intended design life. Due to several impending construction projects on the surface above the pipe line, including a new Minnesota Twins stadium, it was assumed that there was a high potential for damage from the additional loads due to the proposed construction activities, therefore the City of Minneapolis searched for

rehabilitation alternatives to counterbalance the impending additional loads. The sewer had multiple cross-sectional size transitions, ranging from 60 inches to over 96 inches in diameter. The pipe section, summarized in Table 4.1, also had cross-sectional deformation due to crown sags along its 900 foot length.

Table 4.1 Data summary for the sewer project.

Category	Parameter
Length	900 feet
Diameter	86 inches
Deterioration Level	Fully Deteriorated
Cross-Section Reduction Allowed	Medium
Access Available	Manhole or Access Pit
Maximum Bend	22.5°
Cross-Sectional Shape	Circular & Oval
Cross-Section Transitions	Yes
Reverse Crown Curvature	Yes

The data from Table 4.1 was input into TAG-R to find technically feasible alternatives for rehabilitating the interceptor sewer with a minimal amount of disruption. There were five technologies considered to be technically viable by TAG-R for rehabilitating 1-MN-320 as shown in Figure 4.1.

Figure 4.1 Results of the sewer interceptor method selection.

The engineer on the actual project concluded that there were only two technically feasible options based on the condition assessment of the sewer interceptor: a crown repair and sliplining. Among the alternatives that were excluded were cured-in-place pipe (CIPP), spray-on coatings and folded pipe liners. Crown repair is not an option in TAG-R because it involves the excavation of the entire length of pipe, removal of the top arch and replacement with a cast-in-place section, which is not a trenchless application. For that reason the engineer decided to choose sliplining as the preferred rehabilitation technology, pushing a 72 inch pipe liner inside the 86 inch host pipe. When comparing the engineer's results to TAG-R output, one sees that both contain sliplining and exclude CIPP. A steel mesh coated with a cementitious grout was another technically viable method considered by TAG-R, but designers choose to exclude it due to its cost. TAG-R also specified three other viable technologies that were not considered by the designers which would have provided alternatives to sliplining. Grout in place liners, grout in place

pipes and structural panel liners are viable methods for the rehabilitation of fully deteriorated structures that convey gravity driven wastewater flow.

4.3 Case Study #2: Waterline Rehabilitation, Okaloosa County, Florida [49]

When it was discovered that the Brooks Bridge water main was leaking into a nearby conduit, the engineers decided to take it offline and try to rehabilitate it. This high-density polyethylene pipe had a torn pipe joint halfway down the 1400 foot section 70 feet below the bottom of the Santa Rosa Sound. The details for this pipe section are summarized in Table 4.2.

Table 4.2 Data summary for the water project.

Category	Parameter
Length	1400 feet
Diameter	18 inches
Deterioration Level	Partially Deteriorated
Operating Pressure	60 psi
Cross-Section Reduction Allowed	Small
Maximum Bend	11.25°
Service Reconnection	No Service Connections
NSF Certification Required	Yes

The data from Table 4.2 was used in to determine what technically feasible alternatives existed for the rehabilitation of the 18 inch water main. The analysis produced only one technology which was capable of rehabilitating the water main, due to the difficult conditions and pipe size, as shown in Figure 4.2.

Figure 4.2 Results of the water main method selection.

The designers evaluated five options for rehabilitating the pipe: sliplining, close fit lining, pipe bursting, total replacement and a spot repair using stainless steel sleeves. The most cost effective approach was considered to be stainless steel sleeves since the only section of the liner needing rehabilitation was at the location of the torn pipe joint and it would not reduce the flow capacity of the water main, which could not be reduced due its capacity. The only technically viable alternative TAG-R produced was mechanical seals mostly due to the length, which is not a factor for mechanical seals, and its diameter of 18 inches, which is the minimum diameter that mechanical seals are used for. Sliplining was eliminated due to the amount cross-section reduction and folded pipe due to its length limitations. Total replacement is not considered by TAG-R since it is not a trenchless rehabilitation and it was previously addressed in TAG as was pipe bursting [1].

4.4 Case Study #3: Lateral Rehabilitation, Hamilton, Ontario [50]

In 2006, the Hamilton City Council amended their current sewer by-laws which required the City to take control over all of the sewer laterals from the sewer mains to the

owner's property line. This led to the implementation of a city wide trenchless rehabilitation program for sewer laterals. Most of the sewer laterals were vitrified clay pipe (VCP), ranging from four to six inches in diameter, with many being older than 100 years. The size of any excavation had to be limited to 18 inches in diameter and entry onto private properties could only occur under extraordinary circumstances. Table 4.3 summarizes the technical data for a typical sewer lateral needing rehabilitation, which includes the connection to the mainline sewer.

Table 4.3 Data summary for the lateral project.

Category	Parameter
Length	50 feet
Diameter	6 inches
Deterioration Level	Fully Deteriorated Gravity Pipe
Cross-Section Reduction Allowed	Small
Access Available	Mainline, Access Pit or Cleanout
Maximum Bend	22.5°
Cross-Section Transitions	No

The data from Table 4.3 was used in TAG-R the find method suggestions for rehabilitating a sewer lateral and making the reconnection at the main. The results provided four technologies for the rehabilitation of the sewer lateral as shown in Figure 4.3 and one method for reestablishing the connection at the mainline.

Figure 4.3 Results of the sewer lateral method selection.

The rehabilitation results were limited to CIPP, being installed from the mainline or cleanout, and folded pipe, which typically requires small access pits. Since the contract limited the size of access pits to only 18 inches in diameter folded pipe would not have been selected, therefore the only remaining option is CIPP. CIPP was the method used by the contractor that was awarded the project. The only viable option for reconnection to the mainline was a full wrap tee which includes a factory fabricated connection joint between the host pipe and the lateral pipe. The technology includes installing a short section of mainline CIPP (usually 18-24" in length) which is integral to the lateral CIPP.

4.5 Case Study #4: Manhole Rehabilitation, Edmonton, Alberta [51]

The fourth case study involved the creation of a storage zone for the City of Edmonton, Alberta, Canada which created additional operating pressures in the drainage system. This led to an increase in degradation of some the systems deep manholes which were already experiencing corrosion and structural defects. Many of these manholes were deeper than 30 feet with some being as deep as 60 feet, adding to the difficulty of

selecting a technically viable method. The data needed to run the manhole analysis is given in Table 4.4 below.

Table 4.4 Data summary for the manhole project.

Category	Parameter
Manhole Need	Structural Repair
Infiltration/Inflow	Both
Corrosion Level	Heavy Wall Corrosion
Structural Deficiency	Yes
Bench Repair	No
Invert Repair	No
Manhole Collapse	No

The data from Table 4.4 was used to run a manhole evaluation in TAG-R to find construction methods that could rehabilitate a structurally degrading manhole with infiltration and heavy wall corrosion. Although there are very few inputs the results provided only three technologies capable of the rehabilitation as shown in Figure 4.4.
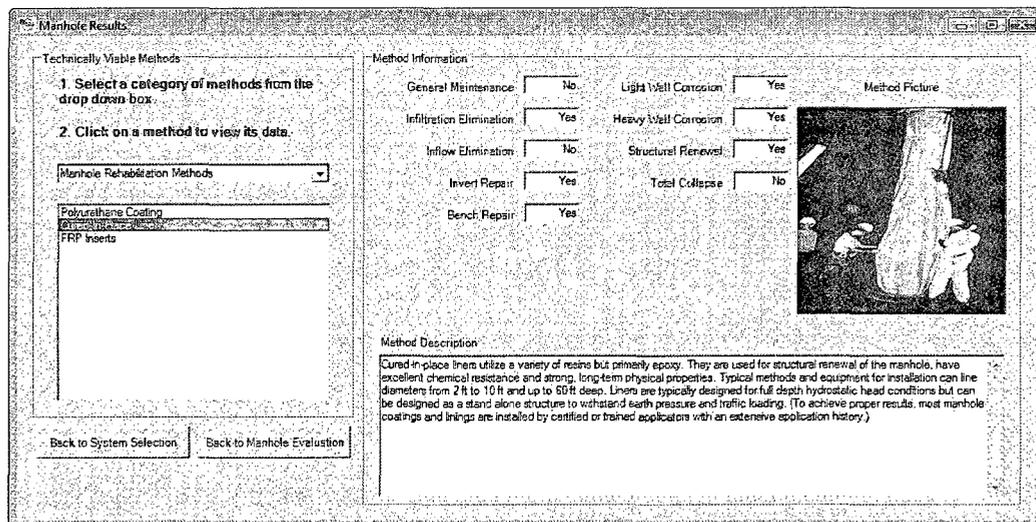
Figure 4.4 Results of the manhole method selection.

The city chose to use a cured-in-place (CIP) liner for the deep manholes which was one of the technologies selected by TAG-R. A polyurethane coating could have also

been used for the rehabilitation, but the City had only tried cementitious coatings in the past with mixed results and did not know of a local contractor that used polyurethane for coating manholes. Fiber reinforced plastic (FRP) inserts would have only rehabilitated the cone and not the complete structure, and thus could not satisfy the full needs of the repair process. The description of CIP liners specifically points out their use down to 60 feet, which is one of the only methods capable of such a deep manhole repair.

4.6 Summary and TAG Online

The strength of TAG-R is its ability to analyze various types of systems, including sewer, water, lateral and manholes. One of the cases above considered technologies that were not considered by TAG-R, but these technologies were considered in its sister software, TAG. The two software programs were recently merged to create a single comprehensive decision support system for all categories of construction methods including rehabilitation, new installation using trenchless technology and open cut technology, and inline replacement methods such as pipe bursting [52]. The new software is available online as a web-based program at the web address <http://138.47.78.37/tagrv2/>. Figure 4.5 shows a screen shot from an analysis run using TAG Online that's specifies new installation, inline replacement and rehabilitation methods. The user manual for the combined software, TAG Online, is provided in Appendix B and the source code for the software is provided on a CD in Appendix E.

61
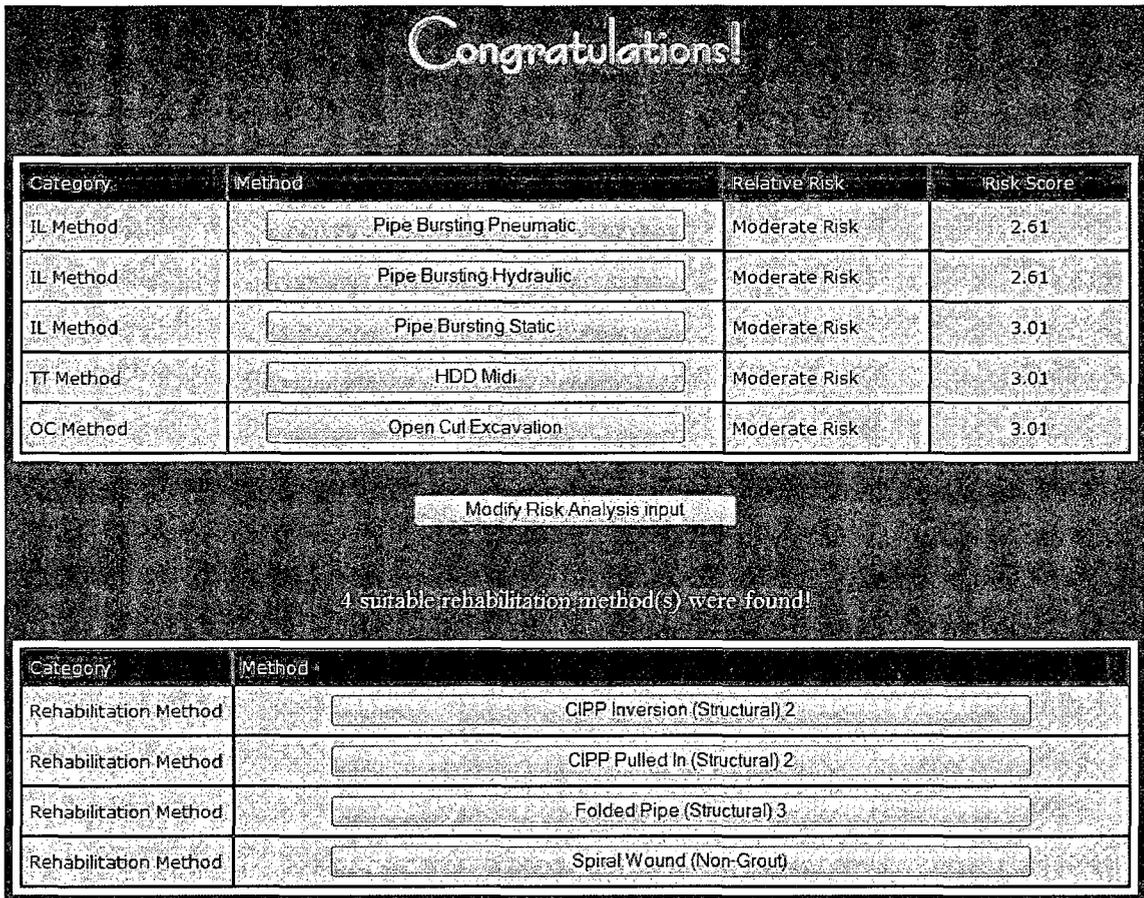
Figure 4.5 Results of a TAG Online evaluation.

CHAPTER 5

SOCIAL COST CALCULATOR FOR UTILITY PROJECTS

5.1 Background

One of the long discussed and studied benefits of trenchless technologies over traditional open trench construction methods is the reduction of costs to parties not engaged in the contractual agreement, commonly referred to as social costs. There are various types of costs associated with a utility construction project some of which are not obvious. In construction projects, costs are commonly classified as direct costs and indirect costs. Direct costs are related physical elements of a construction project and can be estimated. Indirect costs cover administrative costs paid by the owner or contractor for items that cannot be related directly to a given physical element in the project (e.g. supervision). The third, usually unaccounted for, costs are social costs. These are born by parties not directly involved with the contract for which they will not be compensated, but they greatly affect the social and environmental environment within the project's influence area.

Social costs associated with utility type projects have been studied internationally over the past 25 years in relation to the potential reduction accomplished by the utilization of trenchless methods. Early in the development of trenchless technologies such as microtunneling and horizontal directional drilling, direct costs for typical installations were considerably higher compared with open-cut due to the customized

equipment that was used. This led to the study of social costs as the major benefit to using trenchless methods and created the need for valuation methods of social cost factors so that an actual dollar amount could be put on each social cost component. Over the years, many researchers have attempted to quantify social costs using various valuation methods. The research described herein attempts to bring together the most widely accepted methods for estimating social costs in the form of a social cost calculator (SCC) and implores a database which contains acceptable ranges for hard to estimate factors and variables that relate to social cost calculation [53].

5.2 Types of Social Costs

There are many types of social costs that are related to utility construction projects. Some affect people who are in close proximity to the construction site, others affect the environment and others yet affect the infrastructure within the project impact zone. Methods for calculating social costs vary from direct calculation methods to estimation methods using general ranges and conservative estimates. The next four sections describe different categories of social costs and identify the widely accepted methods for calculating (or estimating) them.

5.2.1 Traveler Delays

Traveler Delays are delays which occur due lane and road closures causing vehicular travelers to spend more time on the road, hence less time being productive and delays for pedestrian travelers having to spend more time commuting due to detours. The associated costs include increased vehicle operating costs and delay costs for the

passengers of the vehicles and pedestrians. These three cost subcategories are outlined

below with their respective calculation methods.

5.2.1.1 Traffic Delays

Traffic Delay Costs are due to increased time spent traveling and are based on the

value of time to users (driver and passengers). Traffic delays typically account for more

than 50% of the social cost associated with utility construction projects in urbanized areas

and transportation projects. Several studies have been performed to determine the value

of time to road users. In 1970, the National Cooperative Highway Research (NCHRP)

concluded that the value of time to be $3 per hour per passenger vehicle and $5 per hour

per truck [54]. To adjust these values to current levels a correction factor was applied

based on the All Items Component of the Consumer Price Index (CPI) as shown in Eq.

5.1 [55]

$$F = \frac{215.834 \ (08/09)}{38.8 \ (1970 \ Avg.)} = 5.56273. \tag{5.1}$$

Another approach utilizes a computerized program called MicroBENCOST which was

developed under NCHRP research project 7-12 in 1993. Using this software the value of

time was determined to be $9.75 per hour per passenger vehicle and $18.19 per hour per

truck [56]. These values also need to be adjusted to 2009 levels, and the correction factor

was. A third study by Oregon DOT was used which estimated the value of travel time for

the state in 2003 as $15.31 for passenger vehicles and $24.98 for trucks, respectively

[57]. All of these values are summarized and updated in Table 5.1.

Table 5.1 Summary of value of time for passenger vehicles and trucks.

Passenger Vehicles, ($/Hour/Vehicle)		All Trucks, ($/Hour/Truck)	
NCHRP 133 (1970)	$ 3.00	NCHRP 133 (1970)	$ 5.00
Correction Factor	5.56273	Correction Factor	5.56273
Updated Value (2009)	$ 16.69	Updated Value (2009)	$ 27.81
MicroBENCOST (1990)	$ 9.75	MicroBENCOST (1990)	$ 18.19
Correction Factor	1.65137	Correction Factor	1.65137
Updated Value (2009)	$ 16.10	Updated Value (2009)	$ 30.04
Oregon DOT (2003)	$ 15.31	Oregon DOT (2003)	$ 24.98
Correction Factor	1.17488	Correction Factor	1.17488
Updated Value (2009)	$ 17.99	Updated Value (2009)	$ 29.35
Average	$ 16.93	Average	$ 29.07
Standard Deviation	$ 0.97	Standard Deviation	$ 1.14

Before calculating the delay time the type of delay must first be defined. The three primary delay conditions are: A) a two-lane road with a traffic light or flag person installed to control traffic through the work zone; B) a roadway with one or both ways of traffic being diverted to a detoured route; and C) a multi-lane roadway being delayed by at least one lane being closed down forcing traffic to slow down, converge and queue.

The delay time for the first condition can be estimated by observing several vehicles that pass through the construction zone or it can be calculated using the delay equations from the HCM manual for calculating travel delays [58]. Equations 5.2 and 5.3 outline the formulas for calculating peak hour (TD_P) and off-peak hour (TD_{OP}) traffic delays when a flag person or traffic light is installed

$$TD_P = \frac{\frac{C}{2}\left(1-\frac{g}{C}\right)^2}{1-\left[\min(1,X)\frac{g}{C}\right]} + 900H_P\left[(X_P - 1) + \sqrt{(X_P - 1)^2 + \frac{4X_P}{cPH}}\right] \qquad (5.2)$$

$$TD_{OP} = \frac{\frac{C}{2}\left(1-\frac{g}{C}\right)^2}{1-\left[\min(1,X)\frac{g}{C}\right]} + 900H_{OP}\left[(X_{OP} - 1) + \sqrt{(X_{OP} - 1)^2 + \frac{4X_{OP}}{cOPH}}\right]. \qquad (5.3)$$

The variables g and C refer to the effective green time for each lane group (seconds) and the cycle length of the signal control (seconds), respectively. These values

are chosen based on the average annual daily traffic (AADT) for the lane from Table 5.2. H_P and H_{OP} are the peak and off-peak hours that the traffic stream is being affected over the course of a given day. The saturation of each lane group, or v/c ratio, during peak (X_P) and off-peak (X_{OP}) hours is represented by $X = v/c$, where v is the volume of traffic (vehicles/hour) and c is the lane group capacity (vehicles/hour). The hourly volume of traffic during peak hours (v_P) is used to calculate X_p and is determined by $v_P = AADT \times k$, where $AADT$ is the annual average daily traffic (vehicles/day) and k is a coefficient based on the area of the traffic with $k = 0.1$ in urban areas and $k = 0.09$ in rural areas. X_{OP} is calculated using the off-peak hourly volume (v_{OP}), where $v_{OP} = \frac{AADT - (v_P \times H_P)}{24 - H_{OP}}$. The lane group capacity (c) is determine by first calculating the free flow capacity, $c_{F1} = \frac{1700}{hv}$, where $hv = \frac{1}{1 + (HV\% \times 0.5)}$ and then plugging c_{F1} into the lane group capacity equation, $c = c_{F1}\frac{g}{c}$.

Table 5.2 Values for g and C [23].

