Report No. BC-353-32

OPTIMUM PLACEMENT OF UTILITIES WITHIN FDOT R/W

BC353/RPW#32

S. C. Kranc, Ph.D., P.E.
Principal Investigator
and
William A. Miller, Ph.D.
Co-Principal Investigator

with

Nathan Collier, Research Associate
Vijayakumar Shanmugam, Research Assistant
Steve C. Christian, Research Assistant
Atul Khemuka, Research Assistant

submitted to

The Florida Department of Transportation

by the

Department of Civil and Environmental Engineering
College of Engineering
University of South Florida
Tampa, Florida, 33620
Ph. (813) 974-2275

December, 2005
FINAL REPORT

Document is available to the U.S. public through the
National Technical Information Service,
Springfield, Virginia, 22161

prepared for the

FLORIDA DEPARTMENT OF TRANSPORTATION
and the
U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

OPTIMUM PLACEMENT OF UTILITIES WITHIN FDOT R/W

BC353/RPW#32

S. C. Kranc, Ph.D., P.E.
Principal Investigator
and

William A. Miller, Ph.D.
Co-Principal Investigator

with

Nathan Collier, Research Associate
Vijayakumar Shanmugam, Research Assistant
Steve C. Christian, Research Assistant
Atul Khemuka, Research Assistant

Department of Civil and Environmental Engineering
College of Engineering
University of South Florida
Tampa, Florida, 33620
December, 2005

METRIC CONVERSION TABLE

To convert	British	SI	multiply by
Acceleration	ft/s^2	m/s^2	3.048E-1
Area	ft^2	m^2	9.290E-2
Density	$slugs/ft^3$	kg/m^3	5.154E+2
Length	ft	m	3.048E-1
Pressure	lb/ft^2	N/m^2	4.788E+1
Velocity	ft/s	m/s	3.048E-1
Volume flowrate	ft^3/s	m^3/s	2.832E-2
Volume flowrate	gal/min	l/s	6.310E-2

Technical Report Documentation Page
Form DOT F 1700.7 (8-72)
Reproduction of completed page authorized

<table>
<tr><td>1. Report No.
FL/DOT/RMC/ BC-353-32</td><td>2. Government Accession No.</td><td>3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
OPTIMUM PLACEMENT OF UTILITIES WITHIN FDOT R/W</td><td>5. Report Date
December, 2005</td></tr>
<tr><td>6. Performing Organization Code
FL/DOT</td></tr>
<tr><td colspan="2">7. Author(s) KRANC, SC. et al</td><td>8. Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Department of Civil and Environmental Engineering
ENB118
University of South Florida
Tampa, FL 33620</td><td>10. Work Unit No. (TRAIS)</td></tr>
<tr><td>11. Contract or Grant No.
BC353 RPWO #32</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
Florida Department of Transportation
605 Suwannee St. MS 30
Tallahassee, Florida 32399</td><td>13. Type of Report and Period Covered
Final Report
11/01-12/05</td></tr>
<tr><td>14. Sponsoring Agency Code</td></tr>
<tr><td colspan="3">15. Supplementary Notes
Prepared in cooperation with the USDOT and FHWA</td></tr>
<tr><td colspan="3">16. Abstract
This report details a study of configurations for underground utility installations sharing the transportation right of way. A method for identifying optimal configurations based on total societal cost was developed. A computational model for system planning was formulated and a program was constructed. Methods for application of this research are suggested.</td></tr>
<tr><td colspan="2">17. Key Word
Utilities, Joint use corridor, Right of Way</td><td>18. Distribution Statement
No Restriction</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td>20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages 112   22. Price</td></tr>
</table>

SUMMARY

Problem Statement

To deliver services to the public, utilities are typically routed in corridors located within the transportation right-of-way (R/W). Utility companies usually install facilities in the most desirable locations first, but depending on regulatory constraints, such choices may block efficient placement for other facilities installed later. The eventual consequences of this utility corridor crowding are public safety concerns, damage to the infrastructure and interruption of service to the consumer. Furthermore, in areas of rapid population growth, the need to improve the roadway eventually necessitates modification to the corridor and subsequent utility relocation. Ultimately, the public bears the costs of the corridor infrastructure development and maintenance.

Objectives

This research is intended to develop a methodology to help identify the best placement of utility facilities during the development stages for new transportation corridors, and also during planning for modification of corridors either by the addition of new facilities or relocation of existing facilities (often associated with alterations to the roadway). The goal of this research is to improve efficiency and safety of utility corridors while reducing costs and conflicts. A model was constructed to examine optimal methods for corridor organization. Providing that cost information (both present and future) associated with the physical positioning of facilities within the corridor can be obtained, then optimization techniques may be employed to produce a favorable cost/benefit ratio. It is envisioned that this modeling strategy will eventually evolve into a practical tool available for practitioners to evaluate corridor organization. A discussion of the development of a model to accomplish this task is presented and examples of typical problems are introduced. Projected needs for data acquisition are discussed.

Findings and Conclusions

A strategy for identifying optimal configurations for underground corridors was developed. It was found that the following items were needed as information to accomplish this task:

1. For each utility, identify all absolute positioning constraints (no-installation zones, clearances, restricted installation zones, tolerance uncertainties, and cover requirements).

2. For each utility, summarize all configuration dependent cost factors, reduced to functions of position and brought to present. Much of the cost

information must be obtained from utilities, or other agencies. Consequently, there is a degree of uncertainty associated with cost.

3. Define an overall cost function as a weighted sum of cost components over all utilities. Weighting corresponds to ranking utilities by importance. Here all utilities were weighted equally.

4. Develop a scheme for determining all possible configurations for proposed utility lines within a defined corridor. For each possible configuration, evaluate total cost and a cost per utility.

5. Examine the results to identify those configurations exhibiting the best characteristics, and assess potential for improvement between various acceptable solutions. It is noted that the assessment of performance is a determination ultimately the responsibility of the planner.

Because the tasks outlined above are extensive, a computer program was developed to assist in making the necessary computations and has been delivered to the FDOT. To facilitate the evaluation of corridor configurations, a set of performance ratios (efficiency, flexibility, etc) were constructed. Several examples were presented to illustrate both the method and the capabilities of the program

*Benefit*s

The long and short term benefits of this research are anticipated to be the following:

- Facilitate managing R/W resources
- Minimize disruption of utility services and improve safety during construction, maintenance, or location activities
- Ensure better maintenance of traffic
- Facilitate reimbursement for utility relocation by the FHWA
- Potentially reduce claims and delays on FDOT construction projects

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

In this report, dimensions are given in English units.

Symbols

n	Number of utilities	non-dim
m	Number of component costs	non-dim
w	Cost weighting factor	non-dim
c	Component cost	k$/mi
C	Total cost	k$/mi
W	Utility weighting factor	non-dim
TC	Total cost of a configuration	k$/mi
x	Installation horizontal location	ft
y	Installation depth	ft
D	Diameter	ft
Y	Year	yr
ADT	Average daily traffic	cars*10^3/day
TGR	Traffic growth rate	%
TVC	Traffic volumn cap per lane	cars*10^3/day
NLANE	Total number of lanes	non-dim
T	Years to design year	yr
G	Location dependent cost	k$/mi
A_{dam}	Damage cost coefficients	k$/mi/ft
a_{inst}	Installation cost coefficient	k$/mi/ft
b_{inst}	Installation cost coefficient	k$/mi
a_{reg}	Regulatory coefficient	k$/mi/yr
L_{eq}	Equivalent trench length	ft
f_{acc}	Frequency of access	events/yr/mi
Φ_e	Single encroachment angle	rad
P	Probability of an encroaching vehicle	non-dim
SW	Swath width	ft
EF	Encroachment factor	non-dim
IF	Impact factor	non-dim
f_{dam}	Frequency of damage	incident/event/mi
c_{max}	Maximum cost per incident	k$
MTC	Minimum total cost	k$/mi
$Q_{efficient}$	Configuration efficiency	non-dim
Q_{crowd}	Configuration crowding	non-dim
$Q_{effectiveness}$	Effectiveness	non-dim
$Q_{balance}$	Balance	non-dim
ICR	Individual Cost Ratio	non-dim
MC	Minimum cost	k$/mi
P	Probability of installation	non-dim
Q_{flex}	Flexibility	non-dim
R	Radius	ft
LF	Lane factor	non-dim
N	Number of facilities per mile	1/mi

Subscripts

j	Denotes a utility
i	Denotes a configuration
k	Denotes a component cost
l	Denotes a year in service life
sl	Service life of the corridor
DY	Design year
inst	Installation
dam	Damage
reg	Regulatory burden
r	Regulatory
lw	Lane width
acc	Access
os	Offset from edge of pavement
coll	Collision
snr	supplemental nonrecurring
sr	supplemental recurring
add	Additional facility
x	Horizontal
y	Depth
agf	Above ground facility
rel	Relocation
ren	Renovation

SECTION 1: INTRODUCTION

Need for improved corridor configurations

Utilities (gas, water, electric, telecom, drainage, etc) are an integral part of the national infrastructure. Delivery of these services to customers is accomplished in large part by a distribution system in subsurface and aerial corridors co-located with the roadway network. In the effort reported here, attention will focus on the underground corridor (cross section) occupied by various facilities. Historically, many corridors have developed on a first-come, first-served basis. The lack of advanced planning has invariably led to crowding and inefficient utilization of resources. Problems typically develop when new utilities are installed or when roadway renovation occurs as older lines are often damaged or conflicted by newer installations.

Typically, a number of utility lines are located either beside or possibly underneath the pavement, constrained horizontally by the right-of-way easement and vertically by cover considerations and excavation limitations, as well as by the method of installation and other factors (see Fig 1-1). How these utility lines can be arranged optimally within this corridor is the subject of this investigation. The term optimal is used here to mean “best possible” and is a concept that will require further explanation. There are three circumstances of interest, new construction of roadway and utility corridor, installation of additional utilities in existing corridors, and expansion or renovation of roadway infrastructure with attendant need for utility line relocation.

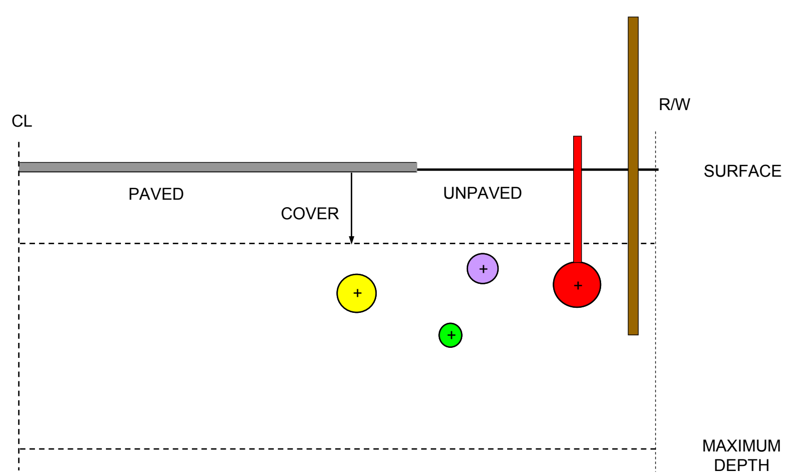


Figure 1-1: Typical subterranean corridor configuration

Various governmental agencies exercise some oversight of the utility corridor, and may be charged with a combination of design and regulatory functions. These agencies provide the important function of liaison with the various utilities and also resolve conflicts between utilities impacting the ROW. In addition to regulatory agencies, a diverse group of other stakeholders, each having an interest in the outcome of any decision making process participate in the development of the corridor configuration. This group includes the public, (as consumers and affected parties), utility owners (both public and private) and other corporate parties (contractors, service, etc). It is likely that each stakeholder has different goals. For instance, utility owners may interact but do not necessarily compete or cooperate. Thus each of these stakeholders participates for different reasons and may be satisfied by different outcomes.

Clearly it is in the best interest of the public to develop an efficient organization of the individual utility lines. Unfortunately this complex problem has received only modest attention. In 2000, the FDOT State Utilities Section developed a need statement to plan for the optimum placement of Utilities within the R/W. The long and short term benefits were anticipated to be the following:

- Facilitate managing R/W resources
- Minimize disruption of utility services and improve safety during construction, maintenance, or location activities
- Ensure better maintenance of traffic
- Facilitate reimbursement for utility relocation by the FHWA
- Potentially reduce claims and delays on FDOT construction projects

Perhaps the easiest situation to envision and analyze is a new highway routed through a rural environment with no serious constraints regarding right of way. In this case, all planning can easily be accomplished in advance of installation. For new construction in urban areas however, the ability to acquire adequate right of way may be much more limited, confining the utilities to occupy a much more limited space. The addition of one more line to an already crowded corridor presents significant challenges. Similar arguments apply to renovation projects requiring relocation, except that planning must consider existing conditions.

The following utilities have been identified as possible occupants of joint use corridors:

- natural gas
- potable water
- reclaimed water
- sanitary sewer, force mains
- sanitary sewer, gravity
- storm water
- electric power
- cable
- telephone
- fiber optic
- other telecom

- chiller water
- alarms
- liquid transport-fuel/oil
- other chemical
- other, unknown, or yet to be developed

Any agency with oversight governing joint use corridors must balance regulatory requirements (ownership, safety, environmental, etc) while maintaining a position in the public interest and competitively neutral towards all users. When considering the organization of utilities within a corridor, several approaches might be taken:

1. First come-first served – obviously puts latecomers in less advantageous position and thus may increase societal (and individual) cost.

2. Assigned location – may be arbitrary or based in part on previous experience.

3. Optimization strategy - while a rational method may tend to produce an optimal result (or minimal total social cost), in some cases application may be limited by uncertain or missing information.