AADT (Vehicles/Day)	g (seconds)	C (seconds)
< 3500	100	400
3500-4000	150	500
4000-6500	250	700
6500-7000	300	800
7000-7500	350	900
7500-8000	400	1000
8000-8500	450	1100
8500-9000	500	1200
9000-9500	570	1340
> 9500	610	1420

If a detour is encountered, like in the second traffic condition, the delay will be calculated using a much simpler method shown in Eq. 5.4

$$TD = \left(\frac{D_D}{S_D}\right) - \left(\frac{D_N}{S_N}\right). \tag{5.4}$$

The distances of the construction section (D_N) and the detour section (D_D) are both in miles and the speed through the construction zones (S_N) and detour zones (S_D) are in miles per hour (mph). The traffic delay (TD) can be substituted for TD_P and TD_{OP} when a detour is encountered.

The third traffic condition requires not only calculation of the delay due to a work zone being implemented, which restricts at least one lane of traffic, but also the delay due to queuing when traffic is forced to slow down due to incapacity of the open lanes. Since the lanes that were left open are not able to handle the required traffic demands, vehicles are forced to slow to a queuing speed (S_Q) which is even slower than the already reduced speed through the construction zone (S_N). Equation 5.5 shows the calculation of the work zone delay (TDW) and Eqs. 5.6 and 5.7 outline the formulas for calculating peak hour (TDQ_P) and off-peak hour (TDQ_{OP}) traffic delays due to traffic queuing

$$TDW = \left(\frac{D_N}{S_W}\right) - \left(\frac{D_N}{S_N}\right) \tag{5.5}$$

$$TDQ_P = \left(\frac{D_{AQ}}{S_{QP}}\right) - \left(\frac{D_{AQ}}{S_N}\right) \tag{5.6}$$

$$TDQ_{OP} = \left(\frac{D_{AQ}}{S_{QOP}}\right) - \left(\frac{D_{AQ}}{S_N}\right). \tag{5.7}$$

For the work zone delay, distances of the construction section (D_N) is again known in miles and the normal speed through the construction zones (S_N) and the slowed work zone speed (S_W) are in miles per hour (mph). The traffic delay due to queuing during peak (TDQ_P) and off-peak hours (TDQ_{OP}) require the length of the average number of queued vehicles (D_{AQ}, miles) as well as the reduced speed through the queue during peak (S_{QP}) and off-peak hours (S_{QOP}) in miles/hour.

Before calculating the length and speed of the queued vehicles, the number of queued vehicles must be determined. The first two factors that must be determined are the normal free-flow capacity (c_{F2}) and the reduced capacity due to lane closures (c_R). The normal free flow capacity is based on the maximum capacity (c_M) under ideal conditions for the particular road configuration and the speed limit of the segment being analyzed. Table 5.3 summarizes the maximum capacity in vehicles per lane per hour (vplph) for eight different road configuration and speed limit combinations.

Table 5.3 Maximum capacity for various traffic conditions [58].

Road Type	Speed Limit (Miles/Hour)	Maximum Capacity (Vehicles/Lane/Hour)
Freeway	70 or more	2400
Freeway	65	2350
Freeway	60	2300
Freeway	55	2250
Multi-Lane Highway	60 or more	2200
Multi-Lane Highway	55	2100
Multi-Lane Highway	50	2000
Multi-Lane Highway	45	1900

Once a value is obtained from the table above it must be adjusted for the inclusion of heavy vehicles (hv) and the total number of lanes (l_T), $c_{F2} = c_M \times hv \times l_T$. The reduced capacity depends on the type construction, either short-term or long term. A short-term construction project uses a base value of 1600 vplph which is then adjusted for the level of intensity of the construction work (i), the inclusion of heavy vehicles (hv) and the total number of open lanes in one direction (l_o), $c_R = (1600 + i) \times hv \times l_o$. The values for i typically range from +160 (vplph) for light intensity work to -160 (vplph) for high intensity work. Based on these ranges, trenchless projects were considered to be light applications (+160), and open-cut projects were assumed to be somewhat heavy

applications (-80). For long-term construction zones, the base value can be taken directly as 1700 (vplph) with no further adjustments needed [58].

The reduced capacity due to lane closures (c_R) and the hourly volume of traffic during peak hours (v_P) and off-peak hours (v_{OP}) are used to calculate the queue rate for peak (QR_P) and off-peak (QR_{OP}) periods in vehicles/hour. The general formula is given as $QR = v - c_R$. If the queue rate is greater than zero, a queue of vehicles has built up reducing the speed of the vehicle through the work zone, called queue speed (S_Q, miles/hour) for a distance, which is the length of the average number of queued vehicles, named (D_{AQ}, miles). If the queue rate is less than or equal to zero, a queue has not occurred and the calculation is not needed. When a queue is encountered the queue speed is calculated from Eq. 5.8, which is based on Figure 5.1, which displays the average queue speed versus the v/c ratio

$$S_Q = 24 \times \left[\frac{c_R}{c_{F2}}\right]^{1.335}. \tag{5.8}$$
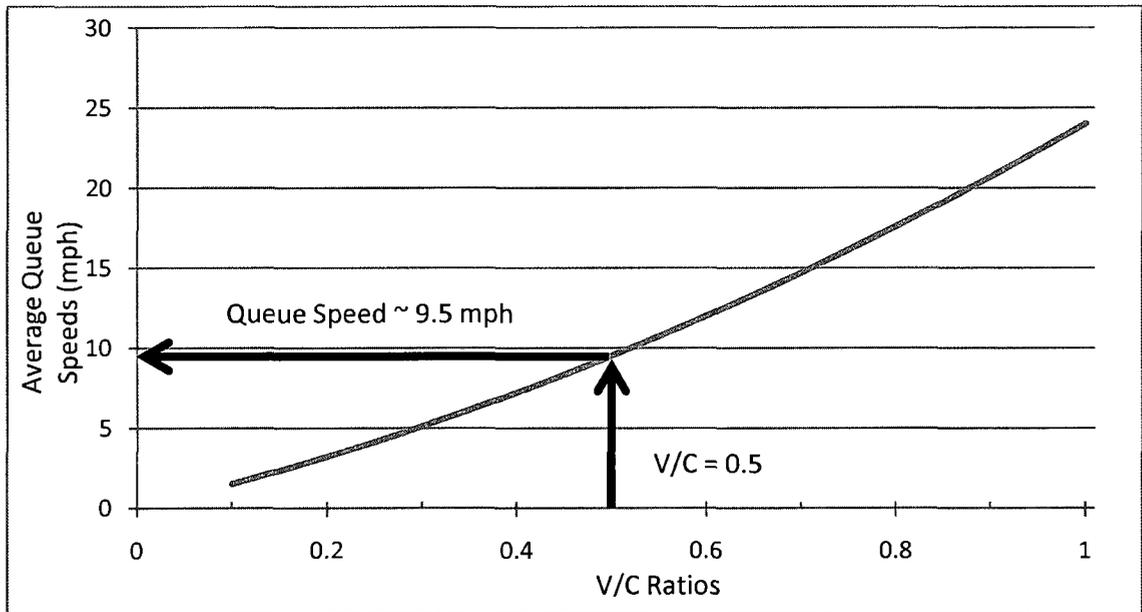
Figure 5.1 Plot showing queue speeds for various v/c ratios [59].

The average queue rate length (vehicles/hour) for peak (DR_{AQP}) and off-peak periods (DR_{AQOP}) is given in general by the formula $DR_{AQ} = QR/l_o$, which is the total number of vehicles sitting in the queue. This is used to determine the length of the average number of queued vehicles (D_{AQ}, miles) by $D_{AQ} = DR_{AQ} \times 0.008$ (*miles/ vehcile*), which the length of the vehicles in the queue using 0.008 miles/vehicle or around 42 feet/vehicle. This value can now be inserted into Eqs. 5.6. and 5.7 to determine the queue delay. The total delay for both peak and off-peak hours is the summation of the work zone delay and the queue delay for that period. These delays can be substituted for TD_P and TD_{OP} when multi-lane traffic conditions exist.

Once TD_P and TD_{OP} have been determined using Eqs. 5.2 and 5.3 for Condition One, or Eqs. 5.5, 5.6 and 5.7 for Condition Three or TD has been determined using Eq. 5.4 for Condition Two, the associated social cost due to traffic delay during peak (C_{TDP}, $) and off-peak ($C_{TDOP}$, $) can be calculated using Eqs. 5.9 and 5.10

$$C_{TDP} = TD_P \times [v_{PV}(HR_C \times C) + v_{PHV}(HR_{HV} \times HV)] \times H_P \times D \qquad (5.9)$$

$$C_{TDOP} = TD_{OP} \times [v_{OPV}(HR_C \times C) + v_{OPHV}(HR_{HV} \times HV)] \times H_{OP} \times D. \qquad (5.10)$$

The hourly rate for the passengers of both regular vehicles (HR_C) and heavy vehicles such as trucks (HR_{HV}) are taken from Table 5.1. The peak hour passenger vehicle traffic (v_{PV}) is determined by $v_{PV} = v_P - (v_P \times HV \%)$, where $HV \%$ is the percentage of heavy vehicles in the vehicle stream. The amount of peak hour heavy vehicle traffic (v_{PHV}) would be equal to ($v_P \times HV \%$). Similarly, the off-peak hour vehicle traffic (v_{OPV}) is determined by $v_{OPV} = v_{OP} - (v_{OP} \times HV \%)$ and the peak hour heavy vehicle traffic (v_{OPHV}) would be equal to ($v_{OP} \times HV \%$). The duration of the project in days (D) is the final

parameter needed for the calculation. The total social cost due to traffic delays (C_{TD}) is determined adding the peak (C_{TDP}) and off-peak (C_{TDOP}) costs together.

5.2.1.2 Vehicle Operating Costs

Vehicle Operating Cost (C_{VO}, $) is increased when a traveler is forced to spend more time on the road in a car or during stop-and-go traffic situations. These costs include fuel costs, as well as maintenance costs due to increased wear and tear on the vehicle and tires. The cost due to numerous speed changes is difficult to estimate, but the increased cost due to longer travel distance can be calculated using established operating cost allowances.

The American Automobile Association (AAA) estimated the average operating costs allowance (OCA) of passenger vehicles as 15.42 cents/mile in 2009 based on an average fuel cost of $2.30/gallon and fuel mileage of 22.7 miles/gallon (mpg) [60]. Other parameters included in the calculation are maintenance and repair costs as well as tire costs. AAA's fuel gage report for the first week of October stated the average gas price as $2.47/gallon [61]. The OCA for passenger vehicles was adjusted using the current gas prices and the Bureau of Labor Statistics (BLS) inflation calculator to 16.18 cents/mile for 2009.

Commercial trucks have a much higher operating cost allowance due to a lower fuel mileage of about 7 mpg and higher maintenance and tire costs due to increased wear [62]. The operating cost for commercial trucks in 2003 was determined to be 35.43 cents/mile based on an average fuel price of $1.50/gallon under highway conditions [62]. AAA's daily fuel gage reports the average price of diesel fuel for October 2009 as $2.62/gallon [61]. When adjusting the OCA estimate for commercial trucks using current

gas prices and adjusting maintenance and tires for inflation, the OCA was found to be

53.86 cents/mile. A summary of the OCA for both passenger vehicles and commercial

trucks are summarized in Table 5.4.

Table 5.4 Operating cost allowances for cars and commercial trucks.

Costs	Passenger Vehicles, (Cents/Mile)		Commercial Trucks, (Cents/Mile)	
	AAA (2009)*	Update**	MNDOT (2003)^	Update^^
Fuel	10.09	10.84	21.43	37.43
Maintenance/Repair	4.56	4.57	10.50	12.32
Tires	0.77	0.77	3.50	4.11
Total	**15.42**	**16.18**	**35.43**	**53.86**

*Based on $2.30/gallon of gas (late 2008)
**Adjusted for $2.47/gallon of gas (9/2009) and inflation
^Based on $1.50/gallon of gas (late 2008)
^^Adjusted on $2.62/gallon of diesel (9/2009) and inflation

Equations for calculating vehicle operating costs for passenger cars and commercial

trucks are shown in Eqs. 5.11 and 5.12, respectively

$$C_1 = ID \times OCA_{PV} \times \left(AADT - (AADT \times HV\%)\right) \times D \qquad (5.11)$$

$$C_2 = ID \times OCA_{CT} \times (AADT \times HV\%) \times D. \qquad (5.12)$$

The increased travel distance (ID) the traveler drives is calculated using the distances of

the construction section (D_N) and the detour section (D_D) both in miles, $ID = D_D - D_N$.

The duration of the project in days (D) is again the final parameter needed for the

calculation. The total vehicle operating cost would be $C_{VO} = C_1 + C_2$.

5.2.1.3 Pedestrian Delays

Pedestrian delays cause the traveler to extend their commute which again leads to

loss of productivity time. Pedestrian delay costs (C_{PD}, $) are due to construction job site

interference of the walkways that pedestrians use. The default value of time used for the

pedestrian is based on their hourly wage rate (HR_P) and can be taken as 50% of that value

to be conservative. The average wage used in the Oregon DOT study was around $16.25/hour making the default wage to be used in this calculation $8.12/hour [57]. Here, the excess time needed to navigate around the interfering construction zone (IT_P, hours) can be estimated, as well as the number of pedestrians being affected (P) since no daily traffic data exists for pedestrian traffic. The equation for calculating a pedestrian delay costs is shown in Eq. 5.13 below

$$C_{PD} = IT_P \times \frac{\$8.12}{Hour} \times P \times D. \tag{5.13}$$

The duration of the project in days (D) is again the final parameter needed for the calculation.

The loss of parking space is an inconvenience to travelers because they are forced to park farther away and spend more time walking and lees time being productive. The associated cost (C_{PS}, $) can be calculated similarly to that for pedestrian delay (C_{PD}, $) in Eq. 5.13.

5.2.2 Access Restrictions

The loss of access to business and companies, due to construction projects, can have a negative impact on society in the form of revenues and comfort. The associated social costs are increased commuting times due to loss of parking spaces, and decreased business revenue, parking meter revenue and parking ticket revenue due to lack of access to parking spaces.

5.2.2.1 Business Losses

Loss of business revenue is affected by lack of access to the business due to lost parking, road and pedestrian access. While some businesses lose business, others might

have problems with making and receiving deliveries which affects how the business runs. There is no direct calculation method for this social cost, but studies have shown that, on average, businesses experience a decrease in total sales of 10% to 50% in the affected area, but whether or not the sales are actually lost to the community or just transferred to other merchants is up for debate.

5.2.2.2 Parking Losses

Loss of Parking Ticket Fines Revenue and Parking Meter Revenues affect local government budgets, especially in smaller municipalities that rely on the on these forms of revenue. These losses can be calculated directly when the frequency of fines and level of occupancy is known for the affected area [34]. The methods for calculating the loss of parking ticket fines revenue (C_{PT}, $) and parking meter revenue (C_{PM}, $) are shown in Eqs. 5.14 and 5.15, respectively

$$C_{PT} = PM \times F \times FT \times D \quad\quad\quad (5.14)$$

$$C_{PM} = PM \times R \times H_O \times O \times D. \quad\quad\quad (5.15)$$

The number of parking meters or spaces (PM, spaces) being affected, the amount of the fine (F, $/fine), the meter rate ($R$, $/meter) and occupancy ($O$), and the duration of the project (D, days) are used along with the frequency that the fines normally occur (FT, fines/space/day) and meter operational hours (H_O, hours) to determine these costs.

5.2.3 Pollution

Pollution can take many forms besides the more traditional occurrences in water and air. Pollution can also be in the form of noise, visual and even dust pollution. These forms of pollution are typically increased when using traditional open-cut methods in lieu

of trenchless technologies. Quantifiable costs such as increased cleaning can be directly calculated where as other forms of pollution must be estimated or determined using the society's wiliness to pay for environmental friendly methods.

5.2.3.1 Noise Pollution

Noise Pollution (C_{NP}, $) can not only affect the productivity of people at work and their happiness at home or leisure, it also contributes to lower housing and property values. Heavy construction machinery, vehicles and increased traffic noise all contribute to this cost. There are two primary ways to account for social cost due to noise pollution. One involves people wiliness to pay for quiet. Some people would gladly pay a fee to free themselves from construction noise and receive peace and quiet [28]. A study performed by Feitelson et.al. showed that home owners would be willing to pay from 2.4% to 4.2% more for their property to avoid an increase of one decibel of noise [63]. One of the most thorough reviews of noise evaluation studies showed on average that a 1 dB increase in noise causes a 0.4% reduction in property values [64]. Another study by Jung and Sinha estimated that housing values decline by 0.17% for each additional decibel (dB) of noise above normal [19]. Yet another study by Allouche and Gilchrist suggested that an increase in noise can actually reduce property values in a range from 0.2% to 1.00% per dBA [16]. Vickridge et.al. (1992) suggested a 0.6% reduction in home prices for every unit increase in noise exposure [38].

Each of the above mentioned studies focuses on the decrease in property value due to permanent noise sources, but construction noise will typically only be applied for fixed period of time. To account for the limited amount of time of construction noise, a reduction factor is applied that reduces the Noise Depreciation Index (*NDI*) depending on

the duration of the project. For projects exceeding one year the NDI is taken at its full value which is conservatively estimated at 0.2% from the studies. The NDI is adjusted to NDI_{ADJ} based on the duration of the project (W) in weeks using Eq. 5.16

$$NDI_{ADJ} = 0.002 \times W/52. \tag{5.16}$$

The method for determining this factor is to reduce the average property value (AVP, $) by a conservative percentage for each of the affected homes (N_H) as shown in Eq. 5.17

$$C_{NP} = (N_C - N_N) \times NDI_{ADJ} \times APV \times N_H. \tag{5.17}$$

The noise due to the construction equipment (N_C) and the normal level of the noise (N_N) in the affected area must be known in decibels to calculate the social cost. The US Department of HUD determined that a site is normally acceptable for residential construction for values as high as 75 dB, which can be assumed to be default value of N_N [65]. One study examined the noise levels or various pieces of construction equipment with the noise levels ranging from 75 – 95 dB on average [66].

5.2.3.2 Dust Pollution

Dust Pollution (C_{DP}, $) can lead to increased cleaning fees or a less acceptable environment which should be cleaned. A simplified approach for calculating this social cost is to directly determine how many additional hours of cleaning (T_{AC}) are required to offset the excess dirt and dust due to the construction process [34]. Another study attempted to quantify this cost based on the area of the windows of adjacent buildings facing the construction area and applying adjustment factors depending on the type of buildings needing the cleaning [28]. The value of this social cost is calculated by determining the increase in frequency that an area must be cleaned using Eq. 5.18

$$C_{DP} = T_{AC} \times R_C \times N_B \times D. \tag{5.18}$$

The wage rate for the extra cleaning (R_C, $/hour) can be input directly using the service rates of the cleaning crew in for the area and is taken by default at a conservative estimate of $15 per hour. The charge needs to be applied for each of the units (N_B) requiring the extra cleanup over the duration of the project (D).

5.2.3.3 Air Pollution

The use of heavy machinery for excavating and trucks used for hauling bedding materials both result in an increase in air pollution. There have been some studies that examined the reduction in property values based on the increase of pollutants concentration. One such study that combined the results of several studies in the US, suggested that for every increase of 1% of the concentration of pollutants in the air resulted in a reduction of approximately 0.1% in property values [38]. The difficulty is in determining the net increase in the concentration of pollutants attributed directly to construction activities.

One method of estimating carbon dioxide emissions was developed by the BCTT [67]. By using this established tool to estimate the carbon footprint of a technology for a given project in terms of tons of CO_2 equivalent, the reduction achieved by various trenchless applications can be computed. Clarkson and Deyes (2000) stated that the generally accepted social cost of a ton of carbon dioxide was between $6-$160/ton [68]. More recent carbon dioxide emission models forecast that the cost of one ton of carbon ranges between $15-$33/ton [69 and 70]. If the increase in CO_2 equivalent emissions (CE_{IN}) is known, it can be multiplied by a conservative value of $30/ton of CO_2 for carbon equivalent emissions to get the cost due air pollution (C_{AP}, $) as shown in Eq. 5.19

$$C_{AP} = CE_{IN} \times \$30/ton. \qquad (5.19)$$

5.2.4 Other Costs

There are many other categories of social costs related to utility construction projects, but only a few can be calculated or estimated reasonably. The loss of pavement life and a reduced level of safety to the public and construction workers are two such factors.

5.2.4.1 Pavement Restoration

Pavement restoration and maintenance costs greatly increase when they are cut into for the purpose of the repair of subsurface utilities and then restored. Open excavations typically result in pavement deformations settlements including cracks near the edge of the trench, which contribute to accelerated degradation of pavements [14]. A study by Boyce and Bried reported that pavement cuts can reduce the design life of a road by as much as 40% [34]. One study in France found that successive repair works at different locations of a road reduced the service life of the street anywhere from 10 to 30 years [37]. A report of recent studies in the U.S. by Downey and Heavens estimated the reduction in pavement life due to trenching to be between 15 and 30% [71].

The most complete study of the effect of pavement service life reduction estimated a 30% reduction once an excavation is made [21]. The study also showed that the increased maintenance and rehabilitation costs could be estimated at C\$146/m^2 for one year old pavement and between C\$85 and C\$140/m^2 for a seven year old pavement over the remaining reduced service life of the pavement. The increased maintenance costs must be added to the reduced value of the pavement to get the total social cost value.

The reduced value of the pavement due to a reduced service life (C_{RS}, \$) can be calculated by Eq. 5.20 using the original construction cost of the pavement (C_O, \$), its

designed service life (L_S, years) and the age of the pavement (A_P, years) at the time it was cut into. After adjusting for inflation and converting into US dollars [72] the increased maintenance costs (C_{IM}) can be estimated conservatively using the area of the excavated road surface (A_{RS}, ft^2) with Eq. 5.21

$$C_{RS} = \left(C_O \times \left(1 - \frac{A_P}{L_S}\right)\right) - \left(C_O \times \left(1 - \frac{A_P}{(0.3 \times A_P) + (0.7 \times L_S)}\right)\right) \qquad (5.20)$$

$$C_{IM} = \$10/ft^2 \times A_{RS}. \qquad (5.21)$$

5.2.4.2 Safety

Safety is also reduced by using traditional open cut methods which can translate into higher insurance costs and more workmen's compensation claims. Open trenches pose a higher risk to the general public and construction workers when compared to trenchless operations. Projects that use trenching operations have accident rates as high as 112% higher than other construction operations in urban environments [70]. Vehicular accidents due to improper traffic signs can lead to increased social costs in the form awarded damages from a civil claim; however these costs cannot be quantified ahead of time. Safety is difficult to quantify as a social cost, but its impact should not be overlooked.

5.3 Social Cost Calculator & Database

The social cost calculator (SCC) uses the characteristics of a given project to estimate its related social costs. The main social cost factor to calculate is the cost due to traffic delays and associated vehicle operating costs. The key to determining this factor is traffic conditions and how the construction method will affect the traffic flow (i.e. lane closures, detour routes, duration of reduction issues). While other factors can be

estimated using the calculator, but the estimation of traffic delays costs is considered to be the most robust and widely recognized social cost factor. Typically it is also the most significant single factor in terms of dollars.

5.3.1 Traffic Delay Costs

Key elements that must be known to calculate traffic delay costs for a given project site are the type of delay (i.e. one-lane closed, detour, multiple lanes closed), the normal capacity (AADT) and the duration of the construction (days traffic will be affected). The type of delay determines how much of the normal traffic flow will be effected. To begin, the delay type should be defined before the actual parameters are input. The software provides four options for the user to choose as shown in Figure 5.2 below.

Figure 5.2 Traffic control plan selection form from SCC.

Once the specific traffic control plan is selected the project data input is displayed. For all traffic conditions the following parameters are to be provided by the user: the duration of the project (days), the 2-Way AADT (can be estimated), the percentage of heavy vehicles in stream, the duration of the peak period of traffic and the area type (urban or rural). When detours are encountered the user is also asked to include

the length of the detour and speed through the detoured zone as well as the length of the normal section of road and normal speed through it. When multi-lane highways are encountered with one or more lanes closed, the user is asked to specify the configuration of the road (i.e. number of lanes, open lanes and posted speed limits). The calculator will use either Eqs. 5.2 and 5.3; 5.4; or 5.5, 5.6 and 5.7; depending on the traffic condition, to determine the delays and import those values into Eqs 5.9 and 5.10 to calculate the social cost due to travel delay.

A key factor for determining vehicle operating cost, if a detour is included in traffic plan, is the operating cost allowance which is given by default as 16.18 and 53.86 cents/mile for passenger vehicles and heavy trucks respectively. The calculator will use Eqs. 5.11 and 5.12 to determine the social cost due to vehicle operating costs for these situations. A comparison between an open cut project utilizing a detour and a trenchless project utilizing only a flag person are compared below in Figure 5.3.

Figure 5.3 Traffic delay and VOC calculation form from SCC.

Since the trenchless project does not call for a detour, the vehicle additional operating costs is assumed to be negligible. Also, due to the shorter duration of the trenchless project the social cost due to traffic delays is only one third of the cost for the open cut project.

5.3.2 Pedestrian Delay Costs

Social costs due to pedestrian delay depends greatly on the number of individuals being affected and the duration over which they are affected. For our previous example, the open cut project had a duration of 20 days as compared to only 10 days for the trenchless project. It is assumed here that the trenchless project only affects pedestrians during the day, whereas the barriers for the open cut project are set up around the clock for safety causing full 24 hour delays. Also, a shorter delay can be expected with trenchless methods since the size of the equipment and scope of the disturbance will generally be greatly reduced. Taking these assumptions into account, Figure 5.4 shows the expected social costs due to pedestrian delay using Eq. 5.13 for the open-cut and the trenchless construction method alternatives.

Figure 5.4 Pedestrian delay cost calculation form from SCC.

construction zone based on an increase in noise pollution in that area. The acceptable level of noise is taken as 75 decibels and for each decibel increase from construction noise the property values are reduced by 0.2 %. Since these studies were performed for cases that consisted permanent increase in noise level (e.g. due to changes in traffic flow or airport traffic), a reduction factor is applied based on the duration of the project. If the project is up to a year or longer the full reduction will be applied to each affected property. The calculator uses Eq. 5.17 to perform the analysis shown in Figure 5.6.

Figure 5.6 Noise pollution cost calculation form from SCC.

5.3.5 Dust Pollution Costs

The calculation of the dust pollution costs uses a direct method based on the increased time needed to clean buildings adjacent to the construction site. The cleaning rate is taken as $15 per hour, but it can be adjusted to reflect the actual costs encountered for a particular project. Figure 5.7 shows the parameters needed for this calculation, which employs Eq. 5.18.

Figure 5.7 Dirt pollution cost calculation form from SCC.

5.3.6 Air Pollution Costs

The air pollution costs are calculated based on studies which estimate the cost

carbon dioxide (CO_2) emissions and an existing calculator that estimates the carbon

footprint of construction projects. The CO_2 emission values need to be known or

estimated using resources external to the SCC software. The CO_2 emissions are

multiplied by a rate, taken as $30 per ton, using Eq. 5.19 as shown below in Figure 5.8

Figure 5.8 Air pollution cost calculation form from SCC.

5.3.7 Pavement Restoration Costs

Pavement restoration costs consist of two components: anticipated reduction in

service life and increased maintenance costs, both results of pavement cuts. The default

value for the initial cost of the pavement section is $3 per square foot. The total cost will be calculated by multiplying this rate by the affected area of pavement, which is length of the repair times the width of the lane being cut into and replaced. The original design life and the current age of the pavement must be known to be able to determine the reduced service life using Eq. 5.20. The increased maintenance cost is based on studies showing an increase in maintenance costs of roughly $10 per square foot over the remaining design life of the excavated pavement which uses Eq. 5.21. The input parameters for calculating the pavement restoration costs are shown in Figure 5.9.

Figure 5.9 Pavement restoration cost calculation form from SCC.

5.4 Discussion

The SCC is useful tool for making realistic estimates about the social impact of construction methods when repairing underground utilities. It brings together the widely accepted methods of calculated and estimating seven social cost categories: (1) traffic delays and VOC, (2) pedestrian delays, (3) parking revenue losses, (4) noise pollution, (5) dust pollution, (6) air pollution, and (7) pavement restoration costs. There are currently no models capable of evaluating all of the seven social cost categories

mentioned above for two competing construction methods as described earlier in the

social cost literature review section and outlined in Table 2.3.

CHAPTER 6

VALIDATION OF SOCIAL COST CALCULATOR

6.1 Validation

Although many case histories are used to create and codify the algorithms adopted by the Social Cost Calculator (SCC) software, it is always necessary to validate the system with real world case studies. This will allow for deficiencies to be identified and for the calculation process to be verified. Since social costs for underground utility projects are hard to quantify, there is very little filed data available for validation purposes. In addition to the lack of data, different assumptions and regional costs can alter the accuracy of the results; therefore the case histories must be understood well so that similar assumptions can be made when running the software. The validation of SCC is outlined below with two case histories conducted by the National Research Council of Canada (NRC) for validating the traffic delay and vehicle operating cost components and one more case histories for validating all of the other parameters. SCC has been validated by running a total of eight total case histories which considered various social costs parameters. Tables C.1 and C.2 in Appendix C summarize the eight case histories.

6.2 Case Study #1: Winnipeg St. and Ross Ave., Regina, Canada [73]

The first project selected involved a railroad crossing repair at a very busy intersection. Although it does not involve an underground utility repair, traffic delay and

vehicle operating cost can be compared to see how well the estimation methods work. The repair only affected traffic for two days, which would eliminate noise and dirt pollution from consideration by SCC. The repair created a detour for the traffic in both directions through a residential area. The traffic data needed to run the SCC is summarized in Table 6.1.

Table 6.1 Data summary for the traffic delay calculation.

Category	Parameter
Traffic Plan	Detour in Both Directions
Duration	2 Days
AADT	12,000 vehicles per day
Peak Period	2 Hours
% Heavy Vehicles	10%
Length of Detour	1.0 Miles
Speed on Detour	30 Mph
Length of Closed Section	0.5 Miles
Speed on Closed Section	45 Mph
Traffic Area	Urban

The data shown in Table 6.1 was input into SCC to compute the traffic delay cost and vehicle operating cost due to the railway repair. The calculation form is shown in Figure 6.1 with the assumptions for value of time (VOT) being a little less than the default values and operating costs allowance (OCA) being a little more than the default values and other estimates made regarding the percentage of heavy vehicles stated in the reference.

Figure 6.1 Results of the traffic delay and VOC calculation.

The traffic delays cost were estimated to be $9,066.67 for the vehicles forced to detour, creating an additional VOC of $1,440.00 based on the SCC calculations. The report determined the traffic delay cost was $8,931 and the VOC to be $1,502. The traffic delay was within 1.5%, which is acceptable. The VOC estimates were found to be within 4.1%, again an acceptable variation.

6.3 Case Study #2: Albert St., Regina, Canada [73]

The second project selected involved a road resurfacing project that took place on the weekend to reduce affect ob the number of peak hour vehicles. The repair created a detour for the traffic travelling in both directions through a highly travelled urban area on Sunday, and the traffic was reduced to only one lane in each direction on Saturday. Traffic data needed to run the SCC is summarized in Table 6.2.

Table 6.2 Data summary for the traffic delay calculation.

Category	Parameter
Traffic Plan (Saturday)	Reduced to 1 lane in Both Directions
Traffic Plan (Sunday)	Detour in Both Directions
Duration	2 Days
AADT (Saturday)	33,000 vehicles per day
AADT (Sunday)	23,000 vehicles per day
Peak Period	1 Hour
% Heavy Vehicles	1%
Length of Detour	1.8 Miles
Speed on Detour	45 Mph
Length of Closed Section	0.2 Miles
Speed on Closed Section	45 Mph
Total Lanes in One Direction	2 Lanes
Open Lanes in One Direction	1 Lane
Traffic Area	Urban

The data from Table 6.2 was input into SCC to determine the traffic delay cost on Saturday and both the traffic delay and vehicle operating cost to society on Sunday due to the roadway repair. The calculation form is shown in Figure 6.2 with the Saturday calculation on the left and the Sunday calculation on the right.

Figure 6.2 Results of the traffic delay and VOC calculation.

The traffic delay cost on Saturday was mostly due to traffic queuing and are estimated to be $737.92 for the day using the SCC. The report determined the traffic delay cost on Saturday to be $759. The traffic delay cost on Sunday was $6,583.11, a significantly larger value due to the log detour of about a mile and half. The report determined the traffic delay to be $6,203 on Sunday. For the VOC, SCC determined it to be $3,753.60 and the report estimated it at $4,656. The traffic delay was within 2.8% for Saturday and 6.1% for Sunday. The VOC for the detour on Sunday was about 19%, lower than determined by the report, this is possibly due to varied values of OCA used in the report with the exact value not being reported. This case study demonstrates the ability of SCC to handle complex traffic control scenarios with a high degree of confidence.

6.4 Case Study #3: Storm Pipe Replacement, Oakland, CA [34]

The first case study that examined multiple social cost factors compared the benefits of using microtunneling versus open cutting a gravity storm drain. Of the seven categories which can be determined with SCC the study addresses five of them (1) traffic delays and VOC, (2) pedestrian delays, (3) dust pollution, (4) road restoration costs, and (5) parking revenue losses. The first section is the traffic delay and VOC and the inputs are summarized in Table 6.3.

Table 6.3 Data summary for the traffic delay and VOC calculation.

Category	Parameter
Traffic Plan	Detour in One Direction
Duration	62 Days
AADT	28,320 vehicles per day
Peak Period	2 Hours
% Heavy Vehicles	5%
Length of Detour	1.9 Miles
Speed on Detour	30 Mph
Length of Closed Section	1.5 Miles
Speed on Closed Section	50 Mph
Traffic Area	Urban
Value of Time	$10.5/HR
OCA	$0.29/Mile

The data shown in Table 6.3 was put into the SCC with the results calculated shown below in Figure 6.3. The traffic delay costs were $307,272 from SCC as compared to $303,555 in the reference, resulting in a difference of 1.2%. The VOC was calculated by SCC to be $101,838.72 and reported as $100,607, resulting in a difference of 1.2%

Figure 6.3 Results of the traffic delay and VOC calculation.

The next parameter considered was the pedestrian delay, which was calculated with the same formula as the reference, meaning that when the same cost parameters are used the results are expected to be very similar. The input parameters are shown in Figure 6.4.
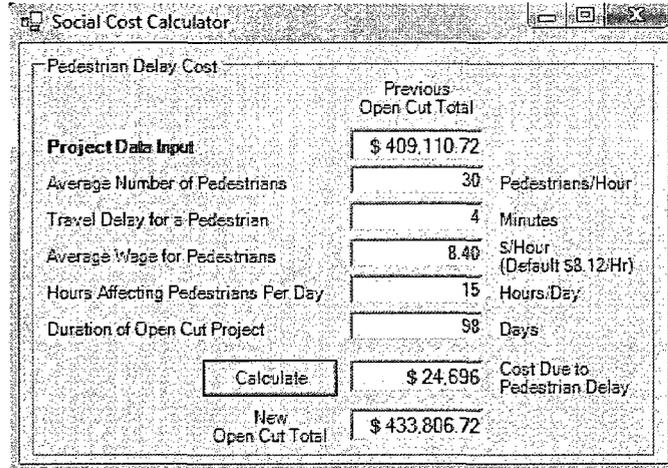
Figure 6.4 Results of the pedestrian delay calculation.

The SCC and report findings were identical, $24,969. Another parameter that uses the same method of calculation as the case study was the dust pollution cost calculation. The input parameters are shown below in Figure 6.5 and as expected the predicted values of this social cost item were found to be identical, at $5,460.
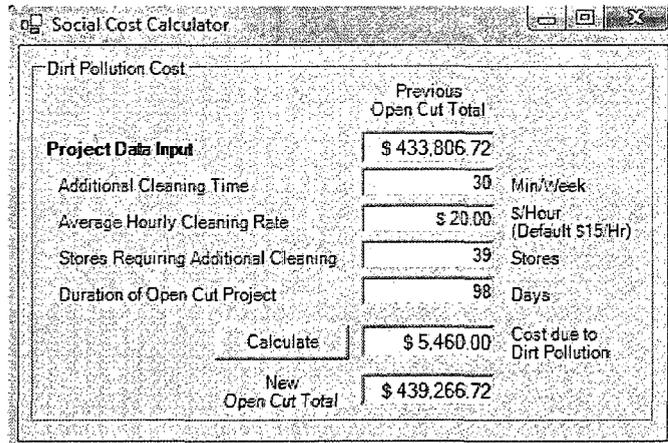
Figure 6.5 Results of the dirt pollution calculation.

The next parameter analyzed was the road restoration costs which the report analyzed by using the direct cost for laying the pavement, but did not include increased maintenance costs or decreased value due to reduced service life. The input parameters for SCC are shown in Table 6.4.

Table 6.4 Data summary for the road restoration calculation.

Category	Open Cut Parameters	Microtunneling Parameters
Cost of Pavement	$3.00/ft^2	$3.00/ft^2
Area of Pavement	25,000 ft^2	2,500 ft^2
Pavement Design Life	30 Years	30 Years
Age of Pavement	30 Years	30 Years
Increased Maintenance Cost	$4.50/ ft^2	$4.50/ ft^2

By assuming the pavement had reached its design life, the reduced service life factor can be neglected (an assumption made in the reference). A conservative factor of $4.50 per square foot was used for an increase in maintenance costs. The results of the calculation are shown in Figure 6.6. It is more likely though that the increased maintenance costs would be higher, perhaps nearly double the rate used. Also, if the pavement was not assumed to have reached its expected design life, a cost would need to be included for that parameter as well.
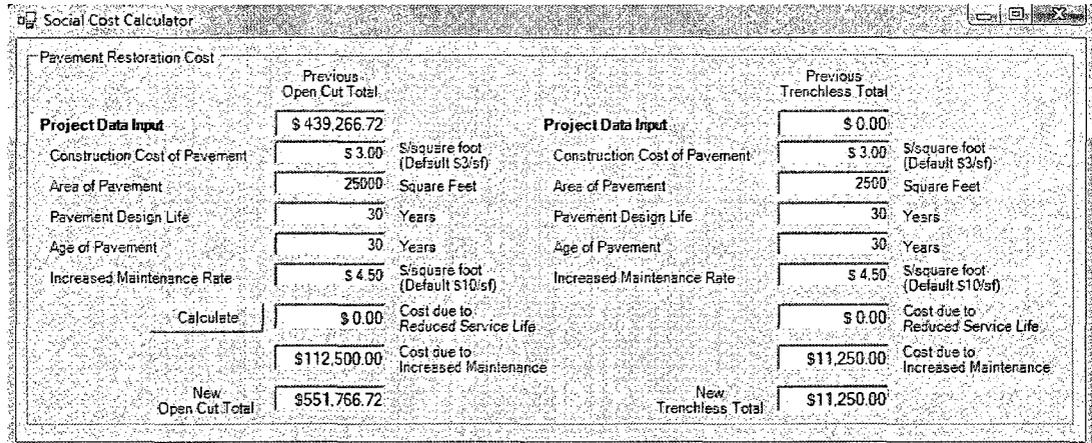
Figure 6.6 Results of the pavement restoration cost calculation.

The report estimated road restoration costs for the trenchless method, microtunneling in this case, to be about 10% of the road restoration costs expected in the case of the open cut construction. The total cost for open cut was stated to be $110,760, while SCC estimated pavement restoration costs to be $112,500, using the assumptions mentioned earlier. In a similar fashion, pavement restoration costs in the case of microtunneling was assumed to be 10% of that of open cut. The difference between the values given in the reference and SCC is 1.6%.

The final parameter analyzed was parking losses due to both loss of parking meter revenue and loss of revenue from parking tickets. This parameter was evaluated using the data shown in Table 6.5.

Table 6.5 Data summary for the parking loss calculation.

Category	Open Cut Parameters	Microtunneling Parameters
Parking Spaces Lost	33	4
Frequency of Tickets	0.38 Tickets/Space/Day	0.38 Tickets/Space/Day
Meter Rate	$0.50/Hour/Space	$0.50/Hour/Space
Normal Occupancy	100%	100%
Meter Operational Hours	8 Hours/day	8 Hours/day

The data above was used to run SCC for the final social cost parameter with the results shown in Figure 6.7.

Figure 6.7 Results of the parking loss cost calculation.

The social cost due to lost parking meter revenue was calculated using the same formula used in the reference; therefore results are equal with the cost for open cut projected at $11,088 and the cost for microtunneling estimated only at $384. The cost due to lost parking fine revenue was calculated in a similar manner, resulting in a value of $24,277.28 for the case of an open-cut construction. The report did not address the parking ticket revenue losses in the case of microtunneling, but SCC calculated this value to be $839.04, as shown in Figure 6.7.

6.5 Conclusion

The advantage presented by SCC is its ability to analyze different social cost factors, and complex traffic control scenarios quickly with a minimal time investment by the user. There is a need for more data for validating the software output, and as the data becomes available different parameters can be adjusted and fine tuned. Future work will include merging SCC with a direct cost database and the TAG method selection software described in Chapter 3 to create a tool that can select technically viable construction methods and then evaluate them based on their direct costs and their social costs factors.