It appears that most often governmental agencies adopt the first approach (and much less often the second). The consequence permitting expansion in an unplanned fashion is that as population growth stimulates the need for expansion it is likely difficult or impossible to find space in already dense location. Because the corridor is not organized efficiently disruption and damage occur during expansion. Here the goal is to examine the third strategy -not arbitrarily assigning placement but dedicating specific locations to individual facilities based on a rational strategy

The resulting configuration of the corridor can be substantially impacted by the methods used to install various facilities within the allotted space. Similarly, provisions must be made to incorporate connections for crossover to customers located on the other side of the pavement and to provide vertical access to the line. Finally, proximity conflicts with other utilities located both parallel and transverse to each other must be considered. While the problem of the location of individual lines within a corridor may appear to be a two dimensional problem, a much more complicated situation can arise at transverse intersections or at utility branch points.

This report is concerned with an investigation of methods for developing optimal configurations for utilities jointly occupying the transportation right of way (R/W). The goal of this investigation is to develop a method for organizing utility lines within a joint use corridor, so that the resulting configuration of lines is economical and efficient. It is projected that such a method could be useful for planning and evaluation, for new construction, the addition of additional facilities and renovation/relocation.

In keeping with the need statement discussed earlier, the overall objective of the research reported here is to develop a procedure for locating utilities in the R/W in an optimal fashion. The very nature of this undertaking is speculative and requires considerable definition to develop an engineering problem statement. As a means to improve clarity and understanding in the body of the report that follows, it seems worthwhile to present a preliminary discussion of several issues surrounding the problem, to set the stage for the methodology presented later in this report. This preface will serve to introduce various definitions and relationships involved, anticipating further refinements in later sections.

Organization of report

The next sections discuss the development of a heuristic model intended to simulate the organization of a corridor, the implementation of this model in a computer program and examples of the use of the model (representative case studies and research problems). Although in many parts of the report, the terms “model” and “program” are used interchangeably, it is important to maintain a distinction between the model, which is a general conceptual framework for understanding the problem and the program which is one of several possible methods for carrying out the computations necessary for corridor simulation and analyses. The report concludes with a summary of results and recommendations for future research. Various appendices are attached for further clarification.

Historical synopsis of research effort

As discussed in the body of this report the principle accomplishment of the work reported here has been the development of a model for corridor simulation, along with a provisional data base and sample calculations. Several software tools to accomplish the computational tasks have been constructed and delivered to the FDOT under separate cover. It is anticipated that if fully implemented, the model and software tools could be utilized by informed professionals to assist in the efficient planning and permitting of utility corridor development.

A number of supplemental items have been produced as a result of this investigation as noted below.

1. Meeting presentations

> "Optimal placement of utilities within the FDOT R/W"
> FDOT/FICE Design Conference, Orlando FL, Aug 2002
>
> "Optimal placement of utilities within the FDOT R/W", presentation at the District 1 Utility Liaison Meeting, Sarasota, FL, Sept 25, 2002
>
> "Optimal placement of utilities within the FDOT R/W"
> Fla. Utilities Coordinating Council (Annual Meeting), St. Petersburg Beach, FL, Nov. 7, 2002.
>
> "A Computer Model for Evaluating Utility Placement in the ROW", presented at the Subcommittee on Right of Way and Utilities Conference, AASHTO/FHWA Newport RI, May 4-8,2003
>
> "Utility Corridor Analysis and Placement", presented at
> *TRANSPORTATION & UTILITIES:TWO SIDES OF THE SAME COIN,*
> sponsored by West Coast Branch of ASCE, Tampa, FL, July 14, 2005

2. MS theses completed by students supported in part by this contract (available through USF library)

A Master's thesis study, by Steve C. Christian, entitled

> "A Sensitivity Analysis of the Simulation Model used for the Placement Allocation of Utilities in Transportation Right of Way Corridors"

A Master's thesis study, by Vijayakumar Shanmugam, entitled

> "Multi-Objective Optimization using Fuzzy and Probabilistic Objective Coefficients for Optimal Placement of Utilities"

3. A consultant report (cf Appendix 2) completed as part of this investigation

4. Tutorial Manual (for program deployment) including instructions and examples

5. A deployment presentation: "SOFTWARE ROLLOUT –OPTIMAL PLACEMENT OF UTILITY FACILITIES IN THE TRANSPORTATION RIGHT OF WAY" (Nov. 16, 2005), including course materials and a Power Point slide package.

6. Papers submitted to technical conferences

“Optimizing Facilities Placement and Automating the Permit Process for Improved Utility Corridor Development”, Nathaniel O. Collier and S.C. Kranc, accepted for presentation at the TRB 85th Annual Meeting, January 22-26, 2006, Washington, D.C.

Organizing Utility Services in Transportation Corridors, with N. Collier and W. Miller, accepted for presentation at the Joint International Conference on Computing and Decision Making in Civil and Building Engineering, to be held in Montreal, Canada, on June 14-16, 2006.

7. Copies of programs

DESIGN/ADD
PERMIT
ANCILLARY COMPUTATIONS

Literature review

A review of the literature pertaining to the accommodation of utilities in the transportation R/W yielded very few references to work directly related to optimal organization of facilities. A number of studies concerned with related areas, were located, however. A review of the entire field of utility accommodation was not attempted; rather a brief discussion of recent work closely related to this study is given below, broken down by subject area. This discussion has been included in the Reference section for convenience.

Problem definition

It is worthwhile at this point to review and summarize the overall problem under investigation. Given that utilities legally share the transportation right-of-way, it is desired to develop a methodology to determine the best configuration for utility facilities installed in the transportation R/W. As is discussed more completely in the section below, the term “best” is interpreted here to mean an optimal choice based on minimizing all societal costs dependent on the location selected for installation.

Determination of optimal positioning is complicated by many conflicting issues as well as a paucity of relevant and necessary data. The task here is to formulate a strategy for accomplishing this objective by invoking realistic simplifying assumptions, gathering background data and developing techniques for obtaining any additional information necessary to identify optimal corridor configurations.

SECTION 2: HEURISTIC MODEL FOR CORRIDOR CONFIGURATIONS

Optimal configurations for utility corridors

Utilities are delivered services, benefiting the public. The various facilities installed in corridors belong to utility providers, both public and private. The installation and maintenance of these facilities is accomplished in part by contractors and engineering firms specializing in such work. Furthermore, interested governmental agencies, some with regulatory functions, must be added to the list of entities (stakeholders) concerned with corridor development. Clearly, economic considerations form a powerful force driving optimal organization in utility corridors. Presumably, if all entities involved see reduced costs to themselves, then the public could realize similar benefits.

It is highly likely that one single parameter will not be sufficient to select a single optimal solution. The concept of an "optimal" corridor evokes thoughts of both cost and efficiency, for example, although neither of these terms has been defined for the present discussion. Even if total costs are minimized, it does not follow that the component costs are born equally among all participants. Thus, in later sections other measures will be introduced in order to assist in the selection process. Some of these factors include efficiency, flexibility and uniformity of burden (all yet to be defined).

It is noted that the "value" of the corridor is a related concept, but the concern here is not so much with the worth of the corridor (as improved real estate) as much as the benefits ultimately derived by the public. All costs are ultimately born by consumers, but total cost is also partitioned among the installed utilities and to some extent public agencies. It is recognized that this cost consists to some extent of intangible items, items relating to future events and possibly items which may not be obvious at first consideration. Furthermore, the configuration cost can be subdivided in different ways among the utilities installed in the corridor.

To help understand the effort reported here, the following analogy is offered to explain the current situation. In a sense, the strategy of locating utilities (first come, first served) resembles a game, where the players (stakeholders) are the consuming public, private utilities, public utilities, and other corporate entities including contractors, service professionals, etc, along with governmental regulatory agencies. Each of these players participates seeking different goals and will be satisfied by different results. There is no reason to believe, however, that the "best" or optimal solution to the overall problem will result from this approach.

The thrust of the effort reported here is to develop and implement a model to simulate corridor organization. Conceptually, such a model is a statement of how different elements of the overall problem interact to form a solution. It is then also a part of the modeling effort to determine, according to some standard, just how good this solution is. The standard by which solutions are tested then also requires definition. The eventual goal of this research is to refine the problem definition and the model used to generate a solution, to the point where one has confidence that an optimal solution has been obtained (recognizing that more than one solution may be generated). Continuing the game analogy to explain a rational approach, the stakeholders agree initially on a set of rules and data (the simulation model). Execution of the model then provides an arbitration function, while simultaneously producing the optimal solution according to the previous agreements of the stakeholders. Eventually, such a technique might be used to help negotiate disputes arising from conflicts and claims.

The model developed for use here consists of a sequence of steps intended to accomplish this result methodically, and should only be viewed as a tool. Ultimately it will be up to the user to provide the underlying data in order to obtain answers to specific questions. It is recognized that some portion of the information needed to construct the cost function may be non-existent or uncertain. A larger question then concerns the ability to provide the detailed information needed for such a model and how deficiencies, if encountered, might be treated. Furthermore combining widely diverse factors such as costs associated with installation, maintenance, vehicular traffic and potential for accidents with the infrastructure, etc., on the same normalized basis is inherently difficult. Later installations, pavement widening and other future events can be treated by assuming that the probability of occurrence provides a suitable weighting for the respective cost function component.

An extension of the game analogy, especially appropriate for new development or additions is for the stakeholders to jointly examine the projected occupancy of the corridor, and then establish the constraints to locating particular facilities. The optimal configuration is subsequently found by minimizing the total cost. Aside from the methods used to find the minimum, there is a significant effort involved in the development of the cost function. This is a complex function, capable of including many diverse factors. Furthermore, it may be desirable to weight these factors, as a means of incorporating other desirable characteristics into the function. Finally, it is also true that the cost function is composed of subunits, the individual cost functions for particular utilities. A global optimization directed at a total cost function does not in general minimize individual costs.

It should also be noted that in the interest of simplicity, much of the discussion will be focused on a relatively straightforward approach to the development of a heuristic simulation model, defined and discussed below. This presentation may appear to be naïve at some points but it is recognized that other, more advanced techniques could be employed and should be considered. Simplifying assumptions are made in the interest of obtaining a tractable model. Nothing in the present treatment appears to be a limitation to further development and introduction of more sophisticated approaches at a later date.

Optimization and total societal cost

In the present study, the description of the best configuration for the underground corridor is the goal of any optimization scheme employed. From an overall societal standpoint, the minimum total cost for the corridor (which is a complex function of configuration and includes many factors beyond initial installation costs) is obviously one very desirable goal and this target will be the present focus. However, it is also true that there may often be a set of acceptable solutions, rather than one unique answer to a particular problem. Furthermore, minimizing overall cost may mean that some utilities are placed in disadvantageous locations in order to achieve a global optimum.

The evaluation of accurate, position sensitive costs associated with the installation of a particular utility over the lifetime of the corridor is quite complex. Here, an attempt has been made to allow for many realistic factors, while excluding less likely scenarios, in the interest of producing an appropriate cost estimate. A tacit assumption in the work that follows is that a satisfactory weighting for the influence of a particular cost is given by the product of the probability for some event and the expected in-service lifetime. Although any cost element could be omitted during analysis, a complete description of all position sensitive costs is important to obtain a meaningful model. It is also noted that at present, no estimates of the uncertainty associated with these costs has been established. It may be that mutual agreement among the stakeholders as to the data quality is all that can be expected.

The optimization problem of finding the minimum total cost for a specific corridor comprising n utility facilities can be posed as follows. Any proposed location for each of the n utilities to be placed in the available corridor can be described by a horizontal and vertical position and constrained by the boundaries of the corridor as well as various clearance requirements. Thus, 2n independent location parameters are taken in pairs to determine n individual facility costs that are each comprised of m component costs c_k (weight w_k).

$$\sum \qquad (2\text{-}1)$$

where the total cost of any particular corridor configuration (denoted by i) is then weighted sum of the individual composite costs C_j, for all facilities (positioned at $x_{i,j}$, $y_{i,j}$):

$$TC_i = \sum_{j=1}^{n} W_j C_j(x_{i,j}, y_{i,j}) \qquad (2\text{-}2)$$

The total is a “societal cost”, and the various stakeholders pay for different components of the individual costs. For completeness, a set of weighting factors, W_j, has been included here (to make valid comparisons between solutions with different weightings, the sum of W_j should equal n). These factors might represent the relative importance attached to individual utilities, for example (although throughout this work the weighting was always taken as unity).

To find an optimal solution, using a minimal societal cost, a straightforward method was employed; first the set of all feasible configurations was identified by examining every possible combination of locations, while simultaneously checking satisfaction of constraints. Then the total cost for each feasible configuration was calculated and the solution set (those configurations having the smallest cost) was located by exhaustive search of the set of feasible solutions. While many elegant methods exist to locate an optimal solution, exhaustive search was chosen for this research so that multiple solutions could be identified and examined.

Corridor model

A model was developed as part of this investigation to provide a basis for making rational decisions regarding the organization of a corridor. Stated simply, the model determines possible configurations for the corridor and values each of these arrangements. It is then also a part of the modeling effort to determine (according to some standard) just how good each possible solution is. The solution set presented by the model consists of optimal configurations chosen by some established criteria (eventually to involve stakeholder participation). For purposes of this discussion, the goal will generally be to minimize total societal costs, along with subsidiary considerations. While all costs are ultimately born by consumers, the model helps to understand how the cost of any configuration is partitioned among the various stakeholders.

To provide input necessary for an effective simulation of corridor organization, a large amount of basic information is required. Some of this information is available from reports in the open engineering literature; some has become available as the result of this research. It must be recognized however that a substantial body of required information is unique to any particular corridor and of necessity will have to be provided by the group impacted by a potential design (the stakeholders). Ultimately it will be up to these stakeholders to agree upon the underlying data in order to obtain answers to specific questions. It is also anticipated that some important information may be uncertain, incomplete or not readily available.