CHAPTER 7

MULTI-SEGMENT OPTIMIZATION OF METHOD SELECTION

7.1 Background

The two software programs developed thus far, TAG and SSC, have focused on the tasks of selecting methods for the construction, replacement or rehabilitation of a particular pipe segment based on its specific characteristics, and determining the associated social costs for each technically viable construction method. Once a TAG evaluation is completed, the user is provided with a list of technically viable methods for that particular segment. However, in most cases multiple segments are involved in a single project. Thus, an optimization of the solution must be made for those multiple pipe segments. One way to determine the optimal solution for multiple line segments is to minimize the number of methods and their anticipated total costs which includes direct costs and social costs. In addition to costs, an associated risk value can be factored into the calculation to account for contingencies. Each technically viable method for a particular pipe segment will have an associated total cost that is comprised of direct and social costs, of which the direct cost is adjusted based on the perceived risk and service life of the pipe material being used. The goal of this chapter is to establish an algorithm that will evaluate all of the combinations of methods capable of installing, replacing or rehabilitating each pipe segment (a solution set). Each solution set, will consist of the number of methods capable of performing the required work, which will be at a

maximum equal to the number of segments needing attention, and will have an adjusted total cost. The total number of solution sets (SS_T) for each project is equal to the product of the number of technically viable methods for each segment as shown in Eq. 7.1

$$SS_T = S_1 \times S_2 \times S_3 \ldots \times S_m \qquad (7.1)$$

where S_1 is equal to number of technically viable methods for Segment 1, S_2 is the number of technically viable methods for Segment 2 and S_m is the number of technically viable for Segment m. The fitness function to be developed should seek to identify the most economical solution based on direct and social costs, while minimizing the number of methods being used. Each solution set will be based on two optimization parameters; the total cost (i.e. direct and social costs) and the number of methods used.

7.2 Optimization Parameters

The first parameter to be considered is the method's direct cost, which is based on historical bid prices compiled at the Trenchless Technology Center (TTC) for various trenchless and open cut construction methods [74]. The direct cost is averaged on a $ per linear foot basis for common pipe diameters. Since the direct unit cost of a method takes into account mobilization and setup costs, it is concluded that the higher the footage that can be completed using a given method, the lower the unit cost will be due to the ability to spread those fixed costs over a longer length. Also, when a given method can be used to address multiple segments, the owner can realize savings in terms of bid preparation and inspector training costs. Therefore an adjustment factor (r) can be applied to the direct cost, which is a function of the length of the segment being installed, replaced or rehabilitated. A summary of the adjustment factors is given in Table 7.1 below.

Table 7.1 Direct cost reduction factors.

Adjustment Factor, r	Length Range, ft.
1.15	< 500
1.05	500 - 1000
1.00	1000 - 2000
0.90	2000 - 3000
0.80	> 3000

The direct cost can also be adjusted based on the perceived risk of the project which is factored in as an increase in the direct unit cost due to difficult site conditions or lack of experience or knowledge with a given technology. The risk calculation, as described in Matthews (2006), is where the risk of a viable method is based on six parameters: the ratios of the drive length (1), diameter (2) and depth (3) to the methods maximum envelope; compatibly with anticipated geological conditions (4); the SET index (5) which is based on the availability of specifications, the owners experience with the method and the method's track record; and, the method's environmental impact (6) [1]. Each risk value is normalized as a percent of the total cost, with a very low risk value of 1.0 being equal to a multiplier of 1.0 and a very high risk value of 5.0 raising the total expected cost of the project by a multiplier of 1.3. The risk multiplier (R_M) can be determined by inserting a method's risk value (R_V) into Eq. 7.2

$$R_M = \left(\frac{(R_V-1)}{4} \times 0.3\right) + 1. \qquad (7.2)$$

Another variable that should be taken into account when determining the direct cost of a given construction method is the expected design life of the rehabilitation method under consideration. This is done by determining the unit cost of the pipe for a base design life of 50 years. If a pipe has a design life of 50 years then its unit cost will remain unchanged. If material had a longer design life, then the design life is adjusted

accordingly. This is accomplished by normalizing the present value of direct cost for 50 years by multiplying the direct cost by a material adjustment factor (M_{DL}), which ranges from 10 (for materials designed for 5 years) to 0.5 (for materials designed for 100 years).

The social cost for each method is calculated using the social cost calculator (SCC) developed as part of this dissertation and described in Chapter 5. Some of the inputs are assumed to fall within typical ranges to make up for the lack of field data and are repeated for each segment in the following example to ensure consistency in the results.

7.3 Case Histories

The multi-segment optimization process can be best explained by using it to evaluate a real world example that involved multiple line segments needing to be replaced or rehabilitated. The three line segments used to show how this process can be used were actual construction projects undertaken by the City of Edmonton, Alberta as part of their Southside Sewer Relief program in the 1990's [75]. All three segments were analyzed with TAG and TAG-R to determine which methods were technically viable along with their associated relative risk values, which are normalized on a scale from 1 to 5. Each of the three segments is defined in the following sections.

7.3.1 Segment #1

The first segment analyzed is a 280 foot long sewer that is 8 inches in diameter. Besides being structurally deficient due to longitudinal cracks and mineral deposits, it was also determined that the line needed to have an increase in hydraulic capacity due to population growth in that area of Edmonton. Thus, it was determined that the sewer line

need to be upgraded to a 12 inch pipe, either by inline replacement or complete replacement by installation of a parallel line segment. The need for increased capacity eliminated rehabilitation options, leaving only new installation and inline replacement methods as viable options. The input required by TAG is summarized in Table 7.2.

Table 7.2 TAG input parameters for Segment #1.

Utility Type	Sewer
Condition	Lacking Hydraulic Capacity
Length of Host Pipe	280 ft.
Host Pipe Diameter	8 in.
New Pipe Diameter	12 in.
Depth of Cover	22 ft.
Accuracy Needed	High (Maximum Deviation +/- 4 in.)
Depth to Ground Water	14 ft.
Host Pipe Material	Vitrified Clay Pipe
New Pipe Materials	PVC and Reinforced Concrete
Soil #1	Firm Clay (50%)
Soil #2	Stiff Hard Clay (50%)
Allowable Extent of Excavation	Continuous
Site Accessibility	Medium (Residential Area)

TAG was used to analyze Segment 1 using the parameters in Table 7.2. Six methods were found to be technically viable. There were three trenchless new installation methods, open cut excavation and two inline replacement methods capable of performing the construction. Table 7.3 provides the methods and their associated risk scores.

Table 7.3 Technically viable methods for Segment #1.

Method	Risk Score	Relative Risk
Pipe Bursting	1.38	Very Low
Microtunneling	1.38	Very Low
Pipe Eating	1.57	Low
HDD Midi	1.74	Low
Open Cut	1.74	Low
Pilot Tubing	2.55	Moderate

7.3.2 Segment #2

The next segment to be analyzed was a 248 foot long, 21 inch gravity sewer. This segment had been upgraded from a 12 inch line to the new diameter due to the need for additional capacity, but the new pipe had become structurally deficient. All options were considered including new installation, inline replacement and rehabilitation methods. The input parameters required by TAG and TAG-R are listed in Table 7.4.

Table 7.4 TAG and TAG-R input parameters for Segment #2.

Utility Type	Sewer
Condition	Lacking Structural Integrity
Length of Host Pipe	248 ft.
Host & New Pipe Diameter	21 in.
Depth of Cover	23 ft.
Accuracy Needed	High (Maximum Deviation +/- 4 in.)
Depth to Ground Water	16 ft.
Host Pipe Material	PVC
New Pipe Materials	PVC and Reinforced Concrete
Soil #1	Firm Clay (50%)
Soil #2	Stiff Hard Clay (50%)
Allowable Extent of Excavation	Access/Receiving Pits Only
Site Accessibility	Limited (Urban Area)
Deterioration Level	Fully Deteriorated
Cross-Section Reduction	Small (Close-Fit Liner Needed)
Access Allowed	Manhole

Even though risk results are not included in TAG-R, a risk value was assigned to each rehabilitation method based on the algorithm developed for TAG. Since depth parameters are not used in the evaluation of rehabilitation methods, a value of 1 (very low risk) was assigned for this parameter. In a similar fashion, soil data is not used for rehabilitation method evaluation and again a value of 1 was used. The final risk parameter needing special consideration for rehabilitation methods is the environmental

impact which was assigned in a similar fashion as it was done for the new construction and inline replacement methods.

TAG and TAG-R software were used to analyze the segment using the above mentioned parameters, and eight construction methods were found to be technically viable. There were three trenchless new installation methods and two inline replacement methods capable of performing the construction from the TAG evaluation. There were also three rehabilitation methods capable of rehabilitating the sewer pipe from the TAG-R analysis. Table 7.5 lists the various methods and their associated risk scores. CIPP was considered to be the least risky method for rehabilitating the segment.

Table 7.5 Technically viable methods for Segment #2.

Method	Risk Score	Relative Risk
CIPP	1.38	Very Low
Microtunneling	1.74	Low
Folded Pipe	2.08	Low
Pipe Splitting	2.08	Low
Spiral Wound	2.40	Low
Pipe Eating	2.40	Low
HDD Midi	2.98	Moderate
Pilot Tubing	3.94	High

7.3.3 Segment #3

The third segment analyzed was a 264 foot long, 12 inch, gravity driven VCP pipe. The CCTV inspection revealed misaligned joints, multiple cracks and several protrusions along the length of the host pipe. This segment was considered to be a fully deteriorated pipe, requiring a structural rehabilitation. It was determined that a new pipe should be installed, with the old alignment being abandoned, which eliminated inline

replacement and rehabilitation methods from further consideration. The input parameters required by TAG are summarized in the Table 7.6.

Table 7.6 TAG input parameters for Segment #3.

Utility Type	Sewer
Condition	Lacking Structural Integrity
Length of Host Pipe	264 ft.
Host & New Pipe Diameter	12 in.
Depth of Cover	15 ft.
Accuracy Needed	High (Maximum Deviation +/- 4 in.)
Depth to Ground Water	16 ft.
Host Pipe Material	Vitrified Clay Tiles
New Pipe Materials	PVC and Reinforced Concrete
Soil #1	Firm Clay (100%)
Allowable Extent of Excavation	Continuous
Site Accessibility	Medium (Residential Area)

TAG was used to analyze Segment 3 utilizing the parameters listed in Table 7.6, with only three methods being recognized as technically viable, two trenchless methods and open cut. Table 7.7 provides the methods and their associated risk scores for Segment 3.

Table 7.7 Technically viable methods for Segment #3.

Method	Risk Score	Relative Risk
Microtunneling	1.19	Very Low
Open Cut	1.74	Low
Pilot Tubing	1.92	Low

7.4 Optimization Parameters for Case History Results

The next step is to determine the optimization parameters so that the best method solution set for the three pipe segments can be determined. The method for determining the direct costs and social costs is described in the following sections.

7.4.1 Direct Costs for Case History Results

The direct costs for each method were compiled from the TTC bid price database and summarized in Table 7.8 [74]. The risk value multipliers, which are determined using the method describer earlier in eq. 7.2, are also shown. Since each of the pipe materials used have at least 50 years expected service life, the associated multiplier was 1.0 and therefore left out of the table [76, 77 and 78]. The direct cost adjustment factors are applied depending on the length of the installation, as per Table 7.1.

Table 7.8 Summary of the direct costs for each method for all three segments.

Segment 1 Methods	Length (ft)	Cost ($/lf)	Cost ($)	Length Adjustment*	Risk Score	Risk Factor	Total ($)
Pipe Bursting	280	100	28,000	1.15	1.38	1.03	33,126
Microtunneling	280	550	154,000	1.15	1.38	1.03	182,192
Pipe Eating	280	240	67,200	1.15	1.57	1.04	80,562
HDD Midi	280	200	56,000	1.15	1.74	1.06	67,991
Open Cut	280	280	78,400	1.15	1.74	1.06	95,188
Pilot Tubing	280	550	154,000	1.15	2.55	1.12	197,706
Segment 2 Methods	Length (ft)	Cost ($/lf)	Cost ($)	Length Adjustment*	Risk Score	Risk Factor	Total ($)
CIPP	248	100	24,800	1.15	1.38	1.03	29,340
Microtunneling	248	600	148,800	1.15	1.74	1.06	180,663
Folded Pipe	248	90	22,320	1.15	2.08	1.08	27,751
Pipe Splitting	248	120	29,760	1.15	2.08	1.08	37,001
Spiral Wound	248	90	22,320	1.15	2.40	1.10	28,363
Pipe Eating	248	600	148,800	1.15	2.40	1.10	189,084
HDD Midi	248	200	49,600	1.15	2.98	1.15	65,505
Pilot Tubing	248	600	148,800	1.15	3.94	1.22	208,863
Segment 3 Methods	Length (ft)	Cost ($/lf)	Cost ($)	Length Adjustment*	Risk Score	Risk Factor	Total ($)
Microtunneling	264	550	145,200	1.15	1.19	1.01	169,359
Open Cut	264	280	73,920	1.15	1.74	1.06	89,726
Pilot Tubing	264	550	145,200	1.15	1.92	1.07	178,502

*All segment lengths less than 500 feet.

7.4.2 Social Costs for Case History Results

Social costs for each segment are described in the following sections. Assumptions are stated and explained for each segment separately. The social costs are

calculated using the SCC described in Chapter 5. The durations for each construction method had to be estimated to be able to determine the full social impact of each method considered to be technically viable.

7.4.2.1 Social Costs for Segment 1

For Segment 1 the length was 280 feet and it was determined that both pipe bursting and HDD installations could be performed in 3 days. The first day would involve digging access pits and stringing out the pipe, while the remaining two days were used for pipe installation and restoration of ground surfaces. Microtunneling, pilot tubing and pipe eating would all require longer equipment setup and takedown times in addition to the actual construction time, resulting in a duration of around six days. While open cut excavation would not require longer setup, it would take longer to restore the pavement resulting in a duration of four days.

Several assumptions had to be made to run the SCC due to a lack of project specific information. However, care was taken to use the same values for each method to avoid biased results. The average annual daily traffic (AADT) was assumed to be 5000 vehicles per day with two peak hours of travel in an urban area for all methods. It was also assumed that all methods would need a flag person installed to help traffic navigate through the construction zone, except for open cut which would require a detour for traffic in one direction around the construction zone.

It was assumed that only the open cut project would delay any pedestrian traffic in the area, with a conservative number of 50 pedestrians per hour being delayed by two minutes each, on average.

Next, it was assumed that 60 parking meters lined the street in the sections where the construction was taking place. Open cut construction would affect all of the meters since the road was closed, whereas microtunneling, pilot tubing and pipe eating would only affect three meters at each access pit location, for a total of six spaces. It was determined that pipe bursting and HDD would only affect two spaces at each access pit location for a total of four spaces, since they have smaller foot prints than microtunneling type construction methods.

For the noise pollution calculation a total of ten properties were assumed to be in the residential area (five on each side of the street) with an average value of $80,000. Since pipe bursting and HDD only take three days, this social cost was considered to be negligible. For all other methods property values were depreciated by 5% of the maximum depreciation value since they took about one week to construct.

Open cut excavation was the only method that would require additional cleaning of buildings around the construction zone for approximately 30 additional minutes. It was assumed that there were only two commercial outfits in this residential area.

The area of pavement needing restoration greatly differs between open cut and the remaining methods. It was assumed that the size of the excavation for the open cut method was 300 feet long and seven feet wide for a total of 2,100 ft^2. Microtunneling, pilot tubing and pipe eating also require two fairly large access pits, roughly five feet by ten feet for a total of 100 ft^2 for both pits. Finally, pipe bursting and HDD would require two pits about five feet by five feet for a total of 50 ft^2. The pavement design life was assumed to be 30 years and age of the pavement was assumed to be 10 years.

Air pollution was determined by inputting in the project data to the BCTT carbon dioxide emissions calculator for determining the CO_2 emissions from the construction operation [67]. A summary of the calculation is provided in Table D.1 located in Appendix D. The social costs for Segment 1 are summarized in Table 7.9.

Table 7.9 Social costs summary for Segment #1.

Segment 1 Methods	Traffic ($)	Pedestrian ($)	Parking ($)	Noise ($)	Dirt ($)	Air ($)	Pavement ($)	Total ($)
Pipe Bursting	5,829	0.00	171	0	0	240	512.50	6,752
Microtunneling	11,657	0.00	513	400	0	300	1025.00	13,895
Pipe Eating	11,657	0.00	513	400	0	300	1025.00	13,895
HDD Midi	5,829	0.00	171	0	0	120	512.50	6,632
Open Cut	4,349	1,949	5,130	1,600	15	2,850	21525.00	37,418
Pilot Tubing	11,657	0.00	513	400	0	300	1025.00	13,895

The total social cost for open cut excavation is nearly three times higher than that of the microtunneling methods and more than eight times higher than the other trenchless methods. This demonstrates the social benefits that trenchless construction methods offer when compared with open cut construction methods.

7.4.2.2 Social Costs for Segment 2

For Segment 2 the length was 248 feet and it was again estimated that both pipe bursting and HDD operations could be performed in three days, where as cured-in-place pipe (CIPP), folded pipe liner and spiral wound liner could be performed in two days. Microtunneling, pilot tubing and pipe eating would all require longer equipment setup and takedown durations resulting, with an estimated duration of six days.

When running the SCC for Segment 2, the assumptions made were similar to those made for Segment 1 (e.g. an AADT of 5000 vehicles per day with two peak hours of travel in an urban area). It was assumed that each method would require a flag person

to help traffic navigate through the construction zone, and that no detours would be needed since open cut excavation was not considered viable in the area.

It was again assumed that a total of 60 parking meters lined the street in the section where construction was taking place. Microtunneling, pilot tubing and pipe eating would only affect three parking meters at each access pit for a total of six spaces. It was determined that pipe bursting and HDD would only affect two spaces for each access pit for a total of four spaces. Since CIPP, folded pipe and spiral wound lining would be installed through the manhole it was assumed that they would not affect any parking spaces.

For noise pollution calculations only two properties were assumed to be in the urban area with an average value of $80,000. Since pipe bursting, HDD, CIPP, folded pipe and spiral lining only take two or three days, this social cost element was considered to be negligible for each of those methods. All other methods depreciated the properties by 5% of the maximum allowable value since they took about a week to complete the project.

The area of pavement needing restoration for microtunneling, pilot tubing and pipe eating methods would again require two fairly large access pits, roughly five feet by ten feet, for a total of 100 ft^2. Pipe bursting and HDD would require two pits about five feet by five feet for a total of 50 ft^2. Since CIPP, folded pipe and spiral wound lining are installed through manholes, no pavement restoration would be needed. The pavement design life was assumed to be 30 years and age of the pavement was assumed to be 10 years.

Air pollution related social cost was computed by inserting the project data into the BCTT carbon dioxide emissions calculator to determine the anticipated CO_2 emissions from the construction operations. A summary of the calculation is provided in Table D.1 located in Appendix D. All of the social costs for Segment 2 are summarized in Table 7.10.

Table 7.10 Social costs summary for Segment #2.

Segment 2 Methods	Traffic ($)	Parking ($)	Noise ($)	Air ($)	Pavement ($)	Total ($)
CIPP	3,886	0	0	60	0	3,946
Microtunneling	11,657	513	80	300	1,025	13,575
Folded Pipe	3,886	0	0	60	0	3,946
Pipe Splitting	5,829	171	0	240	513	6,752
Spiral Wound	3,886	0	0	60	0	3,946
Pipe Eating	11,657	513	80	300	1,025	13,575
HDD Midi	5,829	171	0	120	513	6,632
Pilot Tubing	11,657	513	80	300	1,025	13,575

7.4.2.3 Social Costs for Segment 3

The length of Segment 3 was 264 feet. Microtunneling and pilot tubing were assumed to take six days while construction using open cut excavation was estimated to take about four days.

Pedestrian delays were considered for the open cut alternative, assuming a conservative number of 50 pedestrians per hour being delayed two minutes each on average.

Traffic parameters were similar to those used for Segments 1 and 2, using an AADT of 5000 vehicles per day with two peak hours of travel in an urban area. It was assumed that both trenchless methods would only need a flag person to help traffic navigate through the construction zone. The open cut method would require detours for traffic traveling in one direction.

Parking conditions were assumed to consist of 60 parking meters lining the street in the construction zone. Open cut would affect all 60 meters, but microtunneling and pilot tubing are assumed to only affect three meters at each access pit location for a total of six meters.

Assumptions made in calculating the cost associated with noise pollution were similar to those made for Segment 1, assuming ten properties in a residential area with an average value of $80,000. All three methods depreciated property values by 5% of the maximum depreciation rate since it took about one week to complete the project.