Fundamental data and constraints

In the present study, the definition of corridor configuration is restricted to a description of the subterranean cross section of the transportation R/W, available for utility installation and including the horizontal and vertical positioning of all utilities (Figure 2-1). Only one half of the R/W was analyzed (to the centerline of the pavement). Thus, the horizontal extent of the corridor is the joint use right of way from the center of the pavement to the outer edge of the easement (one side of the roadway). The vertical extent of the corridor is governed by practical considerations (water table, method of installation). The Cartesian coordinate X will be attached to the horizontal position extending from the center line and Y represents the vertical position measured downward from the surface elevation at the edge of the pavement. Utility conduits are assumed to run parallel to the roadway and where necessary the coordinate Z will be associated with distance along the corridor (not necessarily a straight line). Consideration of roadway horizontal curvature is included as necessary.

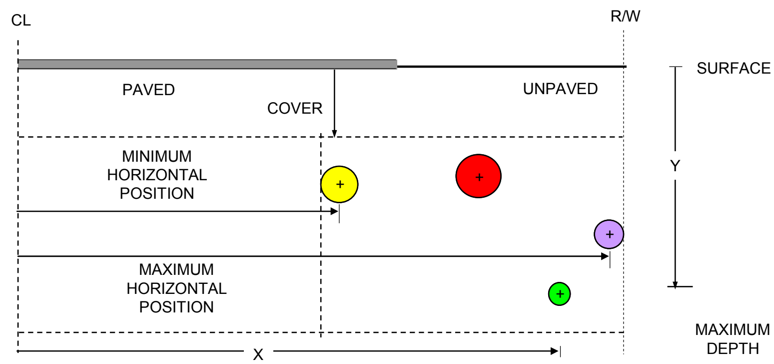


Figure 2-1: Simplified schematic of corridor cross section

For simplicity, all utilities are assumed to be carried and contained in round conduits. In this study, the possibilities of sidewalks, intersections or medians are not considered. Only the subterranean corridor is analyzed, but this restriction will be modified as discussed below. Information describing the utilities planned for installation in the corridor includes the quantity, type, diameter and the requirements for above ground facilities such as hydrants, terminal cabinets, etc. The organization of utilities within the corridor is defined in part by the boundaries and also rules governing the configuration within, such as clearance required between various utilities. Usually a minimum earth cover is specified and there is some possibility that this requirement may vary for paved versus unpaved areas, as well as for individual utilities. Some rules are absolute, as for example, a restriction from interfering with traffic. Other rules may be categorized as regulatory or arbitrary, due to concern for life safety issues (for example the enforcement of a “clear zone”) or environmental restrictions. Eventual widening of the roadway with possible relocation of facilities is a problem of particular interest included in the present discussion.

To summarize:

Corridor boundaries: The maximum extent corridor extends laterally from the centerline of pavement to the right of way. The vertical extent of the corridor is taken from ground level to the anticipated deepest installation (measured to bottom of conduit). Installation with respect to a corridor boundary of a particular utility may be further limited to allow for "clear zones" containing no installations.

Cover: Cover is defined as the vertical distance from ground elevation to the top of a specific conduit (Figure 2-2). This dimension may vary with horizontal position in the corridor and also from utility to utility. While in many figures in this report the ground profile is assumed to be level, most roadways incorporate a profile feature (swale, curb and gutter, etc) along the roadway. For convenience, the term "default cover" will be used to describe a typical minimum cover dimension applicable to the corridor.

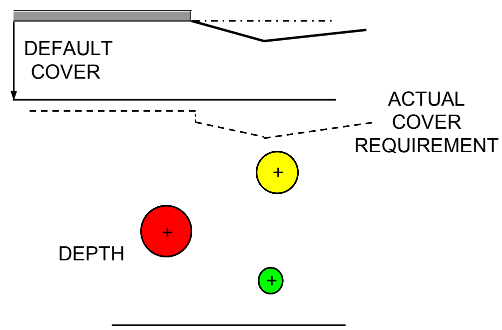


Figure 2-2: Illustrating cover constraint

Clearance: The distance required for separation between adjacent facilities is the clearance, a major constraining factor organization of the corridor. The rules and regulations regarding clearance (and their interpretation) can be extremely complex and vary with jurisdiction. Some of the factors governing clearance are

- types of both facilities
- environmental concerns
- galvanic corrosion concerns
- method of installation of both facilities
- horizontal separation
- vertical separation above
- vertical separation below
- preference for a minimum separation vs an optimum separation
- conduit material
- physical condition of conduit
- rules for exceptions and extraordinary circumstances

At the simplest level, clearance could be stated as a minimum distance of separation between outer conduit surfaces, along a line joining the centers of the conduits. Inspection of regulations suggests that this simple interpretation is almost never applied. Instead a horizontal and vertical clearance dimension is often enforced, but the interpretation of these rules may still be confusing. The most elementary interpretation, that a vertical and horizontal clearance represents the spacing between outer covers of adjacent facilities is used here.

In the interest of formulating a generalized constraint, the concept of a *bounding box* surrounding a specific facility is introduced, as shown in Figure 2.3. The purpose of this formulation is to facilitate the search process for feasible solutions. The facility surrounded may be interpreted as actually being in place as would be true in the case of an addition, or may be in place with regard to the search process. Corresponding to this figure are two arrays of clearance values (Table 2-1), one for vertical clearance and one for horizontal clearance, specified in the following manner. Consider a situation with three utilities of different types: A, B, and C. Each array is labeled with a vertical column representing the facility to be installed and a similar row of utilities representing the facility in place, as seen below.

Table 2-1: Sample clearance table (values are assumed and arbitrary).

1) VERTICAL CLEARANCE (FT)

INSTALL	FACILITY IN PLACE		
FACILITY	A	B	C
A	1.5	2.0	2.0
B	2.0	1.5	1.5
C	2.0	1.5	1.5

2) HORIZONTAL CLEARANCE (FT)

INSTALL	FACILITY IN PLACE		
FACILITY	A	B	C
A	2.0	1.5	1.0
B	1.5	2.0	1.0
C	1.0	1.0	2.0

Both arrays are read and interpreted according to the following convention: the vertical entry represents the facility type being installed versus the horizontal entry as the facility already in place. The same interpretation applies to physical placement or the program search. Each array must be symmetric (i.e. B installed next to A gives the same value as A installed next to B).

As an example, suppose a type B facility (blue) is to be installed near an existing type A facility (red). Information from Table 1), vertical clearance is read as follows: the clearance required by B (vertical column) when located near A (horizontal column) is 2 feet. The horizontal clearance (1.5 feet) is obtained using the same convention. It is noted that there is actually no ambiguity inherent in the choice of reading vertical columns to horizontal rows, as demonstrated here or vice-versa, horizontal row to vertical column. The end result is the same, but for clarity it is important to state a convention. For modeling purposes, values in these arrays are assumed to have values given in Appendix 2 but may be adjusted to suit the specific problem considered, as for example, if extra clearance was desired to allow for spatial uncertainty in the position of either facility. Arrays must be symmetric however and if other values are employed this condition must be met.

As shown in Figure 2-3, a box, where B cannot be installed has been constructed around and existing facility of type A. The vertical dimension is 2.0+D_A+2.0 feet, while the horizontal dimension is 1.5+D_A+1.5 feet.

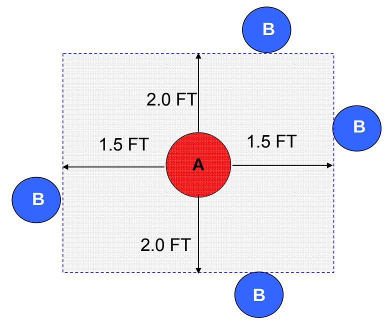


Figure 2-3: Illustration of clearance rules as constructed for model. Facility A is in place, while Facility B is to be installed.

The statement of clearance rules outlined in this way is sufficiently general to accommodate most interpretations for clearance rules unambiguously and with minimal effort. It is however, the responsibility of the planner to ensure that the values are correct. Similar arguments can be made for conduit to utility pole base clearances, although in this case only the horizontal distance is important.

One other issue related to clearance that must be considered for completeness is the possibility of stacking utilities, the placement of one conduit above or below another (Figure 2-4). Enforcement of this type of constraint usually depends on access requirements or interference with an above ground facility, and may influence the cost function in several ways. For example could a vertical riser from a deeply placed utility pass close to a facility at a higher elevation? Here provisions will be made to allow for either situation, stacking allowed or not allowed.

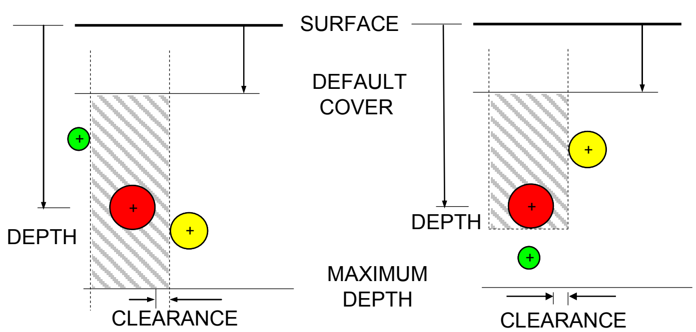


Figure 2-4: Two possible interpretations of stacking rules.

During the conduct of this investigation, the following viewpoint was adopted regarding aerial corridors. If electric lines (possibly accompanied by other telecommunications) are to be placed on poles then the placement of the base of a utility pole will be considered to be another underground facility, for which no other facility could be located in the same vertical position, obviously (Figure 2-5). The cost of placement can then easily be treated just as any other installation (although most likely the best position will be determined to be at the edge of the R/W). Thus arguments concerning the relative merits of "undergrounding" are eliminated from the discussion and the effect of moving an existing line on the cost function is treated as an incident of renovation at some future date. This simplification is in no way restrictive, but rather made for consistency.

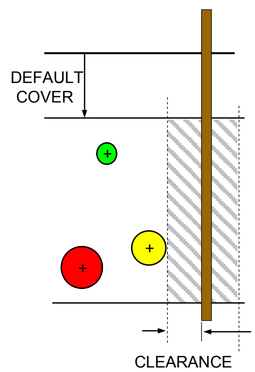


Figure 2-5: Clearance requirement with respect to base of utility pole

Service life

The service life of the corridor is defined as the time interval from the original construction of the roadway/utility corridor until some time in the future when the roadway would be replaced or substantially modified. The service life schedule covers the total economic lifetime of the corridor, with all relevant events identified. These events include (but are not limited to) installation, relocation, renovation, access, traffic volume, accidents and decommissioned (placed out of service). Both the probability of occurrence and the estimated time of occurrence need to be specified.

The following events are especially important: inception of corridor, possible renovation (pavement widening) and end of service life (ESOL) as shown in Figure 2-6. For individual utilities, the year of installation and the year of decommissioning are significant. Obviously, timing is highly speculative, and estimates (however crude) will have to suffice. The following convention will be used here. The date of inception is January 1, Year zero. At this time initial installation of many utilities is assumed to occur. One year later, on January 1, Year one, one year has elapsed with cumulative access, accidents and damage, etc. All events during the year are assumed to occur on January 1 of that year.

For example a new installation occurring in June of Year ten will be represented as having occurred on January 1, Year ten, so by the beginning of Year 11, one full year of recurring events will have taken place. The end of service life of the corridor, denoted $Y_{sl,}$ will be on January 1 of the last year. With regard to economic considerations, recurring and one-time events are mixed in the treatment of the cost function. It is assumed for simplicity that the acceleration of costs exactly equals the time value of investment so that all costs can be converted from an annualized to present value basis (and back) without applying interest charges.

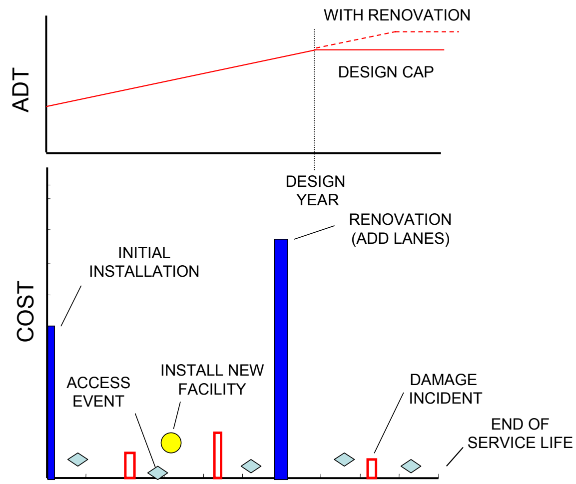


Figure 2-6: Depicting the service life of a typical corridor

Service life of individual utilities

Applying the discussion above to specific facilities, it is possible that the jth utility facility could be placed out of service or deactivated prior to the end of service life (in year $Y_{j,sl}$). Consequently, the lifetime of the jth facility will not extend from the date of installation to the end service life of the corridor, but instead will terminate at the time of deactivation. If the facility is not placed out of service, the default value for $Y_{j,\,sl}$ will be the service life of the corridor Y_{sl}. Additionally, it is assumed that no credit is added to the cost function as a result of decommissioning (in some cases it may be advisable to modify this assumption to correspond to reimbursement rules). It is further assumed that out of service facilities are removed. A future model might examine the possibility that decommissioned facilities would be left in place and could be utilized (perhaps by another utility).

Paved width and cover

Also accounted for in the service life record is the pavement width, so that changes occurring at renovation will be apparent. There are several factors that may depend on the actual pavement boundary, including offset for above ground objects, changes in cover requirements that occur with pavement, and the need for possible facilities relocation if the boundary should be modified. For both two way and one way roads, the paved region on one side of the centerline is obtained by multiplying the number of lanes by the lane width and dividing by two. It is noted however that one way roads having odd numbers of lanes results in a centerline in the middle of a lane. During a renovation event, it is assumed for simplicity that the number of lanes is increased by two for two lane roads and that the lane width remains constant.

Traffic volume

The average daily traffic (total traffic count, independent of direction or number of lanes) for the roadway in year I, ADT_I can be expressed as

$$ADT_I = \frac{ADT_{DY}}{1+TGR^{T_I}} \qquad (2\text{-}3)$$

where ADT_{DY} is the design value for average daily traffic, T_I is the number of years from year I to the design year and TGR is the traffic growth rate expressed as a decimal fraction. The annual ADT is a required quantity associated with the service life of the corridor. In the case of lane addition it is a reasonable assumption to expand the capacity in proportion to the number of lanes added. As a consequence, there will be two alternative pathways for traffic development (renovation or no renovation) and the importance of each is determined by the probability of renovation. If traffic is two-way, as assumed here, the total volume in one direction is one-half the ADT. Traffic is assumed to have the same volume in both directions.

The traffic volume cap (TVC) [22] is expressed <u>per lane</u>, whereas the ADT is given as the total traffic count, independent of direction or number of lanes (NLANE). Thus the total number of lanes in one direction is one half the number of lanes. For two-way traffic, with respect to an above ground feature, the traffic volume in adjacent lanes is ADT_I /2, and the same for opposite flow. The volume per lane is ADT/NLANE and it is assumed that the design capacity (per lane) would be less than or equal to TVC. (If this is not true then a comment should be issued). For one way roads, the capacity per lane is handled in exactly the same way but no traffic flow opposite is present when the accident model is computed.

The average daily traffic in year I (ADT_I) is given by

$$ADT_I = ADT_0\,(1+TGR)^{T_I} \qquad (2\text{-}4)$$

where T_I is the number of years from year I to the design year and TGR is the traffic growth rate. The initial traffic volume can be obtained from

$$ADT_0 = \frac{ADT_{DY}}{(1+TGR)^{T_{DY}}} \qquad (2\text{-}5)$$

where T_{DY} is the design year and TGR is the traffic growth rate.

In the case of lane addition it is assumed that the total volume of traffic/per lane drops then begins to rise again according to the growth rate, until the TVC is once again reached.

Development of models for component costs

The following section describes how each component of the individual utility cost functions has been modeled in this research (Equation 2-1).

1. *Installation costs*

Installation costs are understood to be the initial (non-recurring) cost of placing the utility conduit, including excavation, maintenance of traffic, conflict accommodation, shoring etc, but excluding the material costs of the conduit. With regard to this latter item, in situations where an above ground feature may be present, the installation cost could include added material costs accrued as a result of the installation depth. Figure 2-7 shows a typical installation cost diagram, obtained from a survey request done as part of this study. A simple model is that all utilities have approximately the same installation costs, and that the dependence with depth shown in this figure can be taken as representative. Adjustments to this function may be justified in some situations. For example, generally costs will increase for installation under pavement. Another situation requiring special consideration is the installation of conduits near the ROW boundary. Here additional shoring may be necessary at all depths to avoid impacting adjacent property. Other alternative methods (trenchless installation, utilidors or utilizing decommissioned facilities, etc.) may have different cost models. While trenchless installation techniques (jack and bore, horizontal directional drilling, etc) may not depend on location, it is still essential to represent these charges in the overall cost function so that valid comparisons can be made.

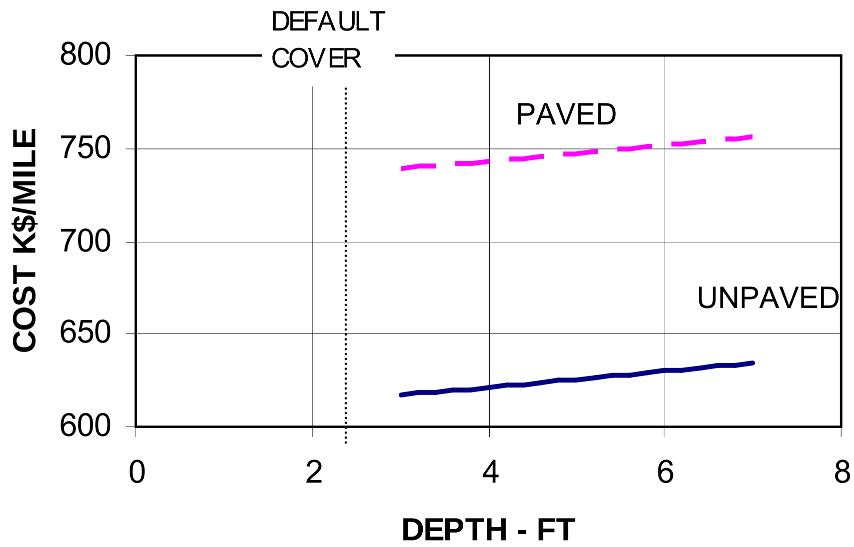


Figure 2-7: Installation costs (cf. Appendix B)

In general the non-recurring cost of installation can be formulated as (units of $K/mile)

$$c_{inst} = [G(x,y) + A_{dam} c_{dam}(y)] \qquad (2\text{-}6)$$

where G represents the location dependent installation cost. A function $c_{dam}(y)$ (having the same units) to account for damage to other facilities during installation, has also been included with multiplication by an adjustment constant A_{dam}. This term is discussed more completely below.

Installation costs were modeled here as function g(y)= ay+b, linear in the vertical direction, plus an additive parameter. The value of the coefficient a is a function of the utility specification (diameter, etc) and the value of b depends on whether or not installation is made under pavement (a step function of x, switching values at the edge of the pavement). Thus

$$c_{inst} = [a_{inst} y + b_{inst}(x) + A_{dam} c_{dam}(y)] \qquad (2\text{-}7)$$

The form of this model is considerably more restrictive than a general function of x and y (and may not cover all types of installations). As mentioned previously, to obtain values for the factors a and b, data for the absolute cost of installation based on an aggregate unit cost approach has been developed and is discussed in Appendix B. It is also possible that this information could come directly from stakeholder input.

A simple model for the cost of deinstallation is to utilize the cost of installation at the installed position. This may be accomplished using the supplemental costs factor described below.

2. *Regulatory burden*

The selection of some locations for installation may result in costs (direct or indirect) determined by the agency overseeing occupancy of the joint use corridor. For example, agencies concerned with maintenance of the roadway could incur or recognize additional costs if installation or access is close to or underneath the pavement. Assuming that this cost can be quantified, a surcharge penalty can be associated with locations deemed undesirable by the agency. It is likely that this cost would be primarily a function of horizontal position and in this analysis a simple step function model has been assumed, with the transition point located by a constant distance from the pavement edge. Thus a_{reg} is a constant for $x<x_{lw}+x_r$, and zero elsewhere, so that

$$c_{reg}(x) = a_{reg}(x_r, x_{lw}, x) \qquad (2\text{-}8)$$

(units of \$K/mile/year). This regulatory function is shown in Figure 2-8. Not all utilities may be affected by this cost (in which case a_{reg}=0) but the regulatory offset, x_r, is assumed to be constant for all affected utilities (a_{reg} may vary with utility). Because the transition point x_r will shift when lane addition occurs, this cost will be treated as a recurring expense.

It is noted that the regulatory burden could be managed in other ways, for example a “clear zone” could be imposed, where no installation whatsoever would be permitted. This approach produces no consequences to the cost function, but instead reduces the set of feasible solutions selected for evaluation.

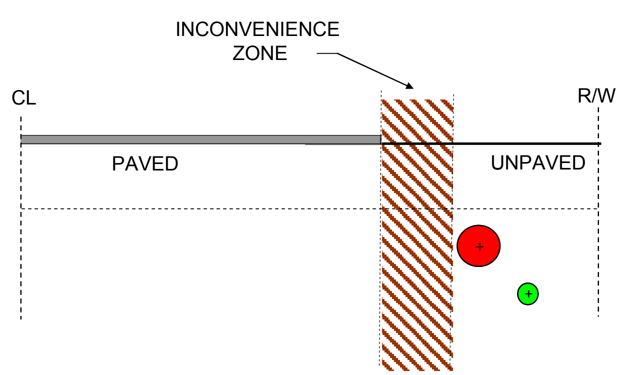


Figure 2-8: Illustrating a regulatory charge

3. *Access costs*

Eventually, access to the subsurface utility installation will be required, perhaps for new connections or maintenance. Access costs are expected to increase with vertical location since it is more costly to excavate for deep installation due to shoring and dewatering, and horizontal location because it is more costly to access facilities installed under pavement. Further complicating this cost component are facilities installed initially in a region free from pavement, but with some probability that paving may cover the facility after possible lane addition, thus increasing access costs later. The same functional dependence used to model the initial installation will be adopted for the present model, but in this case the length of the excavation will determine the actual cost. Thus the access cost can be described in terms of an equivalent trench length L_{eq} for installation (assumed to be a constant for all utilities, and having units of feet/event). The cost of each access event must be multiplied by the rate of access f_{acc}, the number of events/year/distance along corridor for the specific utility:

$$c_{acc}(x,y) = [a_{inst}y + b_{inst} + A_{dam}c_{dam}(y)]L_{eq}f_{acc} \tag{2-9}$$

(units of $K/mile/year)

4. *Traffic accident costs associated with above ground facilities*

The possibility of vehicular accidents with above ground facilities is a strong function of the horizontal placement of the utility and makes up an important component of the individual cost function, if such facilities are present. The evaluation of accident costs is detailed in [22]. For practical purposes, the recurring costs for accidents are handled in much the same way as those for recurring access. In this report, the definition of vehicular accidents with above ground facilities is synonymous with the more commonly used term “crashes”.

The cost of traffic accidents with above ground facilities is an important component of the cost function, primarily dependent on horizontal position. The number of damaging collisions with a fixed object depends not only on the rate of vehicles leaving the road (encroachment) but also on the roadway design speed, the configuration of the object and the offset of the object from the roadway. Generally, the probability and severity of collisions with hydrants, electrical distribution boxes and other similar objects are reduced as the offset of the above ground object from the traveled pavement is increased. A procedure to estimate the economic values for traffic accidents with stationary objects at the side of the roadway has been developed elsewhere [22]. The original intent for this procedure was to analyze cost-benefit ratios associated with the removal or relocation of such objects. In this study, the approach utilized in [22] has been modified and adapted to develop the relationship between the costs attributed to traffic accidents with above ground facilities and the horizontal offset from the traveled roadway, over the service life of the corridor. The discussion of the construction of the accident function below relies on Figure 2-9 and parallels the development in Reference 22, although some additional material has been introduced for clarity. To avoid a cumbersome procedure, only rectangular and circular objects are considered and it is assumed that corrections for features alongside the road such as embankment and curvature will be made as required. Here, two way traffic is assumed and but extension to one way roads is straightforward.

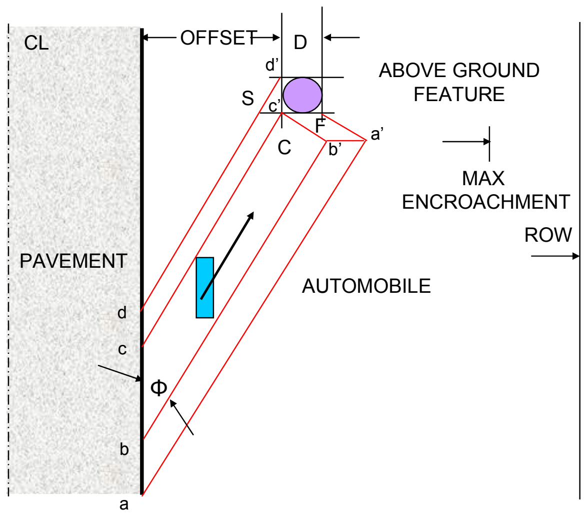


Figure 2-9: Diagram and notation used to model traffic accidents with above ground facilities (after Reference 22)

Consider the traffic traveling in one direction along the roadway in adjacent lanes, those closest to an above ground object. A certain fraction of these vehicles will leave the pavement and travel for some distance beyond the pavement edge. The approach of Reference 22 is to calculate the probability that a vehicle leaving the roadway within an interval along the pavement travels sufficiently far to collide with some portion of the object. For an appropriate mix of vehicular traffic, a single encroachment angle, φ_e , can be defined and characterized as a function of the roadway design speed. P(x), the probability of an encroaching vehicle traveling a perpendicular distance x from the pavement (encroachment distance) for a set of typical design speeds has been tabulated [22]. The nominal offset, x_{os} for an above ground hazard is the perpendicular distance from the outer edge of the adjacent lane to the nearest point on the object.

An above ground object can be partitioned into several zones, each with different likelihood for impact. For a rectangular object, collisions with the face perpendicular (Zone 1) and the face parallel (Zone 3) to the roadway are possible, as is a collision with the corner of an object facing traffic (Zone 2). Round objects are treated in a slightly different manner and may be represented in terms of a reduced diameter. To account for the possibility of skid with rotation, the vehicle path width is taken to be a swath (3.6 meters [22]). Referring to Figure 2-9, the beginning of Zone 1 is defined by the initial encroachment (line aa’) that could result in the left front corner of the vehicle impacting the right corner of the perpendicular face of the object. Zone 1 ends at the same line bb’ where Zone 2 begins, the first impact of the left front corner of the vehicle with the corner of the object. All impacts will be with this corner until the right side of the vehicle is beyond cc'. The last impact with the parallel face occurs when the vehicle is beyond the line dd'. These latter two lines define Zone 3. The offset of point B' is given by x_{os}+SW $\cos\varphi_e$ and the offset of a' equals the offset of b' + S, the dimension of the perpendicular face. Points c' and d' are located at the nominal offset, x_{os}.

The encroachment factor, EF, represents the dimensionless ratio between the distance along the pavement and the distance along the line perpendicular to the pavement defining the impact zone of interest. Thus, the number of impacts with a particular zone occurring as a result of vehicles leaving the pavement within the boundaries of the path leading to the zone is defined as the impact factor, IF and given by the product of the encroachment factor and the integrated probability that a vehicle will travel to the offset distance of the zone. This distance corresponds to the distance along the pavement equivalent to a particular component of the object times the ratio of impacts per encroachment.