Open cut excavation was considered to require additional cleaning around buildings near the construction zone for an additional 30 minutes. It was assumed that there were only two commercial entities in this area.

The size of the excavation for open cut excavation was assumed to be 300 feet long and seven feet wide for a total of 2100 ft^2. Microtunneling and pilot tubing would require two large access pits, each five feet by ten feet, totaling 100 ft^2. Pavement design life was assumed to be 30 years and the age of the pavement 10 years.

Cost associated with air pollution was calculated by inserting the project data to the BCTT CO_2 emissions calculator to determine to the CO_2 emissions (tons) from the construction operation. A summary of the calculation is provided in Table D.1 located in Appendix D. The social costs for Segment 3 are summarized in Table 7.11.

Table 7.11 Social costs summary for Segment #3.

Segment 3 Methods	Traffic ($)	Pedestrian ($)	Parking ($)	Noise ($)	Dirt ($)	Air ($)	Pavement ($)	Total ($)
Microtunneling	11,657	0	513	400	0	90	1,025	13,685
Open Cut	4,349	1,949	5,130	1,600	15	810	21,525	35,378
Pilot Tubing	11,657	0	513	400	0	90	1,025	13,685

7.4.3 Number of Methods for Case History Results

Given that Segment 1 yielded six methods, Segment 2 yielded eight methods and Segment 3 yielded three methods, the total number of method combinations or solution sets (SS_T), for addressing all three segments is 144, using Eq. 7.1.

Since microtunneling and pilot tubing are the only two methods considered technically viable for all three segments, there are only two solution sets out of the 144 solution sets where only one method can be used to address all segments. This can be represented by a matrix with rows representing all technically viable methods (n) and the columns representing the number of segments (m). This is shown graphically in Eq. 7.3

$$m$$

$$n \begin{bmatrix} S_{11} & S_{21} & S_{31} \cdots & S_{m1} \\ S_{12} & S_{22} & S_{32} \cdots & S_{m2} \\ S_{13} & S_{23} & S_{33} \cdots & S_{m3} \\ S_{1n} & S_{2n} & S_{3n} \cdots & S_{mn} \end{bmatrix}$$

$$\text{For } i = \sum_{n}^{1}, \text{ If} \sum (S_{1,i} + S_{2,i} + \cdots + S_{(m-1),i} + S_{m,i}) = m \tag{7.3}$$

then method n_i = a Single Method Solution Set (SS_1), where m = the number of segments (columns), n = the number of technically viable methods (rows), and S_{mn} = the applicability of the nth method for the mth segment (S = 1 if the method can is technically viable and S = 0 if the method is not technically viable for that segment).

This is outlined, for the example presented here, in Table 7.12 where each method is assigned a '1' if it's technically viable for a given segment and a '0' if it is not viable, as per Eq. 7.3. When the sum of a row equals the total number of segments, three in this case, the method in that row is capable of being a Single Method solution set (SS_1), (e.g. microtunneling and pilot tubing). The product of the sum of the columns, 6 x 8 x 3 = 144 would be the total number of solutions sets, as per Eq. 7.1.

Table 7.12 Single method solution sets.

Methods	Segments			
	S_1	S_2	S_3	Σ
CIPP	0	1	0	1
Folded Pipe	0	1	0	1
HDD Midi	1	1	0	2
Microtunneling	**1**	**1**	**1**	**3**
Open Cut	1	0	1	2
Pipe Bursting	1	1	0	2
Pipe Eating	1	1	0	2
Pilot Tubing	**1**	**1**	**1**	**3**
Spiral Wound	0	1	0	1
Σ	**6**	**8**	**3**	

There are 45 solution sets where two of the segments can be addressed with the same method since, in addition to microtunneling and pilot tubing, there are four other methods that were considered technically viable for two of the three segments: pipe busting (or pipe splitting), pipe eating, open cut and horizontal directional drilling (HDD). To determine the number of Two Method solution sets, the methods have to be compared in pairs to determine if each segment contains a solution. Table 7.13 shows the comparison of two methods, namely open cut and pipe bursting, which would have to be repeated for each combination of two methods to determine the number, if any, of solution sets that exist between the two methods being compared. A Two Method solution set (SS_2) exists only if the sum of each pair of columns is not equal to zero, meaning that at least one method in the comparison is capable of rehabilitating of each the segments.

Table 7.13 Pairwise method comparison.

Methods	Segments		
	S_1	S_2	S_3
Open Cut	1	0	1
Pipe Bursting	1	1	0
Σ	2	1	1

The number of Two Method solution sets for each comparison, is equal to the product of the sum of each column minus the number of Single Method solution sets (SS_1), to eliminate duplication. This can be expressed mathematically using Eq. 7.4

$$SS_2 = (a \sum_m^1 j \sum_m^{a+1} i \sum_n^1 (S_{i,a} + S_{i,j}) \times (S_{i+1,a} + S_{i+1,j}) \times ... \times (S_{i+(n-1),a} + S_{i+(n-1),j})) - SS_1 \quad (7.4)$$

where m = the number of segments (columns), n = the number of technically methods (rows), S_{ij} = the applicability of the jth method for the ith segment (S= 1 if the method can is technically viable and S= 0 if the method is not technically viable for that segment), and a, i and j are counters.

For the example in Table 7.13 comparing open cut and pipe bursting one obtains a total of two Two Method solution sets. The first solution set would be: open cut for Segment 1; pipe bursting for Segment 2; and, open cut for Segment 3. The second solution set would be: pipe bursting for Segment 1; pipe bursting for Segment 2; and, open cut for Segment 3.

A Two Method solution set would not exist in the comparison shown in Table 7.14, since the sum of two of the columns is zero. In this example, there are not construction methods capable of addressing Segment 1 or Segment 3.

Table 7.14 Pairwise method comparison – null solution.

Methods	Segments		
	S_1	S_2	S_3
CIPP	0	1	0
Folded Pipe	0	1	0
Σ	0	2	0

If a Single Method solution (SS_1) exists in the comparison of each pair of methods, it must be subtracted out of the solution set to determine the number of Two

Method solution sets without duplicating previously determined solutions sets, as shown in Table 7.15.

Table 7.15 Pairwise method comparison – real solution.

Methods	Segments		
	S_1	S_2	S_3
Microtunneling	1	1	1
Open Cut	1	0	1
Σ	2	1	2

For the method pairwise comparison shown in Table 7.15, there are three Two Method solution sets, (2 x 1 x 2) -1 = 3. The Single Method solution set, microtunneling, must be subtracted out of the total number of solution since it was already earlier. Once this exercise is repeated for two method combination, as per Eq. 7.4, the total number of number of Two Method solution sets can be determined, 45 in this case. Since there are two Single Method and 45 Two Method solution sets, it can be determined that a total of 97 Three Method solution exists, 144 – 47 = 97. If more than three segments existed, the process described earlier for comparing two methods would have to be repeated for three methods, etc, using Eq. 7.5

$$SS_{n-1} = (a \sum_{m}^{1} j \sum_{m}^{a+1} z \sum_{m}^{a+(m-1)} i \sum_{n}^{1} (S_{i,a} + S_{i,j} \ldots + S_{i,z}) \times \ldots \times (S_{i+(n-1),a} + S_{i+(n-1),j} \ldots +$$

$$S_{i+(n-1),z})) - (SS_1 + SS_2 + \cdots SS_{n-2}) \tag{7.5}$$

where m = the number of segments (columns), n = the number of technically methods (rows), S_{ij} = the applicability of the jth method for the ith segment (S = 1 if the method can is technically viable and S = 0 if the method is not technically viable for that segment), and a, i, j and z are counters.

7.5 Multi-Segment Results

The two solutions having only a single method for addressing each segment had relatively high overall costs even prior to the cost adjustment associated with the total length being between 500 and 1000 feet (see Table 7.1). The costs are summarized in Table 7.16 showing the overall cost before and after applying the reduction factors.

Table 7.16 Results for the two single-method solution sets.

Single Method Solution Sets	Direct Cost		Social Cost ($)	Total	
	Pre-Adj. ($)	Adj. ($)		Pre-Adj. ($)	Adj. ($)
Microtunneling	462,795	485,935	41,155	503,951	527,090
Pilot Tubing	508,757	534,194	41,155	549,912	575,350

Of the 45 solution sets containing two construction methods, 37 resulted in a total lower than microtunneling acting as a Single Method solution set, offering more economical alternatives. The least costly options for the Two Method solutions sets are listed in Table 7.17, with their overall costs (before and after the adjustment to the direct cost based using Table 7.1).

Table 7.17 Results for the top four two-method solution sets.

Two Method Solution Sets		Direct Cost		Social Cost ($)	Total	
Segs. 1 & 2	Seg. 3	Pre-Adj. ($)	Adj. ($)		Pre-Adj. ($)	Adj. ($)
Pipe Bursting	Open Cut	139,002	153,755	48,882	187,884	202,636
HDD	Open Cut	194,107	211,61	48,642	242,748	260,256
Pipe Bursting	Microtunneling	208,249	233,388	27,189	235,438	260,578
Pipe Bursting	Pilot Tubing	216,199	242,531	27,189	243,388	269,720

Of the 97 solution sets containing three methods, all but seven solution sets had a lower total cost than the Single Method solution set represented by microtunneling. However, only three solution sets had a lower total cost than the lowest cost Two Method

solution set ($202,637). The three most economic results for the Three Method solution sets are listed in Table 7.18, with their overall costs.

Table 7.18 Results for the top three three-method solution sets.

Three Method Solution Sets			Total
Segment 1	Segment 2	Segment 3	($)
Pipe Bursting	Folded Pipe	Open Cut	196,678
Pipe Bursting	Spiral Wound	Open Cut	197,290
Pipe Bursting	CIPP	Open Cut	198,267

From the results the best overall solution involves the use of three separate methods: pipe bursting using a PVC pipe on Segment 1, a folded PVC pipe liner for Segment 2 and a newly installed PVC pipe using open cut for Segment 3. The reason such a disruptive method is considered for Segment 3, is because of the high installation costs involved in the use of microtunneling or pilot tubing, despite their relatively lower risk and social costs. From Table 7.18 it can be seen that all three Three Method solution sets call for the utilization of pipe bursting on Segment 1 and open cut on Segment 3. Segment 2 calls for the utilization of close-fit lining methods (all three methods were found to be within a couple thousand dollars). The consistency of the results provides a level of confidence in the analytical procedures used at the various levels of the analysis. The actual project utilized pipe bursting for Segment 1, CIPP for Segment 2 and microtunneling for Segment 3.

7.6 Discussion

The framework described above is the only known decision support methodology capable of evaluating construction methods for the installation, replacement and/or rehabilitation of sewers, water systems, laterals and manholes for multiple pipe segments.

This novel methodology uses a risk assessment, mobilization and service life adjustment to account for a method's direct construction cost, while also calculating the social cost associated with each technically viable method using the tool described in Chapter 5. The uniqueness of this framework is shown in Table 2.1 by comparing its capabilities to the current tools described in the decision support system literature review section.

7.7 Future Work

Although this analysis was conducted manually, the true benefit of this algorithm will be to implement it into a fully automated software. The algorithm will have to (1) be able to save method results from separate TAG analyses, (2) retrieve direct cost data from the available software databases, (3) integrate with SCC to determine the social costs, (4) generate all possible solutions for multiple segments based on the TAG results, and (5) be able to choose the solution with the lowest total adjusted cost.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary

A review of the relevant literature in the area of decision support systems for utility replacement, rehabilitation and installation provided the background for the development of TAG-R. A review of relevant literature in the area of social costs estimation was presented and used as a basis for the development of a social cost calculator. Both software programs are easy to use and highly adaptable to real world applications as shown through their respective validations.

8.2 Conclusions

Conclusions from the research work presented in this dissertation are outlined in the items below:

5. TAG-R contains a detailed database covering more than 70 construction methods capable of rehabilitating sewer pipes, water systems, laterals and manholes which were complied based upon a comprehensive literature search and extensive input from members of NASSCO's TAG-R Subcommittee.

6. TAG online, which combines TAG and TAG-R into a single comprehensive web-based software, provides a dynamic decision support system for the selection of methods capable of installing, repairing and/or rehabilitating buried utilities.

7. The social cost calculator (SCC) can evaluate two competing construction methods at a time for up to seven separate social cost categories: (1) traffic delays and VOC, (2) pedestrian delays, (3) noise pollution, (4) dust pollution, (5) air pollution, (6) road restoration, and (7) parking revenue losses.

8. A framework was developed for performing a multi-segment evaluation using an extensive technical feasibility evaluation, risk analysis, direct costs and social costs. The algorithm identifies the most cost effective solution for numerous pipe segments.

8.3 Recommendations

Future research associated with the enhancement and improvement of the algorithms presented herein is outlined below:

1. TAG-R and SCC need to be integrated to allow for easy transitions from method selection to social cost calculations.

2. The newly combined software should include a direct cost database that contains direct costs in terms $ per foot length for different pipe diameters.

3. The new software should incorporate the framework established in Chapter 7 by codifying an algorithm developed for performing the analysis that can identify the most cost effective solution for multiple pipe segments based on the consideration of all relevant technical, constructability, environmental and economic parameters.

4. A framework for prioritizing multiple projects needs to be established, which incorporates PACP codes and benefit/cost ratios into TAG and SCC as well as the multi-segment optimization framework.

APPENDIX A

SUMMARY OF TAG-R CASE HISTORIES

Table A.1 Summary of TAG-R case histories.

No	Location	Description	Recommendations by TAG-R
1	Minneapolis, MN [48]	86" Brick Sewer, 900' Long Fully Deteriorated Med. Cross-Section Red. MH or Access Pit, 22.5° Bend Diameter Transitions Reverse Crown Curvature	Segmental Sliplining* Concrete Liner (Man Entry) Grout in Place Lining (PVC) Grout in Place Pipe (HDPE) Structural Panel Lining
2	Okaloosa, FL [49]	18" HDPE Water, 1400' Long Partially Deteriorated Small Cross-Section Red. 11.25° Bends, 60 Psi NSF Certification Required	Mechanical Seal*
3	Hamilton, ON [50]	6" VCP Lateral, 50' Long Fully Deteriorated Small Cross-Section Red. MH, Access Pit or Cleanout 22.5° Bend	CIPP Inv.(Main to Cleanout)* CIPP Inv. (Cleanout to Main) CIPP Pulled In (Cleanout to Main) Folded Pipe
4	Edmonton, AB [51]	30-60' Deep Manhole Infiltration and Inflow Problem Heavy Wall Corrosion Structurally Deficient	Cured-in-Place Liner* Polyurethane Coating FRP Inserts
5	Cleveland, OH [79]	60" Brick Sewer, 3000' Long Fully Deteriorated MH or Access Pit, 45° Bend Med. Cross-Section Red. Reverse Crown Curvature	Grout in Place Lining (PVC)* Grout in Place Pipe (HDPE) Structural Panel Lining
6	Ottawa, ON [80]	42" Steel Sewer, 1100' Long Partially Deteriorated Small Cross-Section Red. MH Access	CIPP Inversion* Grout in Place Pipe (HDPE) Polymer Coating (Man Entry)

*Successfully Used

Table A.2 Summary of TAG-R case histories (continued).

No	Location	Description	Recommendations by TAG-R
7	Los Angeles, CA [81]	72" Brick Sewer, 41' Long Fully Deteriorated Med. Cross-Section Red. MH or Access Pit Non-Circular	Segmental Sliplining* Grout in Place Lining (PVC) Structural Panel Lining Concrete Liner (Man Entry)
8	McKinney, TX [82]	8" Water, 1000' Long Partially Deteriorated Small Cross-Section Red. MH or Access Pit, 60 Psi NSF Certification Required	Polymer Coating (Non-Man)* Cement Coating (Non-Man) CIPP Inversion Reduced Diameter Pipe Hose Liner
9	Calgary, AB [83]	12" CI Water, 1000' Long Partially Deteriorated Small Cross-Section Red. MH, 100 Psi NSF Certification Required	CIPP Inversion* Folded Pipe (Mechanical) Reduced Diameter Pipe Hose Liner Polymer Coating (Non-Man)
10	Huntington, CA [84]	42" Steel Water, 3650' Long Fully Deteriorated Med. Cross-Section Red. Access Pit, 60 Psi NSF Certification Required	Segmental Sliplining*
11	Roseville, MI [85]	84" Culvert, 900' Long Fully Deteriorated Small Cross-Section Red. Box Shape, MH Access	CIPP Inversion* Grout in Place Pipe (HDPE) Concrete Liner (Man Entry)
12	San Jose, CA [86]	84" RCP Sewer, 1950' Long Fully Deteriorated Med. Cross-Section Red. MH or Access Pit 22.5° Bend	Segmental Sliplining* CIPP Inversion Structural Panel Lining

*Successfully Used

APPENDIX B

TAG ONLINE USER'S MANUAL

TAG/R ONLINE

TRENCHLESS ASSESSMENT GUIDE

User's Manual

Version 3.0 - February 2009

Developed for:

The National Utility Contractors Association

And

The National Association of Sewer Service Companies

By:

The Trenchless Technology Center
Louisiana Tech University

Credits: John C. Matthews, Dr. Zhenyang Duan, Joseph Berchmans and Prof. Erez N. Allouche

TTC DISCLAIMER

This manual and program, entitled Trenchless Assessment Guide (TAG/R), was prepared by the Trenchless Technology Center (TTC) for the National Utility Contractors Association's (NUCA's) Trenchless Technology Committee and for the National Association of Sewer Service Companies (NASSCO). Neither TTC, NUCA, NASSCO, nor any person acting on their behalf, makes a warranty, express or implied, with respect to the use of any information, apparatus, method, or process disclosed in this manual or that such use may not infringe on privately owned rights; or assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this manual or on this program.

NUCA DISCLAIMER

The suggestions, procedures, and precautions set forth in this manual and on this program are a compilation and explanation of methods and equipment successfully used by contractors to install underground utilities. These suggestions, procedures, and precautions should not be considered as an infallible method of installing underground utilities. Accordingly, there is no guarantee that the methods and procedures will be successful in all applications. While the authors have done their best to ensure that the information in this manual is accurate; no liability or responsibility of any kind is accepted by the authors, the National Utility Contractors Association, or the Trenchless Technology Committee.

NASSCO DISCLAIMER

The decision, by an Engineer, Designer or Municipal Official (decision makers) of how to accomplish the renewal of a deteriorated buried pipe, in an urban environment, must be based on tangible parameters. These parameters can then be assembled and inserted in a computer software program to create a tool that simplifies this decision process.

NASSCO and the Trenchless Technology Center (TTC) of Louisiana Tech have developed this comprehensive, yet straightforward and user friendly interactive software for the evaluation of alternative renewal methods. These methods can then be employed in the rehabilitation of gravity pipes, pressure pipes, laterals and manholes.

The software will emphasize simplicity and practicality, and limits input data to those readily available to utility and municipal engineers at the design stage of a renewal project. Based on the specific characteristics of the problem(s) facing the decision-maker, the software performs a preliminary screening, eliminating technologies unlikely to meet the project's requirements. A technical evaluation is then undertaken, during which the technical capabilities of the various technologies identified in the first step are compared with the project's requirements. The TAG-R program takes into account extensive performance data for a number of technologies and sub-technologies for access point to access point pipe renewal, a number of spot repair technologies and manhole renewal methods commonly used for pipe renewal projects.

A INTRODUCTION

A.1 BACKGROUND
The decision of how to accomplish the installation or repair of a buried pipe in an urban environment involves tangible and intangible parameters. To assist with that decision, NUCA's Trenchless Technology Committee commissioned the Trenchless Technology Center (TTC) to develop a straightforward and easy to use interactive software program for the evaluation of alternative construction methods that can be employed in the installation or replacement of buried pipes and conduits. The program, titled TAG (Trenchless Assessment Guide), was designed as a stand-alone software to assist municipal and utility engineers in evaluating the technical feasibility of various traditional new installation open cut, new installation trenchless construction and inline replacement methods for a specific project, and is intended to be a companion to NUCA's Trenchless Construction and Rehabilitation Methods Manual (4th Edition). Trenchless rehabilitation methods were not considered during the technical evaluation of a project by Version 1 of the software, but they were included in Version 2 of the software developed in conjunction with NASSCO called TAG-R. TAG Online combines NUCA's Version 1 with NASSCO's Version 2 to create the complete evaluation software.