For Zone 1, EF_1 is the distance along the traveled way corresponding to a unit length along the perpendicular face of the object, equal to $1/\tan\varphi_e$. To obtain the number of impacts with this face resulting from encroachments from the corresponding interval along the pavement, ab, requires an integration of the probability of impact over the offset of the face (from $x_{A'}$ to $x_{B'}$) then multiplication by the encroachment factor to give

$$IF_1 = \frac{1}{\tan\varphi_e}\left(\int_0^{x_{a'}} P(x)dx - \int_0^{x_{b'}} P(x)dx\right) \tag{2-10}$$

To obtain the encroachment factor for Zone 2, an integrated probability is again required, between the offsets for c' and d' to account for the variable offset across the swath path. Calculation of the encroachment factor for this zone requires the length along the normal distance across the swath that project to give a unit length along the perpendicular $(1/\cos\varphi_e)$. Then this dimension corresponds to a length along the traveled way, so that $EF_2 = (1/\sin\varphi_e)/\cos\varphi_e$. Thus the impact factor for Zone 2 is

$$IF_2 = \frac{1}{\sin\varphi_e\cos\varphi_e}\left(\int_0^{x_{c'}} P(x)dx - \int_0^{x_{b'}} P(x)dx\right) \tag{2-11}$$

For Zone 3, the encroachment factor EF_3= 1, unit length along the traveled way/unit length along the face (since the parallel face has a constant offset) so that the number of impacts with this face along the pavement is

$$IF_3 = P(x_{os})F \qquad (2\text{-}12)$$

A severity index may be utilized to describe the nature of possible accidents, by the type of object involved, and the design speed of the roadway (modeled for an appropriate mix of accident types). To estimate a cost per impact, a relationship between accident costs and severity index has been established. Consistent with the partitioning of the object into separate accident zones, different severity indices are employed for each impact factor defined above. Reference 22 provides tables of the cost $c_{coll}(SI)$. The product of ER, IF and the cost of a single accident is the total cost of accidents expected annually per traffic volume due to a single object at nominal offset x_{os}. The cost of an impact with a specific object at x_{os} is then given in units of cost/annual traffic volume

$$c_{imp}(x_{os}) = ER\sum_{i=1}^{3} IF_i\, c_{coll}(SI_i) \qquad (2\text{-}13)$$

where the summation is over all impact zones considered. For traffic on one side of roadway, going in one direction, the annual encroachment rate (annual encroachments per unit distance along pavement per vehicular volume) is taken as constant, ER=9.144E-08 enc/ft/y/vehicles/day

The information produced by this analysis can be used to generate a representation of accident costs as a function of offset (Figure 2-10). Offset has been defined previously as the distance from the outer edge of the adjacent lane to the nearest part of the above ground object. If a utility is located at horizontal position x_i, then $x_{os}=x_i-x_{lw}$. The distance to the pavement edge x_{lw} will change with any renovation including pavement widening.

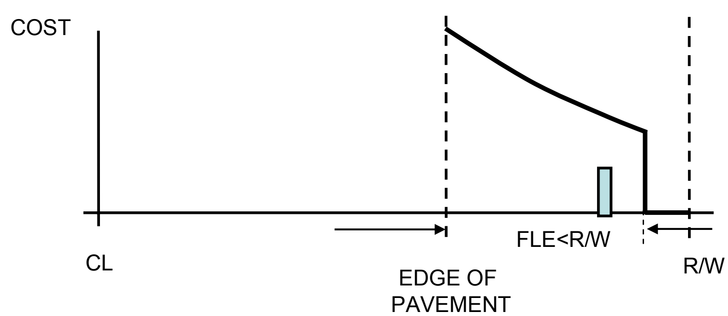


Figure 2-10: Generation of an accident cost function from the model of Reference 22.

5. *Supplemental costs:*

It is possible that other location dependent costs may be justified for inclusion either as recurring or non-recurring charges. For simplicity, these functions will be modeled by the step functions in the x and y directions

$$c_{snr} = a_{snr}(y) + b_{snr}(x) \quad (2\text{-}14)$$

(break points x_{snr} and y_{snr}, units of $K/mile)

$$c_{sr} = a_{sr}(y) + b_{sr}(x) \quad (2\text{-}15)$$

(break points x_{sr} and y_{sr}, units of $K/mile/year)

Here the subscript snr refers to “supplemental nonrecurring”, sr refers to “supplemental recurring”. For simplicity, it is assumed that no more than one supplemental charge occurs, but it would be easy to extend this concept as needed.

Other uses for this component could be to increase the flexibility in modeling any of the component costs discussed above. For example, it is possible that a cost for removal of the relocated facility would be required for completeness but this charge cannot be easily accounted for elsewhere. Other possibilities include adding material costs to account for vertical connections to above ground facilities or to account for removal of facilities placed out of service.

6. *Further discussion of damage and disruption accidents during excavation*

As seen above in items 1 and 3, a term has been added to account for damage for both installation and access. The following is a discussion of the development of this function. During routine excavations (new installations or access events) in the corridor, there is some probability of accidental damage to facilities already located in the corridor. At present there appears to be no established functional relationship for this parameter (and virtually no data upon which to base costs), however it seems reasonable to assume that the number of such incidents should be proportional to the expected number of access events, and also that excavating to conduits buried deep within a corridor will be more likely to result in damage to other facilities. Here, a linear dependence with depth was assumed to model the costs associated with damage for each access event. Thus, as shown in Figure 2-11, access to a particular conduit buried deep in the corridor, would have a higher maximum cost if one or more of the other conduits within the corridor would be expensive to damage. The maximum cost per incident would be lowest if the accessed conduit was not buried deeply and the other conduits did not represent potentially costly damage. Obviously this is an extremely simplistic model and could be improved if further research indicated that this component of the cost function was significant. The cost per damage incident is thus primarily a function of depth, but depends also on which utilities are already in place. Only a fraction of excavation events result in a damage incident, f_{dam} (incidents/event miles, taken here as 1% arbitrarily). Let c_{max} represent the maximum cost per incident (composite of types of incidents and severity levels), so that

$$c_{dam}(y) = c_{max} f_{dam} g_{dam}(y) \qquad (2\text{-}16)$$

A linear dependence with depth (coefficient a_{dam}) was assumed here for lack of a better model. Thus the damage coefficient is potentially different for each utility and has units of $K/mile

$$c_{dam}(y) = c_{max} f_{dam} a_{dam} y \qquad (2\text{-}17)$$

The function is to be constructed so that $c_{dam}(y_{max})=c_{max}f_{dam}$ and $c_{dam}(0)=0$ (for simplicity). The value of a_{dam} is then $1/y_{max}$ with units of 1/ft.

If it is assumed that utilities initially placed in the corridor are installed in a sequence that does not generate extra costs (i.e. lower utilities first to avoid later interference), this term may not be required for initial installations but would certainly be needed for later installations or relocations (assumed to have the same installation costs as initial installation). The adjustment coefficient A_{dam} has been included in the installation model to allow for this contingency and can have the value of zero or unity. At present it is assumed that $A_{dam}=0$ for all installations at corridor inception, and $A_{dam}=1$ otherwise.

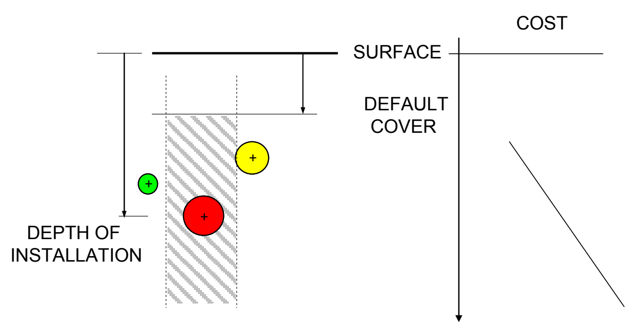


Figure 2-11: Representation of a simple model to describe damage to adjacent facilities during excavation.

The damage model assumed for this investigation is simple and arbitrary. A much more realistic model could be generated by allowing for empirical information parameters (such as the proportionality between access and damage), improving the functional dependence with depth (perhaps a probability argument based on the positioning error), and the use of a mix of the severity of accidental damage. Furthermore a sensitivity analysis might be employed to determine the range of empirical parameters which might actually generate significant costs (i.e. it may not matter).

Inspection of policies regarding "one call" services indicates that some agencies require reporting of all accidents and the circumstances of the event. Insurance records may possibly provide some information. Thus it may be possible to develop and calibrate a model for this cost function. This task would be extensive and has not been undertaken as part of the current effort. Similar considerations may well apply to other issues, such as maintenance of traffic.

Supplemental measures for evaluating configurations

For consistency, the following subscript notation is used in the following text:

i configuration index
j utility index
k component cost index
l year index in service life schedule

Although total societal cost is the principal target for optimization, it is important to understand that there is more information regarding the characteristics of the solution set and specifically any particular configuration within this set. Even if a compression technique is applied to reduce the number of distinctly different solutions identified as optimal, it may still be difficult to pick one superior solution from the array of possibilities, on the basis of total cost alone. This section is concerned with methods to further characterize and evaluate solutions to assist in making final choices.

The societal cost C_j for one facility located at $x_{i,j}$, $y_{i,j}$ within a particular configuration (designated by the subscript i) is defined as the sum of m component costs c_k:

‡” (2-18)

where w_k represents a possible weighting factor for the kth cost component (taken as unity throughout this report). Again, the total societal cost for any configuration i is defined

$$TC_i = \sum_{j=1}^{n} W_j P_j C_j(x_{i,j}, y_{i,j}) \quad (2\text{-}19)$$

where P_j is the probability of installation of the jth utility and a set of weighting factors, W_j, has been included (the sum of W_j should equal n).

For each utility, the absolute minimum of the individual cost function, MC_j, and the sum of the minimal costs for the set of n utilities considered should be computed.

$$MTC = \sum_{j=1}^{n} W_j P_j MC_j \quad (2\text{-}20)$$

It should be recognized that this reference quantity is defined without regard to occupancy. In other words, several utilities could conceivably occupy the same location, in which case MTC would be unattainable, but still represents an important ideal value for reference purposes.

The following parameters are defined to help assess the quality of solutions. These quantities are expressed as non-dimensional ratios, so that meaningful comparisons can be made between the results for different problem statements without regard to absolute values. It is noted that issues of constructability or functionality have not been discussed here.

1. *Efficiency* - For any configuration i, a ratio comparing the actual cost to the minimum total cost can be computed

$$Q_{\text{efficent},i} = \frac{MTC}{TC_i} \tag{2-21}$$

Thus, an entirely efficient corridor configuration results in each utility being placed at a point of absolute minimal cost and the parameter approaches unity in this ideal case (optimal is the same as absolute minimum cost). In most cases of interest, it will not be possible to place each facility at its respective minimum cost point, so that the definition of optimal becomes the best that can actually be attained. Thus, this particular parameter could be used and reported as an equivalent target for optimization, so that the goal is converted to finding the maximum value of Q_{eff} corresponding to TC_{opt}. The efficiency for all members of the solution set will be the same (note that there is a somewhat larger set of "nearly optimal" solutions). It is recognized that for many corridor specifications it may not be possible to configure the corridor so that the minimum cost is obtained, and an efficiency limit results. This fact leads directly to a second, related parameter, described below.

2. *Crowding*- If the best possible efficiency that can be obtained is less than one, the corridor is crowded, since conflicts force some utilities into uneconomic locations. A measure of crowding can be obtained by computing the efficiency for optimal total cost. Again, this quantity is a parameter of the problem rather than the individual solutions. To make the index intuitive, the efficiency is subtracted from unity. Thus

$$Q_{\text{crowd}} = 1 - \frac{MTC}{TC_{opt}} \tag{2-22}$$

where a value of zero indicates no crowding and the worst crowding is indicated if the parameter approaches unity. Since this definition ignores the possibility that no feasible solutions were located, in this situation, TC_{opt} will be interpreted to be infinite cost. A small number of optimal configurations may also mean that the corridor is crowded since there are few alternatives. On the other hand, if there are a large number of solutions and the optimal cost is close to the minimum total cost, the corridor is not congested (see also the flexibility parameter).   A similar definition could be used if it was desired to define a crowding parameter for arbitrary configurations.

3. *Effectiveness* for the set of all feasible solutions, compute the "spread of the solution costs", one minus the ratio of the difference between the average and the optimum compared to the optimal costs (another parameter of the problem rather than individual configurations)

$$Q_{effec} = 1 - \frac{TC_{opt}}{TC_{ave}} \tag{2-23}$$

As the optimal cost approaches the average cost, the effectiveness approaches zero. This parameter represents the variation in the number of solutions, since a narrow spread would indicate little opportunity for improvement. In another sense, this parameter is a measure of the savings possible as a result of the modeling effort (if no solutions were found this parameter would be meaningless).

It may also be of interest to define the effectiveness for any particular configuration, to indicate how far away from optimal that solution lies:

$$Q_{effec,i} = 1 - \frac{TC_{opt}}{TC_i} \tag{2-24}$$

Note that for any particular configuration this quantity could be negative.

4. *Balance*   - A measure of equitable division of costs may be obtained by comparing the individual costs divided by individual minimum costs. Ideally, summing over all utilities yields an index equal to the number of utilities in the corridor. A balanced solution is one where no utility has an unfair advantage or disadvantage. At least in principle, configurations exhibiting the most balanced distribution of costs could be located by finding sets with the smallest outliers or by using multivariate optimization techniques.   Thus for a configuration i, first define the individual cost ratio, the ratio of the absolute minimum sum for component costs for the jth facility to the sum of component costs if the jth facility were positioned at $x_{i,j}$, $y_{i,j}$.

$$ICR = \frac{MC_j}{C_j(x_{i,j} y_{i,j})} \tag{2-25}$$

Then define a mean value for the ICR for a completed corridor configuration

$$\overline{\frac{MC}{C}} = \frac{1}{\sum_j P_j} \sum P_j \frac{MC_j}{C_j(x_{i,j} y_{i,j})} \tag{2-26}$$

where the sum of probabilities has been introduced so that the mean has a value of unity if all facilities are placed at a point of individual minimal value. Then the *balance parameter* (mean of absolute deviation from individual minimums) can be defined

$$Q_{balance} = 1 - \frac{1}{\sum_j P_j} \sum_j^n P_j \left| \overline{\frac{MC}{C}} - \frac{MC_j}{C_j} \right| \tag{2-27}$$

According to this definition, a configuration will be ideally balanced when all individual cost ratios are identical to the mean value and the parameter has a value of unity. Note that this parameter can be less than zero for some situations. Furthermore, with regard to this parameter, it should be observed that when determining individual costs, some components would not be justified if not born by the specific utility. Application of this parameter should be cautious.

5. *Flexibility-* A flexible configuration is one which can accommodate an additional utility economically. An index of flexibility as defined here is a comparison between the cost for optimal addition and the minimum cost for the utility, again on a relative basis (see issue below). A configuration that permits the inclusion of a new utility at a cost not much different than the minimal cost for installation in the corridor is flexible. A specific utility will have to be designated as representative and a numerical experiment conducted. This test utility might or might not incorporate an above ground facility, and the clearance rules to be enforced will require specification. One candidate may be the prospective addition of a utility at a later date, which could form a logical test of flexibility.

Thus, a representative utility (with or without an above ground facility, as appropriate) is added to an optimal configuration (subscript i) on a trial basis. The cost, C_{add}, of an optimal placement of this additional utility is compared to the minimum cost for placement of this utility, as a ratio.

$$Q_{flex,i} = \frac{MC_{add}}{C_{add,i}(x_{add,i}, y_{add,i})} \tag{2-28}$$

Again, a value of unity represents ideal and zero is poor (no solution possible). This parameter should be examined in relationship to crowding, as well as other indications of the occupancy of the corridor.

SECTION 3: COMPUTATIONAL STRATEGY AND PROGRAM DEVELOPMENT

For typical situations of interest in this investigation, the computational task of collecting data, finding optimal solutions and analyzing results may rapidly become overwhelming due to the large number of possible configurations. To assist in completing the computational effort associated with the model, several computer programs were constructed to complete the search for feasible configurations and to then carry out the evaluation of the total cost and find optimums. The overall philosophy of these programs developed to execute the model computations is that they should be a combination of user interface and recording worksheet, so that a record of the problem is available at the conclusion of the problem. In these programs, computations and analyses are operations carried out in the background. Most individual modules discussed and utilized in this report could be easily replaced with alternatives if desired, as future needs may dictate.

The software developed here is intended to be used as an assessment and pricing tool. In other words, the user must pose a specific problem (or set of problems) prior to application of the program. The software package is capable of responding with cost information for specific configurations and providing a rank ordering of possible solutions. The user is responsible for understanding (or perhaps modifying) the assumptions employed when seeking results. For example, while the program will assign default values for most variables, some of the background information (such as cost of installation and access, etc) is extremely difficult to obtain. Complex problems beyond the scope of the current model may sometimes be attacked by breaking into several parts.

The actual programs (along with a user guide and tutorial manual) have been delivered to the FDOT under separate cover. A short appendix (Appendix A) describing the overall operation of the programs is attached. The following discussion is intended to clarify the methods and limitations of the programs as constructed. In the material that follows, reference will be made only to the "program" (singular).

Program embodiment of the heuristic model

To summarize, the model for corridor simulation developed during this investigation comprises the following components:

1. A method that identifies all feasible facility locations given the physical specification of the corridor, the description of utilities to be included in the corridor and a set of rules governing organization.

2. The development of position sensitive costs for each utility, including both present and future expenditures. A technique to assemble this

information and predict costs when applied to the configuration information from Item 1 above is also required.

3. A method to interpret the results obtained from application of Items 1 and 2 above. This step will include the identification and analysis of optimal configurations.

4. Ancillary procedures and methods to further define and characterize subsets of feasible solutions and reevaluate costs associated with these subsets (for comparative purposes). It is recognized that it may also be desirable to impose further constraints.

The purpose of this section is to discuss how this model was implemented as software. As currently constituted, the program can perform several types of operations, including simulating new installations (whole corridor planning or one added utility), the simulation of pavement widening (renovation) and relocation, as well as simply pricing specific configurations.

A list of assumptions and limitations incorporated into the program follows:

1. Service life – the arbitrary length of the service life must be selected by the user and should represent a reasonable study period (for example, twenty years). During this time the program allows for the installation of one or more utilities after original construction and one renovation event consisting of the addition of one or more lanes of traffic. Addition of utilities can take place only before renovation.

2. At present the program does not account for finite medians or sidewalks.

3. The current embodiment of the program developed in this study utilizes a direct search and evaluation method, in order to examine the entire set of feasible solutions for optimal configurations. This method is explained more completely below. It should be noted that several other search and optimization techniques could be utilized to complete these steps. As will be reported in Section 5, part of the research effort lead to the development of faster search methods.

4. At present, trench installation is assumed, due to the strong variation in cost with depth of installation. Alternative methods of installation (jack and bore, etc) can be modeled only in the same way as direct installation. As will be discussed later some effort was made to explore alternate installation methods in a prototype program.

5. Interference between utilities, joint trenching, economic savings by stacked arrangements, and the use of deactivated facilities left in place can be accounted for only in a simple fashion.

6. It is possible to add filters to the program to eliminate some classes of solutions, as desired. At present the only filter that is available examines whether or not a stacking rule is obeyed if imposed.

The process of identifying feasible configurations (by a search technique) is a straightforward extension of the method for adding one utility to an existing corridor, as described above. Starting with an empty corridor, one utility is located at the initial position, the upper right corner. The second utility in the group is then positioned at the next possible location, found by taking a small step to the right and checking constraint conditions. Once the second utility is located, the third is positioned by the same method. Stepping proceeds along a horizontal path and shifts downward to repeat when the left side of the corridor is reached. After the final utility has reached the end of the search, the first utility is moved to the next position and the process repeats.

The fact that less costly solutions tend to place the utilities close to the surface and at the right of way boundary means that an effective search strategy is to start in this quadrant and search along the horizontal direction, following the ground profile, then move to lower depths and repeat the process. For very large corridors, it may be possible to develop most realistic solutions without a complete examination. This idea has been explored and has been partially implemented in the current version of the program (cf Section 5).

Until now the issue of the step size for changes in configuration has been left unresolved. A number of computational experiments were conducted to examine the issue of step size selection. It was found that, in general, the optimal cost decreased with smaller step size and the computational time increased, as would be expected. Obviously, if the step size is too large, it will be possible to miss acceptable and interesting solutions. If the step size is too small, a very long time will be devoted to the search process. It is also possible that certain choices of step size may not work well with the corridor configuration. To avoid challenges to the user, the step size has not been left as a choice but rather implemented as part of the program logic. Although at present an acceptable compromise has been reached, the selection of step size remains an open area of discussion in this research.

In addition to the optimal search routine already implemented, to further explore the quality of any solution a secondary sub-program was developed with the following operational characteristics. For any viable solution near the minimum, each utility was subjected to a small shift in position to explore for slightly cheaper solutions. This process of small changes was continued in the direction leading to solution improvement, or until a predetermined number of steps had been tested. When better answers were found by this process, these solutions were reported. It was found that in many (but not all) cases of interest that improved (less costly) results could be obtained. Thus, the following search strategy is suggested. Beginning with a relatively coarse step, a sweep over a range of step sizes can be made. In turn, the best answer for each step size is then subjected to small positional variations as a means of locating better answers yet. While there are no guarantees, it appears that in most cases a very good solution set can be identified in this manner.

Compression of the optimal solution set

The search and evaluation process as applied in the previous section results in a large number of minimal cost solutions and inspection shows many of these are only small variations of other solutions (i.e., only a small step away). It is highly desirable to identify solutions that closely resemble one another and lump these together into a small number of solution categories. In this section, the possibility of reducing this set by eliminating solutions which are near equivalents to other solutions is considered. For simplicity, a procedure was included in the software that finds solutions in which all facilities are located within a small distance of each other (arbitrary). If each of the individual utilities is within this radius, then the program considers those configurations to be identical.

Furthermore, in view of the uncertainty for cost function information, as a part of the optimization process, it may be desirable to choose a range for total cost slightly larger than the absolute minimum, so that potentially good solutions are not lost. Suppose for example, an arbitrary error estimate of 2% has been chosen, so that any solution within 1.02 times the minimum total cost could be included. For the entire set of all feasible solutions, the minimum, the maximum and the average of total cost should be accumulated.

The following extended discussion has been included for completeness. At present it is not obvious that the methods outlined below will form the basis for useful software development, but are retained for possible future extension. A principal problem with describing and comparing solutions is that the total cost corresponding to any particular configuration within the corridor, is related to a particular solution only by the individual cost functions. Thus it is difficult to connect feasible solutions with any specific cost result so that changes with variation in parameters are evident. This limitation is particularly evident when attempting a sensitivity analysis. What are required are definitions of the relationships between solutions. There several types of metrics that can be defined and use to describe configuration and cost relationships.

One possibility is to use the simple Cartesian distance between two solutions. The problem with this measure is that two comparative solutions may be approximately the same distance from the original solution of interest but quite different from each other. What is needed is a description of the projection, component by component, of a comparative vector along the direction of the original solution. The following simple measures are proposed to add this understanding to the results obtained by the modeling process. Any solution satisfying the initial constraints may be described by the total cost, the 2n vector set of coordinates of the n individual utilities and the n vector set of individual cost function. Suppose that following analysis of an entire ensemble of feasible solutions, it is desired to compare two solutions.

One measure is the relationship between the locations of the various utilities for two different solutions. For any particular configuration, consider the values of the horizontal coordinates and the values of the vertical coordinates as two vectors of length equal to the number of utilities in the corridor (this definition may be modified to include only unfixed utilities). These two vectors define the spatial configuration. Consider the set of individual utility costs as a vector of the same length. Suppose a solution (for example a minimum solution) has been identified and it is desired to compare the configuration of another solution to that of the first.

In order to assess the similarity of a particular configuration to some other solution, the correlation between the two vectors can be computed. This is functionally equivalent to constructing the inner product. Thus, denoting the two vectors with subscript a and b, the normalized vectors, form correlations

$$R_x = \sum_i \frac{x_{ai} x_{bi}}{|x_a||x_b|} \tag{3-1}$$

$$R_y = \sum_i \frac{y_{ai} y_{bi}}{|y_a||y_b|} \tag{3-2}$$

where

$$|x| = \sqrt{\sum_{j=1}^{N} x_j^2} \tag{3-3}$$

$$|y| = \sqrt{\sum_{j=1}^{N} y_j^2} \tag{3-4}$$

The following tests can be made. First the magnitudes of a and b have to be nearly equivalent if the configurations are similar. The correlation numbers R will be nearly unity if the locations of all the utilities in configuration a correspond closely to the locations in configuration b (the correlations correspond to taking the inner product between the two vectors). Since the components have been normalized correlations could range from 0 (no relationship) to 1 (perfect correlation) since negative positions are not possible. The use of the correlation avoids a situation where two configurations could sum to the same value in the Cartesian sense but be different configurations.

A similar analysis may be performed for the cost components. Ignoring for the moment the question of individual weightings, the total cost of a particular configuration i, is

$$TC_i = \sum_{j=1}^{n} C_j(x_{i,j}, y_{i,j}) \qquad (3\text{-}5)$$

The total cost of each configuration within the set designated as optimal will be about the same value. The magnitude of the total cost vector is

$$|TC|_i = \sqrt{\sum_{j=1}^{n} C_j^2(x_{i,j}, y_{i,j})} \qquad (3\text{-}6)$$

Even though the total costs are the same, the magnitude of the vector may be different.

Consider any two configurations (a and b) belonging to the set of optimal solutions. By creating the inner product of individual cost vectors (normalized), it is possible to determine if the solutions are similar with respect to cost

$$R_C = \sum_{j} \frac{C_{aj} C_{bj}}{|C|_a |C|_b} \qquad (3\text{-}7)$$

If these two solutions have similar alignment of costs (i.e. $C_{a1} \approx C_{b1}$, etc) then R_C will be approximately one.

A method to compress the number of solutions may be described as follows. Initially the number of classes (of similar solutions) is not known. Pick the first configuration from the optimal list and compare all other solutions to this, utilizing the metric described below. If agreement is detected (within some error bound) then the solutions have the same vector magnitude so that the correlation for x and y location can be examined. Again, if agreement is detected then the cost correlation metric can be computed, but a strong correlation should occur since the utilities are in the same position. Configurations that correlate with the first solution chosen accumulate in the first class (for which the first solution may be used as the archetype). From the remaining solutions, take the first configuration and repeat, to establish a second class. Continue until all solutions have been classified. Other types of classification are possible, for example it might be desirable to select only by correlation of the cost functions.

These correlation coefficients may be utilized to characterize all the solutions with respect to how the coordinates of the individual utilities correlate as well as individual costs. For example, once analysis of a particular problem has been completed, it is often true that a group of solutions at or very near the minimum total cost. In principle any one of these is as good as the other but it is of interest to know how they differ. In comparing any two solutions within this group, if $R_y \approx 1$, it would be concluded that both configurations had each utility at about the same individual vertical position. With regard to cost, if two solutions do not have R_C near unity then it would be concluded that each solution favors some utilities over others, but not the same utilities. This conclusion would be extremely important in identifying so-called “balanced” solutions (discussed more completely below) where each utility invests a nearly proportional share to install in the corridor.

SECTION 4: CASE STUDIES

Formulation of model problems

The software developed here is intended to be used as an assessment and pricing tool. In other words, the user must pose a specific problem (or set of problems) prior to application of the software. A considerable amount of information concerning constraints and cost data are also required (although the program will supply default values in most cases). The software package is capable of responding with cost information for specific configurations and providing a rank ordering of possible solutions. The user is responsible for understanding (or perhaps modifying) the assumptions used when seeking results. For example, while the program will assign default values for most variables, some of the background information (cost of installation and access, etc) is extremely difficult to obtain.