TAG/R takes into account extensive performance data for more than 70 construction methods commonly used in utility type projects. The software emphasizes simplicity and practicality, and limits input data to that which is readily available to utility engineers at the design stage of the project. Based on the characteristics of the problem(s) facing the decision-maker, the software performs a preliminary screening aimed at eliminating technologies unlikely to meet the project's technical requirements. A technical evaluation is then undertaken during which the technical capabilities of various technologies identified in the first step are compared with the project's attributes. Next, a risk analysis is performed, if a new alignment or inline replacement is considered, based on the characteristics of the project's environment and anticipated soil conditions. Finally, the recommendations of the program are shown with their respective risk score's if applicable.

A.2 SYSTEM REQUIREMENTS
TAG Online is compatible with Microsoft® Windows® Internet Explorer.

A.3 ACCESS
The web address to access TAG Online is <http://138.47.78.37/tagrv2/>. The user is asked to enter a Username and Password. The temporary login information is given here and is followed by screen shot of the login page: **Username:** ttc   **Password:** ttc123
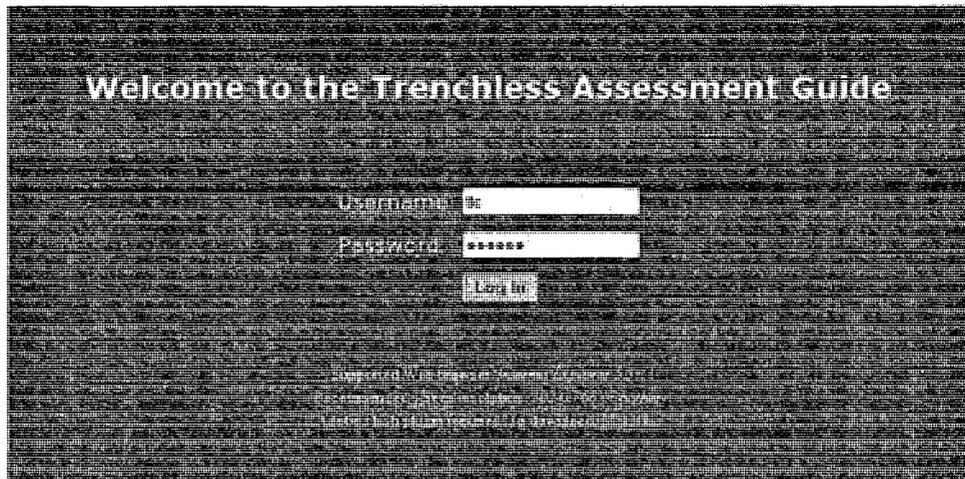
B CONSTRUCTION METHOD DATABASE
B.1 STRUCTURE
The relational method databases contain a plethora of information about each method. The general information section includes a detailed description and a representative color picture. The method's technical capabilities include maximum and minimum pipe diameters, maximum and minimum drive lengths, etc. Other technical information embedded in the database is the method's level of compatibility with ten common types of soil (defined in Appendix E.1); compatibility with various common pipe materials; environmental impact factor; required extent of excavation; groundwater table classification; alignment accuracy; profile accuracy; ability to navigate bends; ability to rehabilitate different deterioration levels; etc.. All of the construction parameters are defined in Appendix E.1.
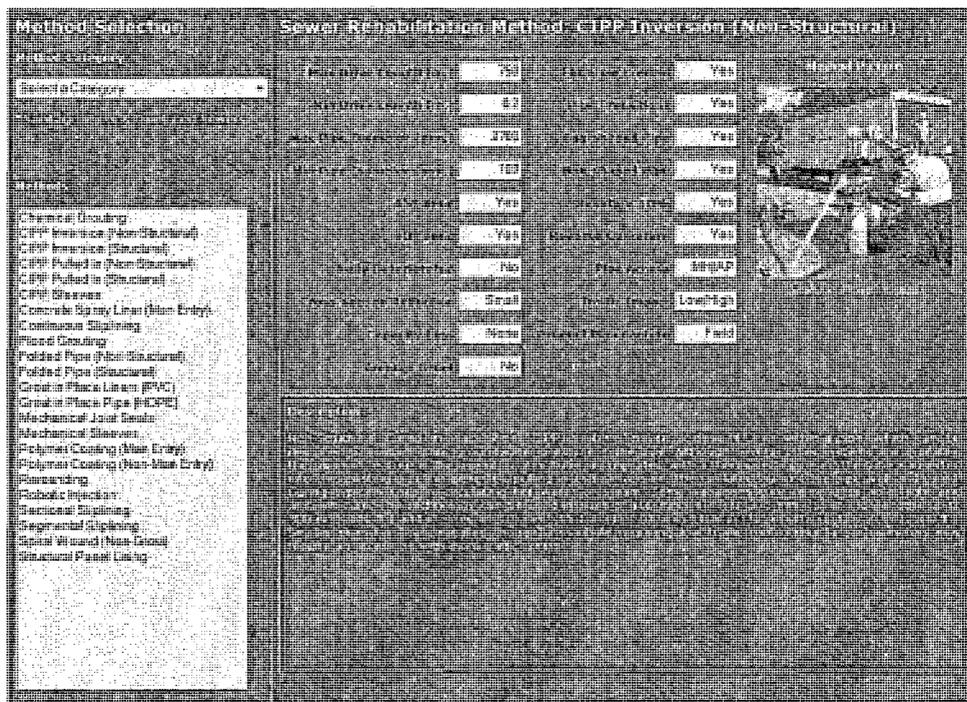
C TUTORIAL
C.1 CASE STUDY 1

This case history was taken from the J. Edward Drain Interceptor Project in Westfield, Indiana. Due to the rapid growth of the town, which is located about 24 km. (15 m.) north of Indianapolis; a new sewer system was required to satisfy the increasing volume of wastewater. This particular segment considered was constructed in 2004 on a 175 m. (575 ft.) stretch of 600 mm. (24 in.) vitrified clay pipe. Relevant input parameters are summarized below.

J. Edward Drain Interceptor - Information Summary

Length	175 m. (575 ft.)
Depth	6 m. (20 ft.)
GWT Depth	4.5 m. (15 ft.)
Host Pipe Diameter	N/A*
Host Pipe Material	N/A*
New Pipe Diameter	600 mm. (24 in.)
New Pipe Material	VCP
Alignment Accuracy	4 (High)
Profile Accuracy	4 (High)
Soil Type #1	Medium Sand (40%)
Soil Type #2	Soft Clay (35%)
Soil Type #3	Gravel (25%)
Excessive Sagging	N/A*
Pipe Upsize > 2.5	N/A*
Extent of Excavation	Access/Receiving Pits Only
Site Accessibility	Limited Accessibility (Golf Course)

*N/A – Not Applicable

TAG consists of 2 primary phases, a technical evaluation and a risk analysis. The verification exercise begins with the extraction of the relevant technical information from the design documents for use as input data. Rehabilitation methods were not considered due to the fact that more capacity was needed.

C.1.1 Problem Selection
Begin by clicking on **Technical Evaluation** at the top of the main page which leads to the Structure Selection page. Select the type of structure that needs addressing, which in Case #1 is **Pipelines** and **Sanitary Sewer (Gravity Flow)** and then click **Next.**

Since the pipe is lacking capacity select **Capacity Problem**. Then select **Consider New Alignment (Includes Open Cut Methods)** and then click **Next**.

C.1.2 Project Input

Based on the definition of the problem the software will only be considering New Alignment methods, but trenchless methods for Inline Replacement and Rehabilitation methods can be added to the evaluation by checking their respective check boxes. Next, the user is asked to input the following installation parameters: **Drive Length** = 175 m, new **Pipe Diameter** = 600 mm, **Depth of Cover** = 6 m, **Alignment Accuracy** = 4 (High; defined in Section D.1.), **Profile Accuracy** = 4 (High; defined in Section D.1.), and **Ground Water Table Depth** = 4 m. Input these values into the **Construction Parameters** page and then click the **Next** tab.

The three dominant soils along the alignment are **Medium Sand** (40%), **Soft Clay** (35%) and **Gravel** (25%). Input these values into the **Soil Parameters** page by first selecting the three soils and then adjusting their respective percentages. Then click **Next**.

For the **Pipe Installation Details** specify the **Allowable Extent of Excavation** as **Access/Receiving Pits Only**, since the project is on a golf course and select **Vitrified Clay Pipe** as the pipe material and click **Next** to go to the Risk Analysis.

C.1.3 Risk Analysis

Although only one method was found to be technically viable the risk analysis will still assign a level of risk relative to the project data. To begin the risk analysis, input the **SET Criteria** by selecting one option from each of the three categories based on your experience: **Specifications** availability (**National/ASTM** for Microtunneling Slurry), owner's **Experience** (**Some** for Microtunneling Slurry), and method **Track Record** (**More than 5 Years** for Microtunneling Slurry). After selecting one option from each category go to the **Weight Adjustment** section and assign a weight to each of the six risk factors based on their importance in relation to the project under consideration.

You may choose to leave the weights at their default values, with each risk factor having an equal weight. Now, select the **Site Accessibility** from one of the five options shown (**Limited Accessibility** in this case) and then click **Calculate Risk Scores**.

Please select the level of Site Accessibility for the given project.

Site Accessibility

○ **High Accessibility**
The installation right-of-way is fully accessible over the entire length of the alignment. An example of this site would be a green field.

○ **Medium High Accessibility**
The installation right-of-way is almost completely accessible. An example of this site would be low density housing.

○ **Medium Accessibility**
The installation right-of-way is accessible with some difficulty. An example of this site would be an industrial or residential area.

◉ **Limited Accessibility**
The installation right-of-way is accessible in a limited number of sections. An example of this site would be a downtown area.

○ **No Accessibility**
The installation right-of-way is not accessible over the entire length of the alignment. An example of this site would be an airport runway or river crossing.

Calculate Risk Scores

C.1.4 Results

The results of the complete analysis are displayed on the **Risk Scores** page which contains all technically viable methods, their respective values, and risk classifications.

Risk Scores

Congratulations!

Category	Method	Relative Risk	Risk Score
TT Method	Microtunneling Slurry	Low Risk	2.39

Modify Risk Analysis input

Only one construction method was found to satisfy all of the project's technical requirements. Microtunneling Slurry was considered to offer a relatively low level of risk/potential for adverse impact when compared to project parameters. Some other methods might be able to complete the installation described above, but only Microtunneling Slurry is found to be viable based on the recommended and reasonable data found in the database.

C.2 CASE STUDY 2
C.2.1 Problem Selection

The second case history is from the City of Calgary, AB, Canada, which was trying to identify a suitable repair methodology for a deep sewer located in the downtown area.

Problem Type

Select the type of Construction you want to consider

⦿ Structural Problem

☑ Consider New Alignment (Includes Open Cut Methods)
☑ Consider Inline Replacement
☑ Consider Rehabilitation

Does the number of repairs for the proposed line exceed 3?

⦿ Yes ○ No

○ Capacity Problem

☐ Consider New Alignment (Includes Open Cut Methods)
☐ Consider Inline Replacement
☐ Consider Rehabilitation

Does the number of repairs for the proposed line exceed 3?

○ Yes ○ No

Next

C.2.2 Project Input

The gravity driven sewer was a 95 m (300 ft.) long, 600 mm (24 in.) diameter vitrified clay pipe, with an average depth of about 6 m (20 ft.). The input form for the inline replacement data is shown below.

Construction Parameters

Input the construction parameters below

Drive Length	95	m
Pipe Diameter	600	mm
Depth of Cover	6	m
Alignment Accuracy	4 - Maximum Deviation of +/- 0.1 m.	▼
Profile Accuracy	4 - Maximum Deviation of +/- 0.1 m.	▼
Ground Water Table Depth*	6	m

*Defined in the User's Manual

Next

Based on CCTV inspection data it was concluded that the host pipe was fully deteriorated, and thus a structural solution capable of resisting earth loads, any relevant live loads and the hydrostatic pressure applied by the groundwater was needed.

Construction Parameters (for Rehabilitation)

Input the Construction parameters below

Length	95	m Need help!
Diameter	600	mm Need help!
What is the deterioration level of the host pipe?	Fully Deteriorated (Structural) ▼	Need help!
How much can the cross-section of the host pipe be reduced by the renewal?	Minimal ▼	Need help!
What type of access is available to install the technology?	Either ▼	Need help!
Does the host pipe contain any bends?	11.25° ▼	Need help!
What is the cross-sectional shape of the host pipe?	Circular ▼	Need help!
Does the pipe have a cross-section size transition?	No ▼	Need help!
Does the host pipe have a reverse crown curvature?	No ▼	Need help!

Next

Soil conditions and the host and new pipe details are input next. Typical soil conditions in Calgary's down town area consists of river valley flood plain deposits (a mix of medium sand, 70%; and gravel, 30%). As for the replacement pipe, PVC and HDPE pipes were considered as the best options.

Pipe Installation Details

Input the details for the host pipe and the new pipe

Please specify the allowable extent of excavation.

Continuous Excavations ▼

Please specify the host pipe material.

Vitrified Clay Pipe ▼

Does the existing pipe suffer from excessive sagging or misalignment?

No ▼

Does the pipe diameter need to be increased by a factor greater than 2.5?

No ▼

Please specify the new pipe material(s). *(Press Ctrl for mutiple selections)*

Ductile Iron
PVC
Fiber Glass Reinforced Plastic
High Density PE/Medium Density PE
Vitrified Clay Pipe

Next

C.2.3 Results

The detailed project data was input into TAG Online, which identified static pipe bursting as the least risky construction approach. TAG also identified structural cured-in-place

pipe (CIPP), structural folded pipe and spiral wound lining as viable rehabilitation technologies for the pipe in question. The City of Calgary initially selected static pipe bursting as the construction method of choice for this project, but decided to opt for pneumatic pipe bursting once it was determined that no utilities were sufficiently close to be disrupted by the method and the project was completed successfully, on time and budget.

Congratulations!

Category	Method	Relative Cost	Risk Score
IL Method	Pipe Bursting Pneumatic	Moderate Risk	2.01
IL Method	Pipe Bursting Hydraulic	Moderate Risk	2.01
IL Method	Pipe Bursting Static	Moderate Risk	2.01
TT Method	HDD Method	Moderate Risk	3.01
OC Method	Open Cut Excavation	Moderate Risk	3.01

Modify Risk Analysis Input

4 suitable rehabilitation methods were found.

Category	Method
Rehabilitation Method	CIPP Inversion (Structural) 2
Rehabilitation Method	CIPP Pulled In (Structural) 2
Rehabilitation Method	Folded Pipe (Structural) 3
Rehabilitation Method	Spiral Wound (Non-Struc)

C.3 CASE STUDY 3
C.3.1 Problem Selection
TAG is also capable of identifying suitable manhole rehabilitation methods based on standard condition assessment data. The evaluation is based on the following conditions: level of infiltration/inflow, level of corrosion, structural integrity, and the condition of the bench and invert. This capability is demonstrated by assessing the following project undertook by the City of Columbus in 2003.

C.3.2 Project Input
Segment 1 of the Franklin-Main interceptor sewer consists of 580 m. (1900 ft.) of 600 mm. (24 in.) vitrified clay at depths of up to 5 m. (15 ft.) that was originally constructed in 1913. The sewer extends through heavily developed residential areas and is adjacent to the Olentangy River. Review of CCTV images revealed that between a third and a half of the sewer cross-sectional area was filled with debris. The maximum ovality in the host pipe was less than 10% and the pipe was considered to be only partially deteriorated. It was also decided that by-passing of the line for the duration of the project was doable. There were no significant bends (greater than 12°) in the host pipe or cross-section

transitions. The design report concluded that the entire length of the pipe should be rehabilitated using CIPP, and each of the existing manholes rehabilitated with cementitious linings to improve their structural integrity.

Manhole Conditions

General Cases

Does the manhole require maintenance, a protective coating or structural renewal?	Structural Renewal ▾	Need help!
Does the manhole have Infiltration or Inflow?	No ▾	Need help!
What is the corrosion level in the manhole?	No Corrosion ▾	Need help!
Does the manhole have structural deficiencies?	Yes ▾	Need help!

Invert / Bench Repair

Does the manhole bench require repair?	No ▾	Need help!
Does the manhole invert require repair?	No ▾	Need help!

Manhole Collapse

Has the manhole collapsed?	No ▾	Need help!

Next

C.3.3 Results

The program suggested that only CIPP or a Spiral wound liner could be used to rehabilitate the 580 meters of interceptor sewer in a single operation. While identifying cementitious coating as a viable rehabilitation method for the manholes, TAG suggested that several alternative approaches might also be deemed adequate for this project.

Manhole Rehabilitation Methods

Congratulations!

Category	Name of Method
Manhole Rehabilitation Method	Cementitious Coating
Manhole Rehabilitation Method	Cementitious - Cast-In-Place
Manhole Rehabilitation Method	Epoxy Coating
Manhole Rehabilitation Method	Polyurethane Coating
Manhole Rehabilitation Method	Cured-In-Place Liner
Manhole Rehabilitation Method	FRP Inserts
Manhole Rehabilitation Method	Replacement

D RISK SCORE
D.1 COMPUTING A METHOD'S RISK SCORE

This section provides additional insight into the mathematical formulation used for calculating the risk score for each construction method. The risk score is the weighted average of six contributing risk factors. Four of these factors (Length Ratio, Diameter Ratio, Depth Ratio and Soil Compatibility Index) reflect the level of comfort with which a construction method meets the project's technical requirements. In other words, regardless of whether the installation length is at the 25th or 95th percentile of the method's range, the method will be deemed technically viable. However, it is argued that the potential risk in the latter case is greater than it is in the former case. The relative level of risk is expressed as the ratio of the installation's length to the maximum installation range of the method under consideration. The same rationale is applied to the depth of installation and product diameter.

For soil compatibility, the level of risk is based on the percentage of **Possibly Compatible** soils along the project's alignment. For example, in the second case study soil conditions were specified as: medium sand (60%); stiff hard clay (35%); and gravel (5%). If a method is only possibly compatible with medium sand and gravel (65% of alignment), and fully compatible with hard clay then the perceived risk is considered to be higher than if the method was fully compatible with medium sand and stiff hard clay, but only possibly compatible with gravel (5% of alignment).

The remaining two parameters that comprise the risk score measures of the owner's level of comfort with the method (direct experience, method's track record, and availability of specifications) and the potential adverse impact on the natural and built environments.

A user might choose to give all contributing parameters an equal degree of importance (i.e., weight) or different degrees of importance. In some cases, the user might choose to completely ignore some of the parameters. Adjusting the importance of a given factor is accomplished by dragging the 'handle' on the sliding bar with the mouse.

As an example, let us assume that the owner in Case Study 2 has an established working relationship with a competent and environmentally conscious HDD contractor. Thus, the owner wishes to re-run the analysis giving lower weights to the four technical aspects. The following screen shot shows the **SET Index** and **Environmental Impact** factors set to 100% (or high importance), while the remaining contributing factors are set to 20% (or low importance).
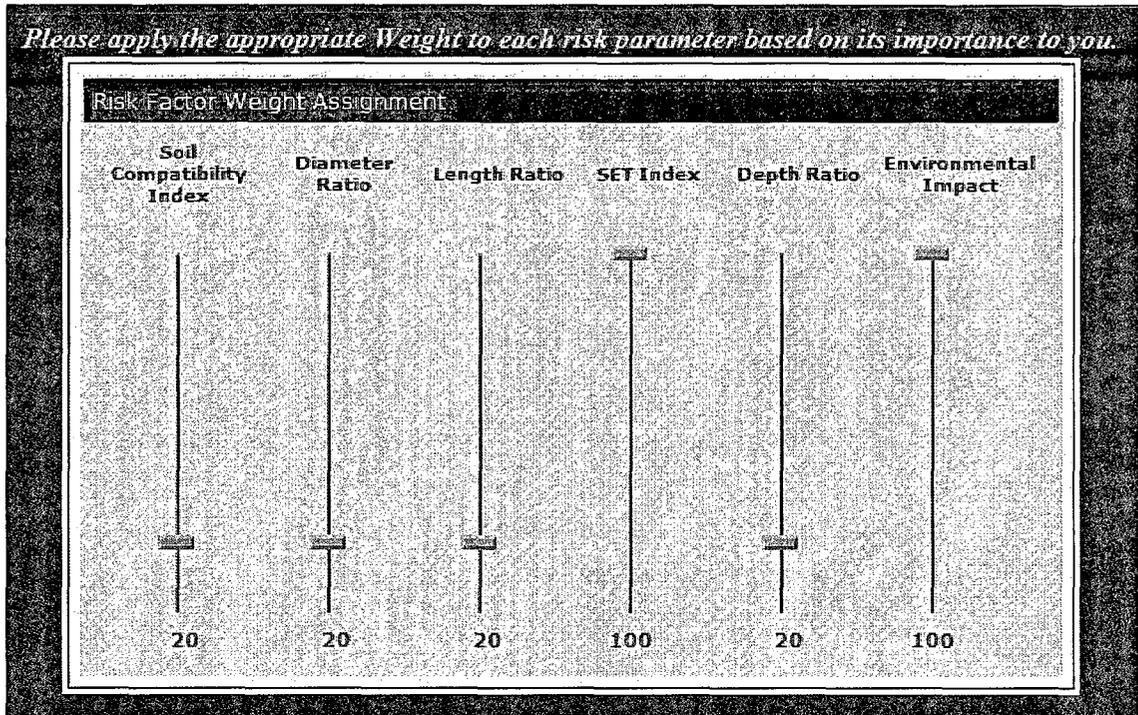
The impact of modifying the weights of the contributing factors on the risk final score is shown below. The same five construction methods were identified by the program. However, the risk score for HDD Midi was decreased from 3.01 to 2.87 while all other risk scores increased. This shows that the owner's comfort with an HDD contractor can effectively place HDD as the preferred method relative to the project data.