In the next section, a discussion of typical examples based on these model problems is presented. This section presents four examples to demonstrate optimizing the corridor configuration in different situations. As a reminder, the following subscript notation has been utilized in this section

i configuration index
j utility index
k component cost index
l year index in service life schedule

A. Locating a new utility in a populated corridor

The question posed in this section concerns the introduction of a new (but originally unanticipated) utility into a corridor that already contains previously installed facilities. How can the new utility be located economically? This problem is relatively easy to solve assuming that the cost function for the utility is available. The solution is determined by finding all places that the new facility could be located (subject to constraints) and evaluating the price of each possibility. This problem should be thought of as a single event, occurring at some time, however for purposes of developing costs, the service life schedule continues and recurring costs must be accounted for. This problem will be used to introduce in detail how the component costs are obtained from the models discussed previously.

For simplicity in the present discussion, it is assumed that the coordinates of the existing utilities are known exactly. The added utility is positioned in the first available location, starting in the upper right hand corner of the corridor. Each constraint imposed is checked for violation, including clearance requirements with existing utilities. Acceptable locations are recorded and the process is repeated after changing the location by small increments. The cost of placing the added utility at each acceptable location is evaluated, using the cost function information applied. Once all acceptable locations have been found and evaluated, the least expensive of these can be selected.

The process of selecting and optimizing potential installation sites is dependent on the cost of the installed utility as a function of position. Designating the specific utility being installed in configuration i by the subscript j, the individual cost function consists of the following component costs (units of $K/mile)

1. *Installation plus damage:*

For utility j, located at $x_{i,j}, y_{i,j}$ the installation costs (including damage) are

$$c_{1j}(x_{i,j}, y_{i,j}) = [a_{inst,j} y_{i,j} + b_{inst,j}(x_{i,j}, x_{lw}) + A_j c_{max} f_{dam} a_{dam,j} y_{i,j}] \quad (4\text{-}1)$$

2. *Regulatory:*

For consistency in later examples, regulatory surcharges will be imposed on a recurring basis, over the service life of the facility. In this case, the service life begins at the time of addition. For utility j, added to an existing corridor

$$c_{2j}(x_{i,j}) = a_{reg,j}(x_r, x_{lw}, x_i)(Y_{sl,j} - Y_{inst,j}) \quad (4\text{-}2)$$

3. *Access plus damage:*

Since access is a recurring activity, multiplication by the number of years of service is required. For utility j

$$c_{3j}(x_{i,j}, y_{i,j}) = [a_{inst,j} y_i + b_{inst,j}(x_{i,j}, x_{lw}) + A_j f_{dam} c_{max} a_{dam,j} y_i] L_{eq} f_{acc,j}(Y_{sl,j} - Y_{inst,j}) \quad (4\text{-}3)$$

4. *Traffic accidents with above ground facilities:*

For each above ground facility associated with utility j, the cost of impact at offset is obtained by multiplying the cost of impact at offset by the sum of traffic volume for each year, available from the projections of the service life schedule. For an above ground facility located at x_i, the offset from the lanes adjacent to the object is $x_{os}=x_i-x_{lw}$, and for the opposing lanes (if traffic is two way) $x_{os}=x_i$. [22]. A lane factor, to account for one way (LF=1) or two way traffic (LF=2) has been incorporated in the calculation of collision costs. For traffic in the opposite direction offset is measured from the centerline and so is just x_i. For one way traffic this term does not apply.

Costs for the lanes adjacent to the object are combined with costs for the lanes with opposing flow (for one-way traffic, the factor LF-1 will remove the latter term)

$$c_{t,j}(x_{i,j}) = [c_{imp,j}(x_{i,j} - x_{lw}) \sum_{l=Y_{inst,j}}^{Y_{sl,j}} ADT_l / LF]$$

$$+ [c_{imp,j}(x_{i,j}) \sum_{l=Y_{inst,j}}^{Y_{sl,j}} ADT_l / LF](LF - 1) \qquad (4\text{-}4)$$

Finally, the component cost associated with accidents is obtained by multiplying this cost by the number of objects per unit length along the roadway, N_j

$$c_{4j}(x_{i,j}) = N_j P_{agf,j} c_{t,j}(x_{i,j}, x_{lw}) \qquad (4\text{-}5)$$

Here, the factor $P_{agf,j}$ has been inserted to eliminate the component cost if no above ground facility is present.

5. *Supplemental costs:*

For generality, the possibility of other costs, both recurring and nonrecurring will be included as follows:

$$c_{5,j}(x_{i,j}, y_{i,j}) = A_j c_{snr}(x_{i,j}, y_{i,j}) + B_j c_{sr}(x_{i,j}, y_{i,j})(Y_{sl,j} - Y_{inst,j}) \qquad (4\text{-}6)$$

Here A_j and B_j are adjustment coefficients which may have value zero.

Composite costs:

The cost function for the added utility, j, located at position $x_{i,j}$,$y_{i,j}$ consists of the five component costs as detailed above

$$C_{i,j}(x_{i,j}, y_{i,j}) = \sum_{k=1}^{5} c_{j,k}(x_{i,j}, y_{i,j}) \qquad (4\text{-}7)$$

Only this cost is considered when determining optimal placement. Other utilities in the corridor are not to be included in the cost structure because they are in place and it is assumed no alteration to recurring costs for these utilities occurs.

B. Planning the development of a new utility corridor

Suppose a corridor has been specified, with occupancy proposed to occur according to a schedule, mutually agreeable among all stakeholders. In contrast to the "first come- first served" evolutionary development, an opportunity exists to plan for a configuration that minimizes total societal costs. Furthermore, analysis of possible solutions before actual construction begins presents options to include other factors in the final selection of a plan, such as the potential for cost-effective development in the future, if needed. Two steps are required to implement this strategy. The first step consists of identifying feasible configurations (those consistent with constraints imposed). Subsequently, each feasible configuration is associated with a total cost.

The process of identifying feasible configurations is a straightforward extension of the method for adding one utility to an existing corridor, as described above. Starting with an empty corridor, one utility is located at the initial position, the upper right corner. The second utility in the group is then positioned at the next possible location, found by taking a small step to the right and checking constraint conditions. Once the second utility is located, the third is positioned by the same method. Stepping proceeds along a horizontal path and shifts downward to repeat when the left side of the corridor is reached. After the final utility has reached the end of the search, the first utility is moved to the next position and the process repeats. The question of how large this step size should be will be deferred until a later section.

Assumptions:

a) Ignoring the possibility of decommissioning or relocation of any utility

b) Excluding renovation events

The components of the individual cost functions for each utility are given in the same manner as that for the case of addition of a single utility, discussed above.

1. *Installation plus damage:*

$$c_{1j}(x_{i,j}, y_{i,j}) = [a_{inst,j} y_{i,j} + b_{inst,j}(x_{i,j}, x_{lw}) + A_j c_{max} f_{dam} a_{dam,j} y_{i,j}] \quad (4\text{-}8)$$

2. *Regulatory:*

$$c_{2j}(x_i) = a_{reg,j}(x_r, x_{lw}, x_i)(Y_{sl,j} - Y_{inst,j}) \quad (4\text{-}9)$$

3. *Access plus damage:*

$$c_{3j}(x_{i,j}, y_{i,j}) = [a_{inst,j} y_{i,j} + b_{inst,j}(x_{i,j}, x_{lw}) + A_j f_{dam} c_{max} a_{dam,j} y_{i,j}] L_{eq} f_{acc,j}(Y_{sl,j} - Y_{inst,j}) \quad (4\text{-}10)$$

4. *Traffic accidents with above ground facilities (if applicable):*

$$c_{4j}(x_{i,j}) = N_j P_{agf,j} c_{t,j}(x_{i,j}, x_{lw}) \quad (4\text{-}11)$$

5. *Other costs:*

$$c_{5,j}(x_{i,j}, y_{i,j}) = A_j c_{snr}(x_{i,j}, y_{i,j}) + B_j c_{sr}(x_{i,j}, y_{i,j})(Y_{sl,j} - Y_{inst,j}) \quad (4\text{-}12)$$

Composite cost:

The individual cost function for a specific utility j is again given by

$$C_{i,j} = \sum_{k=1}^{5} c_{j,k}(x_{i,j}, y_{i,j}) \quad (4\text{-}13)$$

According the service life schedule, each utility could be installed at a different time and with different probability, P_j. Ignoring for the moment the question of individual weightings for the utilities, the total cost of a particular configuration i, incorporating n utilities is given by

$$TC_i = \sum_{j=1}^{n} P_j C_{i,j}(x_{i,j}, y_{i,j}) \quad (4\text{-}14)$$

C. Relocation

A significant problem in the analysis of corridor organization occurs when accounting for relocation of facilities during some modification to the corridor during the service life. To correctly account for total cost, the relocated position is required. As a consequence of relocation, the service life schedule for the corridor is altered beginning at this time.

The next section following comprises a general discussion of the issue of relocation associated with pavement widening. As a simple illustration however, suppose the problem of the addition of a new utility to an existing corridor considered earlier is reexamined, but expanded now to include a stipulation that one of the existing utilities can be relocated to accommodate the added facility. While the simple approach is to place the new utility where the relocated facility was originally, a complete analysis considers the entire spectrum of feasible solutions, especially when the clearance constraints are important.

The problem now is the same as asking how to add two new utilities to an existing corridor (not containing the utility eligible for relocation). The new utility, introduced to replace the utility being relocated, will be referred to as a surrogate (although the introduction of this concept may seem unduly complex, the real benefit will be apparent in the next section).

Assumptions:

a) Pavement width does not change over service life

b) The candidate utility for relocation will be identified by stakeholders.

c) During relocation of the candidate utility, the original facilities are completely removed so that the whole space (including clearance) originally occupied by the relocated utility is then available for new occupancy.

d) For each utility, $Y_{inst,j} = Y_{rel}$ corresponds to the date for candidate relocation.

The construction of total societal cost now includes three utilities (the added utility, the surrogate utility introduced to account for relocation and the candidate relocated utility) and proceeds in the same manner as before. Only charges accumulated as a result of the relocation and the period following are included.

For the deactivated utility (j=1) the non-recurring component of the supplemental costs (snr) could be used to model the removal costs, if required

$$c_{5,j}(x_{i,j}, y_{i,j}) = A_j c_{snr}(x_{i,j}, y_{i,j}) \quad (4\text{-}15)$$

Alternatively, the cost of de-installation will be taken as equal to the cost of installation at $x_{i,j}, y_{i,j}$.

$$c_{1j}(x_{i,j}, y_{i,j}) = [a_{inst,j} y_{i,j} + b_{inst,j}(x_{i,j}, x_{lw}) + A_j c_{max} f_{dam} a_{dam,j} y_{i,j}] \quad (4\text{-}16)$$

For the surrogate utility (j=2, representing the relocation of a previously installed utility)

1. *Installation plus damage:*

$$c_{1j}(x_{i,j}, y_{i,j}) = [a_{inst,j} y_{i,j} + b_{inst,j}(x_{i,j}, x_{lw}) + A_j c_{max} f_{dam} a_{dam,j} y_{i,j}] \quad (4\text{-}17)$$

2. *Regulatory:*

$$c_{2j}(x_{i,j}) = a_{reg,j}(x_r, x_{lw}, x_{i,j})(Y_{sl,j} - Y_{rel}) \quad (4\text{-}18)$$

3. *Access plus damage:*

$$c_{3j}(x_{i,j}, y_{i,j}) = [a_{inst,j} y_{i,j} + b_{inst,j}(x_{i,j}, x_{lw}) + A_j f_{dam} c_{max} a_{dam,j} y_{i,j}] L_{eq} f_{acc,j}(Y_{sl,j} - Y_{rel}) \quad (4\text{-}19)$$

4. *Traffic accidents with above ground facilities (if applicable):*

$$c_{4j}(x_{i,j}) = N_j P_{agf,js} c_{t,j}(x_{i,j}, x_{lw}) \quad (4\text{-}20)$$

5. *Other costs:*

$$c_{5,j}(x_{i,j}, y_{i,j}) = A_j c_{snr}(x_{i,j}, y_{i,j}) + B_j c_{sr}(x_{i,j}, y_{i,j})(Y_{sl,j} - Y_{rel}) \quad (4\text{-}21)$$

Composite cost:

The individual cost function for the relocated surrogate utility j is given by

$$C_{i,j} = \sum_{k=1}^{5} c_{j,k}(x_{i,j}, y_{i,j}) \tag{4-22}$$

Although each of the three utilities has been separated in the present accounting, when analyzing the individual costs, removal costs for the relocated utility should be combined with surrogate costs.

For the added utility (j=3),

1. *Installation plus damage:*

$$c_{1j}(x_{i,j}, y_{i,j}) = [a_{inst,j} y_{i,j} + b_{inst,j}(x_{i,j}, x_{lw}) + A_j c_{max} f_{dam} a_{dam,j} y_{i,j}] \tag{4-23}$$

2. *Regulatory:*

$$c_{2j}(x_{i,j}) = a_{reg,j}(x_r, x_{lw}, x_{i,j})(Y_{sl,j} - Y_{rel}) \tag{4-24}$$

3. *Access plus damage:*

$$c_{3j}(x_{i,j}, y_{i,j}) = [a_{inst,j} y_{i,j} + b_{inst,j}(x_{i,j}, x_{lw}) + A_j f_{dam} c_{max} a_{dam,j} y_{i,j}] L_{eq} f_{acc,j}(Y_{sl,j} - Y_{rel}) \tag{4-25}$$

4. *Traffic accidents with above ground facilities (if applicable):*

$$c_{4j}(x_{i,j}) = N_j P_{agf,j} c_{t,j}(x_{i,j}, x_{lw}) \tag{4-26}$$

5. *Other costs:*

$$c_{5,j}(x_{i,j}, y_{i,j}) = A_j c_{snr}(x_{i,j}, y_{i,j}) + B_j c_{sr}(x_{i,j}, y_{i,j})(Y_{sl,j} - Y_{rel}) \tag{4-27}$$

Composite cost:

The individual cost function for a specific utility j is again given by

$$C_{i,j} = \sum_{k=1}^{5} c_{j,k}(x_{i,j}, y_{i,j}) \tag{4-28}$$

Total cost is sum over three utilities to include relocated, surrogate and added

$$TC_i = \sum_{j=1}^{3} C_{i,j}(x_{i,j}, y_{i,j}) \qquad (4\text{-}29)$$

Because in the process of locating two new utilities it is possible that the facilities eligible for relocation could be placed in the position originally occupied, the question of the worth of considering relocation is automatically answered. In this situation however, the total cost should be taken as the solution developed previously, since only the added utility would be considered and no cost would be imputed for relocation. This case is exceptional and it would be prudent to flag for further consideration.