Category	Method	Relative Risk	Risk Score
TT Method	HDD Midi	Moderate Risk	2.87
IL Method	Pipe Bursting Pneumatic	Moderate Risk	3.26
IL Method	Pipe Bursting Hydraulic	Moderate Risk	3.26
IL Method	Pipe Bursting Static	Moderate Risk	3.40
OC Method	Open Cut Excavation	High Risk	3.59

E APPENDIX
E.1 DEFINITION OF PROGRAM PARAMETERS
Many of the method parameters listed in the construction method database are listed by their classifications which must be defined to fully understand the methods' capabilities. The following parameters are defined below: soil compatibility, environmental impact, extent of excavation, groundwater table classification, alignment accuracy and profile accuracy.

E.1.1 Soil Compatibility

The construction method database contains soil compatibility information for ten categories of geological conditions, with soil types being further quantified in terms of the number of blows per foot (as per ASTM 1452). The geological conditions considered by TAG are:

Soils	Blows per Foot
Soft Cohesive Soils	$(N < 5)$
Firm Cohesive Soils	$(5 < N < 15)$
Stiff Hard Cohesive Soils	$(N > 15)$
Loose Cohesionless Soils	$(N < 10)$
Medium Cohesionless Soils	$(10 < N < 30)$
Dense Cohesionless Soils	$(N > 30)$
Gravel	-
Cobble / Boulders	-
Sandstone	-
Bedrock	-

The compatibility of each construction method with the ten soil classes is designated as either:

Compatibility	Database Symbol
Fully Compatible	(Y)
Possibly Compatible	(P)
Incompatible	(N)

E.1.2 Environmental Impact

The values for potential environmental impact are provided with a relative ranking in the construction method database. These values are based on many factors which include: potential for ground settlement and heave (potential damage to paved surfaces, nearby utilities and foundations); erosion; removal of trees and flora; creation of temporary hazards (i.e. open trenches); and the potential for the migration of drilling fluids to the surface.

Environmental Impact	Database Symbol
Very Low	1
Low	2
Medium	3
High	4
Very High	5

E.1.3 Extent of Excavation

The values for allowable extent of excavation are fixed in the construction method database.

Extent of Excavation	Database Symbol	Methods
Continuous Excavations	1	All methods can be used
Limited Excavations	2	Excludes backhoe excavation
Access/Receiving Pits Only	3	Excludes all open cut methods

E.1.4 Groundwater Table Classification

The technical feasibility of certain trenchless construction methods is conditioned upon the height of the hydrostatic head acting on the cavity; in other words, the elevation of the proposed alignment with respect to the elevation of the groundwater table (GWT). The values for groundwater table classification are fixed in the construction method database.

Groundwater Table Classification	Database Symbol
Can handle at least 10 ft. of hydrostatic head	C1
Can handle up to 10 ft. of hydrostatic head	C2
Can handle up to 3 ft. of hydrostatic head	C3

The formula for height of hydrostatic head is as follows:

Hydrostatic Head, ft. = (Depth of the Installation, ft.) – (Pipe Diameter, ft.) – (Depth of GWT, ft.)

E.1.5 Alignment and Profile Accuracy

These parameters refer to the anticipated level of installation accuracy that will be needed.

Accuracy	Database Symbol	Description
Very Low	1	No Steering Capabilities
Low	2	Limited Steering Capabilities
Medium	3	Dedicated Tracking and Steering Capabilities
High	4	Maximum Deviation of +/- 4"
Very High	5	Maximum Deviation of +/- 2"

E.2 DEFINITION OF REHABILITATION PARAMETERS

The rehabilitation parameters can be defined by clicking the Need Help links next to their names on the input screens. The following parameters are defined below: length, diameter, pipe deterioration, cross-section reduction, pipe access, bends, shape, size transition, reverse curvature, service connection and lateral access.

E.2.1 Length

The maximum length of any host pipeline section on the project to be renewed.

E.2.2 Diameter

The diameter of the host pipe which requires renewal.

E.2.3 Pipe Deterioration

Partially Deteriorated (Non-Structural)
The original pipe can support the soil and surcharge load throughout the design life of the rehabilitated pipe. The soil adjacent to the existing pipe must provide adequate side support. The pipe may have longitudinal cracks and up to 10% distortion of the diameter.

Fully Deteriorated (Structural)
The original pipe is not structurally sound and cannot support soil and live loads, nor is it expected to reach this condition over the design life of the rehabilitated pipe.

E.2.4 Cross-Section Reduction

Small
A tight fitting field manufactured renewal system with no annular space between the host pipe and the new liner system.

Medium
A loose fitting factory manufactured pipe inserted into the host pipe can be designed with or without the use of annular space grout.

Large
A significantly smaller pipe inserted into the host pipe.

E.2.5 Pipe Access

Manhole
Includes technologies that, due to their size and material make-up, can be installed directly through a manhole opening of the existing pipe.

Access Pit
Includes technologies that, due to their size and material make-up cannot be installed directly through a manhole opening of the existing pipe.

E.2.6 Bends

For bends not listed in the selection menu choose the next highest degree bend.

E.2.7 Pipe Shape

For other pipe shapes contact the product manufacturers directly.

E.2.8 Size Transition

A cross-section size transition may be encountered in a constructed in place brick pipe. Some technologies can accommodate this type of size change. A point repair, where a smaller diameter pipe is installed to repair a larger pipe, is not considered a cross-section pipe size change and should be replaced before renewing the host pipeline.

E.2.9 Reverse Curvature

When the crown of the pipe (typically in brick pipe) begins to collapse and forms a reverse curvature, technologies that rely on an arch design, no longer are applicable as a structural design solution. A reverse arch configuration can be lined with a smaller round pipe and then back-grouted to provide a structural solution.

E.2.10 Service Connection

No Service Connections

The pipe has no domestic or commercial connections in the section being renewed.

Internally

The service connections in the new pipe can be opened internally to provide the applicable level of service.

Externally

The service connections must be reconnected externally to provide the required level of service.

Either

The service connections can be connected by either method to provide the required level of service.

E.2.11 Lateral Access

Cleanout

Includes technologies that, due to their size and material make-up, are installed from a cleanout to the mainline sewer.

Manhole, Access Pit or Cleanout

Includes technologies that, due to their size and material make-up, are installed from the mainline sewer to a cleanout or access pit.

E.3 DEFINITION OF MANHOLE PARAMETERS

The manhole parameters can be defined by clicking the Need Help links next to their names on the input screens. The following parameters are defined below: condition, infiltration/inflow, corrosion, structural deficiencies, bench repair, invert repair and collapse.

E.3.1 Condition

General Maintenance

The manhole is considered structurally sound with little indication of settlement, cracking or other signs of structural fatigue including minor corrosion, infiltration or exfiltration through precast joints, mortar joints or around the pipe connections.

Protective Coating

The manhole is exhibiting early signs of structural fatigue evidenced by minor cracks, loss of mortar or brick, corrosion (less than 0.5 in. in depth), minor cross sectional distortion (less than 10 %); however the existing structure is currently supporting the soil and live loads.

Structural Renewal

The manhole is exhibiting severe structural fatigue and collapse is eminent. Conditions indicating this degree of deterioration would be distortion beyond 10 %, severe corrosion (exposed reinforcing) or large sections of the existing structure are missing.

E.3.2 Infiltration/Inflow

Infiltration

Typically groundwater that flows into the manhole through joints, cracks, bench, invert, pipe connections, etc.

Inflow

Typically runoff water during a rainfall event that flows through manhole cover holes, between the casting and the chimney.

E.3.3 Corrosion

No Corrosion

The manhole is in very good condition with some of the brick mortar or concrete surface in a solid hard condition.

Light Wall Corrosion

The brick mortar is deteriorated and missing or concrete surfaces are soft and flaking in spots.

Heavy Wall Corrosion

Bricks and mortar are missing in a number of areas of the manhole or several inches of soft concrete wall and sections of the wall surface are missing.

E.3.4 Structural Deficiencies

<u>Yes</u>

Bricks are missing in a number of areas of the manhole with distortion of the manhole wall. Concrete manholes with portions of the wall missing, rebar's showing or missing.

<u>No</u>

The manhole is generally in good structural condition.

E.3.5 Bench Repair

<u>Yes</u>

The manhole bench is cracked and deteriorated with sections missing, bench does not exist or groundwater is infiltrating at the bench.

<u>No</u>

The bench is generally in good condition and channels the flow in the intended direction.

E.3.6 Invert Repair

<u>Yes</u>

The invert is missing or eroded, pipe running through the invert is fractured and dislodged or the elevation does not match the elevations of the incoming and outgoing pipe elevations.

<u>No</u>

The invert is in good shape and directs the flow through the manhole in the intended direction. The invert provides a smooth transition of flow from the incoming pipe to the outgoing pipe.

E.3.7 Collapse

<u>Yes</u>

The manhole wall has partially collapsed and requires that it be totally rebuilt with a structurally sound lining system or new structure.

<u>No</u>

The manhole is a candidate for one or more of the many coating and/or lining systems available.

APPENDIX C

SUMMARY OF SCC CASE HISTORIES

Table C.1 Summary of SCC case histories.

No	Location	SC Categories	Costs, ($)	SCC Costs, ($)	Change
1	Regina, AB [73]	Traffic Delay	8,931	9,067	1.5%
		VOC	1,502	1,440	4.1%
2	Regina, AB [73]	Traffic Delay (Day 1)	759	738	2.8%
		Traffic Delay (Day 2)	6,203	6,583	6.1%
		VOC (Day 2)	4,656	3,754	19.4%
3	Oakland, CA [34]	Traffic Delay	303,555	307,272	1.2%
		VOC	100,607	101,839	1.2%
		Pedestrian Delay	24,969	24,969	0.0%
		Dust Pollution	5,460	5,460	0.0%
		Road Restoration (OC)	110,760	112,500	1.6%
		Road Restoration (TT)	11,076	11,250	1.6%
		Parking Meter Loss (OC)	11,088	11,088	0.0%
		Parking Meter Loss (TT)	384	384	0.0%
		Parking Ticket Loss (OC)	24,150	24,227	0.3%
		Parking Ticket Loss (TT)	N/A	839	N/A
4	Austria [87]	Traffic Delay (OC)	236,091	228,803	3.1%
		Dust Pollution (OC)	16,276	15,000	7.8%
		Dust Pollution (TT)	3,887	3,750	3.5%
		Road Restoration (OC)	36,538	33,917	7.2%
		Road Restoration (TT)	2,181	2,158	1.1%
		Parking Meter Loss (OC)	9,977	10,500	5.2%
		Parking Meter Loss (TT)	2,281	2,400	5.2%

Table C.2 Summary of SCC case histories (continued).

No	Location	SC Categories	Costs, ($)	SCC Costs, ($)	Change
5	Austria [87]	Traffic Delay (OC)	4,521	4,658	3.0%
		Traffic Delay (TT)	5,245	5,670	8.1%
		VOC (OC)	2,895	3,830	32.3%
		Dust Pollution (OC)	6,058	6,161	1.7%
		Dust Pollution (TT)	962	1,232	28.1%
		Parking Meter Loss (OC)	9,439	9,936	5.3%
		Parking Meter Loss (TT)	2,558	2,688	5.1%
6	Italy [24]	Traffic Delay (OC)	53,758	59,138	10.0%
		Traffic Delay (TT)	6,465	2,957	54.3%
		VOC (OC)	58,114	56,430	2.9%
		VOC (TT)	3,412	2,822	17.3%
		Noise Pollution	52,368	48,000	8.3%
7	Belgium [15]	Traffic Delay (OC)	2,084,700	2,082,800	0.1%
		Traffic Delay (TT)	488,455	260,350	46.7%
		VOC (OC)	487,469	492,000	0.9%
		VOC (TT)	60,264	61,500	2.1%
8	Regina, AB [73]	Traffic Delay	170,719	169,195	0.9%
		VOC	50,010	44,856	10.3%

APPENDIX D

SUMMARY OF CARBON CALCULATOR RESULTS

Table D.1 Carbon calculator results for Segments 1, 2 and 3.

Project Description		Project Description		Project Description	
City of Edmonton		City of Edmonton		City of Edmonton	
Segment #1		Segment #2		Segment #3	
Depth (m)	0.05	Depth (m)	0.05	Depth (m)	0.05
Length (m)	85	Length (m)	75	Length (m)	80
Diameter (m)	0.3	Diameter (m)	0.525	Diameter (m)	0.3
Depth of Backfill (m)	7	Depth of Backfill (m)	7	Depth of Backfill (m)	5
Depth of Bedding (m)	0.015	Depth of Bedding (m)	0.015	Depth of Bedding (m)	0.015
Number of Pumps	5	Number of Pumps	5	Number of Pumps	0
Daily Traffic	5000	Daily Traffic	5000	Daily Traffic	5000
Traffic Control Days	4	Traffic Control Days	2	Traffic Control Days	4
Total CO$_2$ Emissions		**Total CO$_2$ Emissions**		**Total CO$_2$ Emissions**	
Open Cut	95	Microtunneling	10	Open Cut	27
Microtunneling	10	Pipe Bursting	8	Microtunneling	3
Pipe Bursting	8	HDD	4		
HDD	4	CIPP	1		

APPENDIX E

TAG-R PROGRAM CD

APPENDIX F

SOCIAL COST METHODOLOGIES

F.1 Indirect Costs of a Sewer Installation [15]

Michielsen (2005) presented a comparison of the social and total costs of a sewer installation project, comparing open cut and pipe jacking alternatives. A comparison of the cost of time on the diversion route due to traffic diversion, attributed to loss of productivity, additional fuel costs and loss of sale revenue was compared for both construction methods. Pipe jacking was found to result in only 20% of the total social costs associated with the open cut alternative. Social costs for the open cut solution were about 63% of the total direct costs, where as for pipe jacking they were between 9% and 10% of the total direct cost. A formula was also presented for the inclusion of the social costs mentioned above.

F.2 Quantifying Social Costs [16]

Allouche and Gilchrist (2004) provided a summary of the potential impacts due to construction activities and identified the related adverse impacts and social cost indicators. Social cost indicators are defined as measurable costs that can be quantified in monetary terms and are the results of construction related adverse affects on the environment around a construction site. The four impact areas are traffic, economic activities, pollution, and social ecological and health systems.

Traffic has adverse impacts such as prolong closure of road space, detours and utility cuts. Social cost indicators due to these adverse impacts include loss of parking space, additional fuel consumption, travel delay, increased traffic accident rate and accelerated deterioration of roads.

Social cost indicators for economic activities include loss of income, reduction in productivity, loss of tax revenues, reduction in value of properties and property damage. Pollution can have adverse impacts in the form of noise, dust, vibrations, air and water contamination.

Some of the adverse impacts to ecological, social and heath systems include surface disruption, damage to recreational facilities, and damage to historical and cultural heritage. Social cost indicators due to these adverse impacts included resources for treating compromised physical and mental health, reduced quality of life and restoration costs.

There are direct and indirect techniques for assigning monetary values to these social costs. The direct techniques are loss of productivity, human capital, replacement cost, and lane closure costs. Indirect methods include hedonic pricing and user delay costs based on highway principles.

F.3 Life Cycle Cost Analysis including User Delays [17]

Perrin and Jhaveri (2004) proposed a method for including user delays and risk factors into Life Cycle Cost Analysis (LCCA) of culvert structures. The proposed method for calculating the total cost of constructing and maintaining a culvert over a given design life (usually 100 years) is the summation of the installation, maintenance, rehabilitation and replacement costs within the given design period and the associated cost due to user

delays. The authors also proposed a second method for calculating the total cost by tracking culvert failures based on their material type, costs for emergency replacement and cost due to user delays associated with unplanned closures (e.g. catastrophic failure). The calculation would include a risk factor based on the pipe material (probability of failure), an emergency replacement factor based on the pipe material (the ratio of emergency to normal replacement costs), and the unplanned closure user delay costs. Both proposed methods included the calculation of user delay costs that are often not considered during a LCC analysis because those costs are experienced by traffic users.

F.4 Prediction Model for Social Costs [18]

Gangavarapu et al. (2004) developed a prediction model for the quantification of social costs during pipe installations. Using information gathered from case studies and a literature review, the authors developed a prediction model for the calculation of traffic disruption costs. The costs included: fuel costs due to detours, delay costs due to increased travel times, depreciation costs due to increased miles and increased fuel consumption. The model was limited to only projects on college campuses. Cost of damage to pavements and adjacent utilities were not considered by the model.

F.5 Practical Social Cost Considerations [19]

Jung and Sinha (2004) provided several practical examples of how the consideration of social costs could make trenchless technologies effective and environmentally sound alternatives for the installation, maintenance and repair of buried pipelines and cables.

The first social cost considered was traffic delay costs. The authors used equations developed by Tighe et al. (1999) to show that using open cut construction, project taking 344 hours to complete would have associated traffic delay costs $284,527 greater than if a trenchless method taking 152 hours was used.

One of the environmental costs considered was noise pollution. This factor is quantified by a numerical measure of the degree to which additional noise impacts housing values. The authors used an estimate of 0.17% per dBA. The equation for calculating the environmental costs is, *0.0017 x K x OHP*, where *0.0017* = reduction in the house value per decibel, *K* = increase in noise level (dBA) and *OHP* = Original Housing Price. The example used assumed that the open cut project had an average noise level of 90 dBA, which is 20 dBA above the norm in that neighborhood (70 dBA). Pipe bursting only the noise level to 80 dBA. The average adjacent housing price was $118,900 for the 30 surrounding houses, therefore the total cost due noise pollution for open cut and pipe bursting was $121,278 and $60,639, respectively.

Another social cost was the loss of business due to reduced access associated with open cut projects. It was stated that a decrease of 25% in overall revenues was a conservative expectation for loss of revenue due to open cut construction. The expected business loss for the 11 affected businesses was estimated at $14,685 in the case of an open cut project lasting 55 days, and $2,401 in the case of a trenchless construction method used over a reduced duration of 9 days. Duration is the primary factor in determining the loss of business social cost.

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F.6 Construction Noise in an Urban Environment [20]

Gilchrist et al. (2003) introduced a model to help mitigate construction noise in an urban environment. Noise can be generated by activities such as highway resurfacing projects, replacement of buried pipes, pavement breaking, etc. There are many different types of equipment that contribute to noise pollution such as jackhammers and back up alarms. The authors developed and validated a noise prediction model and demonstrated that the best technique for minimizing construction noise is to reduce them at source through proper method selection.

F.7 Eliminating Pavement Excavation using Trenchless [21]

Tighe et al. (2002) conducted a study to determine the effect on the life cycle of pavements due to utility excavations. The study showed that a 30% reduction in pavement useful life can be anticipated if an excavation is made in a road. Another finding was that rehabilitation and maintenance costs of excavating a 1-year old pavement were about $146/m^2 Canadian and between $85/m^2 and $140/m^2 Canadian for a 7-year old pavement. The conclusion was that the use of trenchless technology can greatly reduce maintenance and rehabilitation costs throughout the life cycle of pavements.

F.8 Social Cost Evaluation [22]

Fea et al. (2000) discussed a model for quantifying social and environmental impacts in terms monetary values to show the benefits of using trenchless technologies. The main cost elements analyzed are direct installation costs, road traffic delay costs and environmental impact costs. The traffic costs are comprised of costs due to increased travel times and costs due to additional fuel consumption. Environmental impacts are

comprised of negative effects associated with air and water pollution. Noise and visual impacts were not considered in the evaluation. A case study comparing directional drilling, microtrench and minitrench to traditional trenching showed a total savings of 69%, 90% and 73% respectively.

F.9 Traffic Delay Cost Savings [23]

Tighe et al. (1999) developed a methodology for quantitatively assessing typical traffic delays that are normally associated with utility construction projects. The authors focused on the three basic variables of a traffic capacity analysis which are the volume of flow, speed and density. User delays are composed of two elements: delays caused by reduced speeds through the construction area and queuing delays due to the congestion of traffic as demand exceeds capacity.

The analysis began by identifying three typical traffic control scenarios: A) one of two lanes is closed and a flagperson or signal is utilized; B) both lanes remain open and the shoulder is utilized; C) the road is closed and a detour is used. Next, delays due to reduced speed are calculated as the additional time required to travel through the construction area as compared to traveling under normal conditions. The normal capacity for scenarios (A) and (B) is given by Eq. F.1

$$C_N = 1400 \times 0.72 \times F_{WN} \qquad (F.1)$$

where, C_N = One lane normal capacity for two lane roads (vehicles/hour/lane), 1440 = Passenger cars under ideal conditions (vehicles/hour/lane), 0.72 = Adjustment factor for the presence of heavy vehicles, and F_{WN} = Adjustment factor for narrow lanes. The reduced capacity for scenario (A), which is determined by factoring in green time and cycle lengths used in signalized intersection calculations, is given in Eq. F.2

$$C_R = C_N \times \left(\frac{g}{c}\right). \tag{F.2}$$

In this equation, C_R = One lane reduced capacity for two lane roads using scenarios (A) (vehicles/hour/lane), C_N = One lane normal capacity for two lane roads (vehicles/hour/lane), g = Green time taken from Table F.1 (seconds), and C = Cycle length taken from Table F.1 (seconds). The reduced capacity for scenario (B) uses Eq. F.1 with the restricted shoulder width input for F_{WN} to account for the narrower lane width. The hourly volume of the road is calculated and this value along with the reduced capacity is used in calculating the speed delay for scenario (B) and the queuing delay for scenarios (A).

Table F.1 Green times and cycle lengths based on AADT.

AADT	g (sec)	C (sec)
< 3500	100	400
3500-4000	150	500
4000-6500	250	700
6500-7000	300	800
7000-7500	350	900
7500-8000	400	1000
8000-8500	450	1100
8500-9000	500	1200
9000-9500	570	1340
> 9500	610	1420

The detour delay for scenario (C) is calculated using the hourly volume and the detour velocity as a direct calculation. A case study demonstrated open cut to be more costly compared with trenchless methods for all three scenarios, when considering user delays in the cost calculations. It was recommended that the engineer should consider both direct construction costs and user delay costs when selecting the method of construction.

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F.10 Evaluation of Social Costs in Pipeline Rehabilitation [24]

Lonardo et al. (1999) compared the direct, indirect and social costs involved in a pipeline rehabilitation project for conventional and trenchless technologies. Loss of time due to traffic delays, increased fuel consumption, increased atmospheric pollution and accidents to workers were the social costs analyzed. Traffic delays were calculated using Highway Capacity Manual methodologies and the associated fuel costs were applied using the average price of fuel. The noise factor was determined by surveying those affected who would have paid more out of their own pocket to reduce the uneasiness caused by conventional methods. Of those interviewed, 70% said they would pay 32% more than the cost of the installation to avoid this uneasiness, therefore a theoretical surcharge of 22% was applied for the whole population for inclusion as a social cost. When all social costs were combined they accounted for 70% of the cost of the open cut construction and only 11% of the cost of the no-dig construction method.

F.11 Using Highway Principle to Estimate Social Costs [25]

McKim (1998) presented a methodology based on highway management principles to estimate traffic delays due to construction. Methods for determining normal and reduced capacities, hourly volumes and shoulder width factors were used to determine slow down and queuing delays due to construction activities. The delay costs can then be calculated by assuming an hourly value of time for each vehicle ($25/hour in this case), and multiplying that by the resulting delay (expressed in hours).

F.12 Social Cost Considerations [26]

Bried and Boyce (1998) proposed a method showing where and how to incorporate social cost into the selection of a construction method. The authors identified four issues that trigger high social costs: deep pipeline installations, contaminated ground, disruption of roadways, and the presence of parks, wetlands or established recreation areas along the proposed alignment. Next, they presented a logic diagram based on four "Yes" or "No" questions that could help determine if trenchless methods were preferred over trenching. The four questions in the logic diagram are listed below:

1. Is the pipeline deeper than 5 meters?

2. Is the ground contaminated?

3. Is the number of cars affected per lane per hour more than the pipe diameter in mm/5?

4. Will the pipeline cross established parks, wetlands or recreation areas?

If the answer to any of the questions was yes, then trenchless methods would be preferred over the more traditional trenching techniques.

F.13 Monetary Valuation of Sewer Rehabilitation [27]

Grunwald (1998) provided equations for valuation of social costs that are not paid by the owner over the life of a sewer collection system. For each social cost a list of factors that would influence the calculation of each cost is provided. The factors that would influence the calculation of business loss are the duration of the project, extent of the influence and the reduced sales. The factors that influence road users are project duration, length and characteristics of the affected road sections, number of vehicles affected, speeds, increase travel times, vehicle operating costs and value of time. Noise is

another factor incurred by society due to construction machines, effect of productivity and duration of the noise emission. Extent of damage to road pavement will be controlled by the remaining useful life, decreased life due to the techniques used, repair and maintenance costs and the interest rate used to capitalize those costs.

F.14 Social Costs in Pipeline Construction [28]

Kolator (1998) discussed the problems in estimating social cost and described an assessment scheme for considering social costs. One hindrance to the use of trenchless technology is the lack of estimating methods for quantifying social benefits. The second major problem is that official agencies tend to neglect external factors such noise, dirt and traffic to save money in their budgets.

The social factors considered include adverse effects on road users such as: loss of time, increased operating costs of vehicles and loss of parking spaces. Factors that will affect adjacent residences are: noise nuisances, dust and vibrations. Air pollution was not considered because of the difficulty in quantifying it. The only other factor considered was the reduction of pavement life due to excavations.

The loss of time experienced by road user involves three factors: an estimation of the increase in travel distance, an estimation of the loss of time and an assessment of the value of time. Vehicle operating cost includes an estimation of the increased travel distance, as well an assessment of the market value of vehicle operating costs (VOC). The loss of parking spaces involves not only the number of spaces lost, but also the increased travel distance of the pedestrians walking from farther away and the value of their time.

Noise nuisance and vibrations causing noise involve measuring the increased noise due to construction and diversion, and then applying a value based on a direct survey to those affected. Dust control involve determining the area of windows being affected and the subsequent cost for the additional cleaning. Pavement life reductions simply involve the amount of pavement being disturbed and the subsequent loss of life cycle due the excavations.

Using the methods described, Kolator compared the application of open cut and microtunneling to 700 m. long, 400 mm sewer. The direct costs for open cut and microtunneling were $5,040,000 and $5,600,000, respectively. However, the inclusion of the social costs mentioned earlier (i.e. time loss, VOC, loss of parking, noise, dust and pavement) raised the total direct plus social costs of open cut to $6,594,057 where the total costs associated with the microtunneling option increased to $5,862,299, resulting in net savings of $731,758.

F.15 Bidding Strategies Considering Social Costs [29]

McKim (1997) proposed a bidding strategy where the bidder can optimize the bid based on a probabilistic approach using the expected bid value. Some of the potential social costs included are the cost to redirect traffic, lost business revenues, reinstatement of pavements and structures, and public awareness factors (i.e. dust and noise pollution, environmental risks).

F.16 Analysis of Social Costs in Taiwan [30]

Hsu and Jiang (1997) discussed a method for determining social costs of underground pipeline construction projects in Taiwan. Noise pollution, traffic delays, air

pollution, commerce influence and risk to workers, inhabitants and passengers are the social cost categories considered. Noise can cause many problems such as loss of hearing, adverse effects on of the body (i.e. increased level of stress and loss of concentration), and sleep disturbances. Noises above 88 dBA are considered unacceptable by the Housing and Urban Development and need to be considered as a social cost. For air pollution, the EPA charges $2.63/m^2/month for open cut, but only $1.76/m^2/month for trenchless methods. For dirt and dust a washing cost can be calculated at $30/m^2 for a building and $300/car. The amount of business loss was determined to be between 25% and 35% of normal total sales.

F.17 Cost Benefit Comparison of Trenchless Technologies [31]

Hsieh et al. (1997) analyzed the costs and benefits of using trenchless technologies in underground pipelaying in urban areas in Taiwan. Social costs considered in this analysis were adverse traffic impacts, environmental influence, business loss and influence to social activities. Traffic impact includes many factors such as obstructions to traffic causing reduced road area, loss due to detours, reduced site safety and loss due to accidents. Environmental factors include influence on green vegetables, noise pollution, air pollution and surface water pollution. Business loss includes a reduction in selling capacity of shops along the excavated street and in productivity of factories along the street. The social and civil influences include an increase in repair and maintenance costs of the road surface. Trenchless methods have a very low impact on all of these areas when compared to open cut construction creating the benefit to society as a whole.

F.18 Social Cost Influence of using No-Dig Techniques [32]

Voorhoeve (1995) studied the social costs associated with no-dig techniques and discussed an example of the benefit to using trenchless technologies. Social costs were classified into four groups: traffic, environment, commerce and industry, and citizens and society. Traffic could include partial or full road closures, less safe construction sites due to open trenches, increased accident rates and damage to secondary roads due to detours of commercial traffic. Environmental factors include damage to trees or plants, noise and air pollution, as well as ground and surface water pollution. Loss of business and an increase in road maintenance costs make up the final two groups. For a project in Amsterdam where trench and trenchless methods were used to repair a sewer in the same street the loss of business was estimated to be between 3 to 7 times more for the trenched repair than the trenchless one. The estimations were made by inquiries to the shopkeepers and the shoppers.

F.19 Estimating Social Costs Savings [33]

Boyce and Bried (1994a) defined cost benefit and cost effectiveness analyses for comparing the total economic costs of trenching versus trenchless methods. The Cost Benefit Analysis (CBA) and Cost Effectiveness Analysis (CEA) included five elements: project statement, underlying assumptions, statement of costs, cost analysis, and results and discussions. The three cost areas considered were the direct costs, indirect costs and transfers. Direct costs include any money paid for the construction, patching costs after an excavation and costs paid for worker's safety which are typically higher on trenching jobs. Indirect costs include the fallout from a project such as traffic and pedestrian disruptions, decreased sale revenue, and dust and noise pollution. Repaving in the near

future, which normally would not have been needed if an excavation was not made, is also an indirect cost. Transfers, which are not true social costs, represent actual financial considerations for the jurisdiction of the project, but are not included in the CBA. Transfers include sales tax, parking meter revenue and parking ticket revenue. The costs analysis including the impacts to society demonstrated that trenchless methods are more cost effective than trenching when the overall cost of the project is considered.

F.20 Benefit-Cost Analysis of Microtunneling [34]

Boyce and Bried (1994b) examined the social and economic costs associated with trenching versus trenchless installation of a storm drain in a busy commercial area. The authors considered several indirect and social factors in determining the total costs associated with trenching and microtunneling. The first indirect cost factor considered was worker safety which was calculated using Eq. F.3

$$WSC = IP \times W \times M \times N_E \times D. \tag{F.3}$$

In the equation, WSC = Cost due to Worker Safety ($), IP = Insurance Premium ($/$100 of payroll), W = Employees Wage ($/hour), M = Safety Multiplier (2 for both), N_E = Number of Employees, and D = Project Duration (hours).

The next factor, traffic disruptions, is a social factor because it is not actually paid for by the parties engaged in the contract. There are primarily two components of traffic disruptions: one is due to wear on the vehicle plus the consumption of gas commonly called vehicle operating expenses (VOC), and the second is the time costs to the individuals in their vehicles during a traffic delay.

In 1994, the Federal Government specified $0.29/mile operating cost allowance (OCA) for travel associated with highway projects. AAA (2008) reported in their annual

Your Driving Costs brochure that the average operating cost of driving your car including fuel, maintenance and tires was $0.17/mile which does not include insurance, license, registration, taxes, depreciation and finance costs. When including all of the other factors the average cost for driving a vehicle 15,000 miles per year is $0.54/mile. The methods for calculating the costs due to vehicle operating expenses and travel delays are shown in Eqs. F.4 and F.5, respectively

$$VOC = IT \times N_V \times OCA \times D \qquad (F.4)$$

$$TDC = TD \times N_V \times P \times VT \times D. \qquad (F.5)$$

In Eqs. F.4 and F.5, VOC = Vehicle Operating Cost ($), IT = Increase in Travel Distance (miles/vehicle), N_V = Number of Vehicles (vehicle/hour), OCA = Operating Cost Allowance ($0.17/mile), D = Project Duration (hours), TDC = Travel Delay Costs ($), TD = Travel Delay (minutes/vehicle), P = Passengers (persons/vehicle), and VT = Value of Time ($/min./person).

The next social factor considered is the disruption to pedestrians caused by signal timing, altered vehicular traffic flows and secured works areas causing detours. The method for calculating the cost due to pedestrian disruptions is shown in Eq. F.6

$$PDC = ITT \times N_P \times VT \times D. \qquad (F.6)$$

In Eq. F.6, PDC = Pedestrian Delay Costs ($), ITT = Increase in Travel Time (minutes), N_P = Number of Pedestrians (persons/hour), VT = Value of Time ($/min./person), and D = Project Duration (hours).

Another social factor is the loss of productivity due to noise pollution. Due to lack of data the factor was not considered in the paper, but the method for calculating it is given in Eq. F.7

$$NPC = TL \times N_P \times VT \times D. \tag{F.7}$$

In this equation, NPC = Noise Pollution Costs (\$), TL = Time Lost (minutes), N_P = Number of Affected People (persons/day), VT = Value of Time (\$/min./person), and D = Project Duration (days).

Dust control is another social factor due to the location, number of windows and amount of foot traffic during work hours at local businesses. The cost of janitorial services was used to estimate the cost of this factor and is described in the Eq. F.8

$$DDC = ICT \times HR \times N_U \times D. \tag{F.8}$$

In this equation, DDC = Dust and Dirt Control Costs (\$), ICT = Increased Cleaning Time (hours/week), HR = Hourly Rate (\$/hour), N_U = Number of Units Impacted, and D = Project Duration (weeks).

The next social cost factor is parking meter revenue which is not available due to blocked off parking spaces. The formula for calculating this cost is shown below in Eq. F.9

$$PMR = MR \times N_M \times OH \times O \times D. \tag{F.9}$$

In this equation, PMR = Parking Meter Revenue (\$), MR = Meter Rate (\$/hour/meter), N_M = Number of Meters, OH = Operational Hours (hours/day), O = Percentage of Occupancy, and D = Project Duration (days).

The final social cost factor considered related to parking is parking ticket revenue which is not available due to blocked off parking spaces as well. The equation for calculating this cost is shown below in Eq. F.10

$$PTR = F \times FT \times A \times D. \tag{F.10}$$

In this equation, *PTR* = Parking Ticket Revenue ($), *F* = Ticket Fine ($/ticket), *FT* = Frequency of Tickets (tickets/day/area), *A* = Area Affected, and *D* = Project Duration (days which tickets are issued).

F.21 Economics of Trenchless vs. Cut and Fill [35]

Budhu and Iseley (1994) proposed a conceptual flow chart diagram for the incorporation of trenchless technology methods in high-density activity urban areas and identified how the process may be applied for quantifying specific societal costs for a case study in the City of Shreveport, Louisiana. The indirect costs considered included lane closings, traffic diversions, business losses, accidents, increased fuel consumption and pollution.

F.22 Reducing Social Costs [36]

Thomson et al. (1994) described the potential for reducing social costs through the use of trenchless methods for the installation of utilities under roads. The paper indentified the areas where reduced social costs are important and outlines previous studies on social cost consideration.

F.23 Social Cost and Pipelaying [37]

Berosch and Angot (1992) described the social and indirect costs aspects of current (1992) pipelaying techniques. They discussed a survey that asked about disturbances from construction projects. Noise (90%) was identified to be the most common and significant disturbance, with dust (58%) and congested traffic (55%) following it as highly annoying. Access to houses (50%), detours (45%), parking (41%), visual intrusion (41%), pedestrian delay (31%), air pollution (24%) and fear of accidents

(20%) rounded out the remaining disturbances. It was found that the consent to pay more was directly proportional to the degree of disturbance felt.

F.24 Social Cost Evaluation [38]

Vickridge et al. (1992) proposed a methodology for considering social costs in the selection of a construction method for installing or repairing underground assets. The social costs examined were disruption of the local economy through the loss of trade and increased costs of operation; congestion, delays and diversions to traffic, with the associated increase in traffic accidents; damage to underground utilities, adjacent buildings and the highway itself; and environmental damage from the work and traffic congestion, including the nuisance of noise, vibration, visual intrusions, dust, dirt and smell. The authors also proposed a methodology for setting road space rental charges to reduce the total economic costs to the community as a whole through the adoption of less disruptive construction methods.

F.25 Life Cycle Cost Program for Evaluating Sewer Projects [39]

Daley (1992) created an automated program incorporating apparent and hidden costs associated with sewer reconstruction projects. The hidden or social costs taken into account by the program are traffic disruptions and disruption to commerce and the resulting loss of tax revenue. For traffic disruption, the average cost per mile of vehicle operation is combined with average daily volume of traffic to determine the cost of detours for each construction alternative. These costs along with the direct construction costs are calculated for a 50 year life cycle for each alternative. The cost is then

combined with the benefit due to improved flow and the alternative with the best cost/benefit ratio would be considered the most ideal method.

F.26 Cost Comparison of Tunneling versus Trenching [40]

Norgrove and O'Reilly (1990) conducted a study to compare the cost of installing sewers by tunneling and trenching, and evaluate the difference in traffic delays. Cost data from sixteen tenders and eleven final accounts which were tendered for between 1970 and 1981 were used in this study. The authors made a total of 216 costs comparison between and within the contracts. A case study of one of the contracts determined the traffic delay costs associated with a trenching project as compared to a tunneling one. Over 50 calendar weeks of the trenching project a total of 42,878 hours of traffic delay were encountered by motorists travelling within the project zone. These delays would have been greatly reduced by the use of tunneling instead of trenching.

F.27 Social Cost Sewer Rehabilitation [41]

Bristow et al. (1988) discussed the inclusion of social costs in the decision making process for sewer rehabilitation projects. Social costs considered to have the highest influence were noise pollution, air pollution and traffic problems. It was shown that while trenchless methods did not eliminate social costs, they greatly reduced these costs in terms of fewer traffic delays, less pollution and fewer excavations.

The first method proposed for including social costs in the decision making process was to rent the road space, thereby charging the contractor a fee for everyday they occupy the road space. Another proposal was to charge the contractor a per diem payment to each owner or occupier of a building that had its access denied. Also, travel

time costs could be included in the project appraisal to show a social cost benefit analysis of using methods that cause less travel delays.

F.28 Estimating Social Costs [42]

Green and Wood (1987) reported on the types of social costs arising from sewer projects and described methods for estimating these costs. In a case where an open cut solution was estimated and compared to a trenchless approach delays and diversions to traffic were compiled for both using software that estimates traffic delays. The social costs associated with traffic delays were estimated to be more than twice as much for the open cut when compared with the trenchless method and accounted for more than one and half times the direct cost of the construction work.

F.29 Minimizing Traffic Disruptions with Impact Moling [43]

Noden (1987) described a project in Oxford where the need to keep traffic disruption and damage the existing roadway to minimum, leading to the use of an impact mole instead of open cut construction. Also, since the road would be resurfaced with asphalt right after the completion of the project, the method with the smallest chance of settling was a preferred method. Moling was selected because of the speed of construction, limited amount of excavation and a minimal amount of traffic disruption in this highly traveled area.

F.30 Social Cost Case Studies [44]

Glennie and Reed (1985) presented two case studies outlining the social costs associated with trenchless in-line replacement versus trenching. Traffic disruptions and

business losses were the principal costs considered as well as pavement reinstatement costs.

The first case was an 1100 m section of 9" sewer which was replaced by moling and sliplining. The road was closed to most of the through traffic, but local traffic was still able to use the road. If open cut had been used, the road would have been completely closed off and the project would have lasted an additional three weeks. Also, since local access was maintained business losses were lower than in the case where the road was completely shut down.

The second case involved the replacement of 660 m of 150 mm diameter cast iron water main under a street of asphalt and concrete paving by moling. Traffic access was maintained with the use of temporary traffic lights, which would not have been possible with open trenching. This would again have increased the traffic delay costs and potentially business losses.

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