The cost should be the sum of the cost of installation and continuing costs for the added utility

> plus the cost of installation for the relocated facility <u>except</u> if installed at the same location as originally located
>
> plus the <u>difference</u> in cost for continuing operations for the relocated utility from old location to new location. This term is also zero if relocated at the same position
>
> plus cost for removal, if planned.

Thus first step should be to get cost of each continuing component for remainder of service life for utility to be relocated. The total cost of any configuration is then the sum described. A flag $P_{no\ rel} = 0$ if surrogate not actually moved could be used to weight the special terms. To be realistic, "no relocation" should be tested for a small interval around the original location.

D. Design including the possibility of pavement widening

The most challenging modeling problem undertaken in this study involved determining the best corridor configuration strategy in light of a possible pavement widening at some time during the service life of the corridor. This renovation event potentially impacts every utility installed in the corridor, irrespective of timing, due to changes in installation and access requirements, adequate clearance for above ground objects and the likely relocation of at least some facilities. The method of analysis can be developed from the more elementary steps implemented in the previous examples.

To begin, it is essential to have specified a detailed service life for the corridor, including proposed dates for the installation of each utility along with the probability of each installation, and similarly the date of the proposed renovation and associated probability. For simplicity, only one such event is assumed to occur over the life of the corridor. The proposed date for this renovation separates the service life in to pre- and post-renovation periods for the purpose of developing the individual cost functions for each utility.

Relocation events present a significant problem for model development. For example, suppose a utility with above ground facilities is located where an additional lane will be placed. Obviously, relocation is required, but in order to assess costs it is necessary to understand where this utility will be placed during relocation. Because the placement of all other utilities depends at least to some extent on this decision, it is important to determine the relocated position. A second problem is to determine whether or not a utility should actually be relocated. If no above ground facility exists then it might be less expensive to not relocate and absorb the cost of additional inconvenience during access events. Mandatory relocation during renovation will be required for some facilities, as for example when an above ground facility is present and would reside within a paved region or a clear zone. Mandatory relocation may also occur in some situations where the original facility will be covered by new pavement or interferes in other ways with the renovation, even if there is no aboveground component. Stakeholder input would be required to determine if continued location beneath pavement would be acceptable.

For simplicity the following scenarios will not be considered here

a) Relocation after installation due to subsequent installation another facility.

b) Decommissioning of facility without removal

c) Optional relocation (this situation can be addressed by analyzing two different models)

d) Addition of facilities after the proposed renovation event (this case could be handled separately using the method for adding a utility to an existing corridor).

e) End of service life for the relocated utility, Y_{ren}.

The probability and proposed time for renovation are presumed known and this event marks an important division in time for each utility. The cost function for a specific utility depends the timing of individual events to the overall service life of the corridor. A renovation event separates the course of utility cost development into two paths, with the renovated path having probability P_{ren}, while the unrenovated path has probability $1-P_{ren}$.

The cost components for this case are as follows:

1. *Installation plus damage:*

By assumption all installations are assumed to take place during the pre-renovation period so that

$$c_{1j}(x_{i,j}, y_{i,j}) = [a_{inst,j} y_{i,j} + b_{inst,j}(x_{i,j}, x_{lw}) + A_j c_{max} f_{dam} a_{dam,j} y_{i,j}] \qquad (4\text{-}30)$$

2. *Regulatory:*

Because in general regulatory costs vary with horizontal position, some impact may occur post-renovation. Thus

$$\begin{aligned} c_{2j}(x_{i,j}) &= a_{reg,j}(x_r, x_{lw}, x_{i,j})(Y_{ren} - Y_{inst,j}) \\ &+ a_{reg,j}(x_r, x_{lw}, x_{i,j})(Y_{sl,j} - Y_{ren})(1 - P_{ren}) \\ &+ a_{reg,j}(x_r, x_{lw}, x_{i,j})(Y_{sl,j} - Y_{ren}) P_{ren} \end{aligned} \qquad (4\text{-}31)$$

where the break point for the coefficient a will change with the lane width, x_{lw}, depending on the state of renovation.

3. *Access plus damage:*

Development of a generalized access component is complicated by the fact that some utilities will be relocated in a renovation and others will only see a difference in access cost, if covered by pavement. Since two courses of action are possible, two terms weighted by their respective probabilities must be combined with the pre-renovation cost estimate.

$$\begin{aligned} c_{3j}(x_i, y_i) &= [a_{inst,j} y_i + b_{inst,j}(x_{i,j}, x_{lw}) + A_j f_{dam} c_{max} a_{dam,j} y_i] L_{eq} f_{acc,j}(Y_{ren} - Y_{inst,j}) \\ &+ [a_{inst,j} y_{i,j} + b_{inst,j}(x_{i,j}, x_{lw}) + A_j f_{dam} c_{max} a_{dam,j} y_{i,j}] L_{eq} f_{acc,j}(Y_{sl,j} - Y_{ren}) P_{ren}(1 - P_{rel,j}) \\ &+ [a_{inst,j} y_{i,j} + b_{inst,j}(x_{i,j}, x_{lw}) + A_j f_{dam} c_{max} a_{dam,j} y_{i,j}] L_{eq} f_{acc,j}(Y_{sl,j} - Y_{ren})(1 - P_{ren})(1 - P_{rel,j}) \\ &+ [a_{inst,j} y_{i,j} + b_{inst,j}(x_{i,j}, x_{lw}) + A_j f_{dam} c_{max} a_{dam,j} y_{i,j}] L_{eq} f_{acc,j}(Y_{sl,j} - Y_{ren})(1 - P_{ren}) P_{rel,j} \end{aligned} \qquad (4\text{-}32)$$

Here each term can be explained as follows:

Term 1: The pre-renovation period of occupancy

Term 2: A utility that does not have to relocate during a renovation, but potentially has a change in access condition due to pave over (probability P_{ren})

Term 3: The alternate case of no renovation (1-P_{ren}), no relocation required ($P_{rel,j}$=0)

Term 4: A utility for which relocation is required, but no renovation occurs.

It is noted that the third and fourth term combine to eliminate the consideration of relocation but these terms have been left separate for clarity.

4. *Traffic accidents with above ground facilities:*

For utilities with above ground facilities, the cost component due to traffic accidents is a function of the cost of impact, the offset, the traffic volume and the number of objects per mile (N_j). Since costs vary with the changing traffic volume, a sum over years until a possible renovation occurs is required for the initial period. The yearly volume was discussed and evaluated as a part of the service life parameters. For each object

$$c_{tpre,j}(x_{i,j}) = [c_{imp,j}(x_{i,j} - x_{lw}) \sum_{l=Y_{inst,j}}^{Y_{ren}} ADT_l / LF] \quad (4\text{-}33)$$

$$+ [c_{imp,j}(x_{i,j}) \sum_{l=Y_{inst,j}}^{Y_{ren}} ADT_l / LF](LF - 1) \quad (4\text{-}34)$$

For an above ground facility located at x_i, the offset from the lanes adjacent to the object is $x_{os}=x_i-x_{lw}$, and for the opposing lanes (if traffic is two way) $x_{os}=x_i$.

Roadway renovations such as lane addition pose special problems for utilities with above ground facilities requiring relocation and it is necessary to develop pre- and post- renovation costs, apportioning costs over the service life of the corridor between two values, depending on the probability of renovation in year Y_{ren}.

For the post-renovation period, for situations where relocation is not required ($P_{rel}=0$)

$$c_{tren,j}(x_{i,j}) = [c_{imp}(x_{i,j} - x_r) \sum_{l=Y_{ren}}^{Y_{sl,j}} ADT_l / LF]$$

$$+ [c_{imp}(x_{i,j}) \sum_{l=Y_{ren}}^{Y_{sl,j}} ADT_l / LF](LF - 1) \quad (4\text{-}35)$$

where the summation of the average daily traffic is taken over the renovated values (refer to definition of Service Life).

If no renovation occurs,

$$c_{tnoren,j}(x_{i,j}) = [c_{imp}(x_{i,j} - x_{lw}) \sum_{l=Y_{ren}}^{Y_{sl,j}} ADT_l / LF]$$
$$+ [c_{imp}(x_{i,j}) \sum_{l=Y_{ren}}^{Y_{sl,j}} ADT_l/LF](LF - 1) \quad (4\text{-}36)$$

where the summation of the average daily traffic is taken over the unrenovated values.

A general expression for the traffic component can be formulated. The necessity for relocation must be determined and is indicated by a flag $P_{rel,j}$. The factor $P_{agf,j}$ (1 or 0) indicates whether or not an above ground facility is present.

$$c_{4j}(x_{i,j}) = N_j P_{agf,j} c_{tpre,j}(x_{i,j}, x_{lw})$$
$$+ N_j P_{agf,j}[(1 - P_{ren}) c_{tnoren,j}(x_{i,j}, x_{lw}) + P_{ren} c_{tren,j}(x_{i,j}, x_r)(1 - P_{rel,j})] \quad (4\text{-}37)$$

where N_j represents the number of objects per unit distance along the roadway. The units of the accident cost, c_{4j}, are cost/unit distance along the roadway.

5. *Supplemental costs:*

Both recurring and non-recurring supplemental costs are combined into a single expression through the use of adjustment coefficients A_j and B_j. The supplemental functions have been retained in the generalized form.

$$c_{5,j}(x_i, y_i) = A_j c_{snr,j}(x_i, y_i) + B_j c_{sr,j}(x_i, y_i)(Y_{ren} - Y_{inst,j})$$
$$+ B_j c_{sr,j}(x_i, y_i)(Y_{sl,j} - Y_{ren})(1 - P_{ren})$$
$$+ B_j c_{sr,j}(x_i, y_i)(Y_{sl,j} - Y_{ren}) P_{ren} \quad (4\text{-}38)$$

For any utility which is a candidate for relocation and a surrogate has been designated, an additional charge for de-installation may be required and can be handled in this manner (multiplied by the probability of renovation).

Composite costs:

$$C_{i,j} = \sum_{k=1}^{5} P_j c_{j,k}(x_{i,j}, y_{i,j}) \quad (4\text{-}39)$$

For the <u>surrogate utility</u> (designated js), the year of installation is the same as Y_{ren} and the following terms are derived

1. *Installation plus damage:*

$$c_{1js}(x_{i,js}, y_{i,js}) = [a_{inst,js} y_{i,js} + b_{inst,js}(x_{i,js}, x_{lw}) + A_{js} c_{max} f_{dam} a_{dam,js} y_{i,js}] P_{ren} \quad (4\text{-}40)$$

Surrogate installations occur at the renovation period and costs are given in the same form, with A_{sj}=1 and a probability of P_{ren}. It is noted that the problem of adding facilities post renovation could be treated as the problem of a simple addition to an existing corridor.

2. *Regulatory:*

$$c_{2js}(x_{i,js}) = a_{reg,js}(x_r, x_{lw}, x_{i,js})(Y_{sl,js} - Y_{rel})P_{ren} \tag{4-41}$$

3. *Access plus damage:*

$$c_{3js}(x_{i,js}, y_{i,js}) = [a_{inst,js} y_{i,js} + b_{inst,js}(x_{i,js}, x_{lw}) + A_{js} f_{dam} c_{max} a_{dam,js} y_{i,js}] L_{eq} f_{acc,js}(Y_{sl,js} - Y_{rel})P_{ren} \tag{4-42}$$

Where the surrogate is located at coordinates x_{is},y_{is}, $P_{rel,j}$=1 and $f_{acc,js}$=$f_{acc,j}$.

4. *Traffic accidents with above ground facilities (if applicable):*

$$c_{4js}(x_{i,js}) = N_{js} P_{agf,js} c_{t,js}(x_{i,js}, x_{lw}) \tag{4-43}$$

If a renovation occurs, and due to original positioning the object requires relocation, a surrogate utility is inserted into the process of finding feasible solutions as before and the cost (denoted with subscript js) is evaluated at x_{is}, the relocated position as

$$c_{tsur,js}(x_i) = [c_{imp}(x_{is} - x_r) \sum_{l=Y_{ren}}^{Y_{sl,j}} ADT_l / LF + (LF - 1)c_{imp}(x_{is}) \sum_{l=Y_{ren}}^{Y_{sl,j}} ADT_l / LF] P_{ren} \tag{4-44}$$

Note that even though the term c_{ren} was constructed for a relocated position, this cost is still attributed to the original placement of the above ground feature at x_i.

5. *Other costs:*

$$c_{5,js}(x_{i,js}, y_{i,js}) = [A_{js} c_{snr}(x_{i,js}, y_{i,js}) + B_{js} c_{sr}(x_{i,js}, y_{i,js})(Y_{sl,js} - Y_{rel})] P_{ren} \tag{4-45}$$

Composite cost:

The individual cost function for the surrogate utility is again given by

$$C_{i,js} = \sum_{k=1}^{5} c_{js,k}(x_{i,js}, y_{i,js}) \tag{4-46}$$

When considering individual costs for specific utilities, the surrogate charges would be combined with the relocated facility as discussed previously, so that

$$C_{i,j} = \sum_{k=1}^{5} c_{j,k}(x_{i,j}, y_{i,j}) + \sum_{k=1}^{5} c_{js,k}(x_{i,js}, y_{i,js}) \tag{4-47}$$

The total societal cost for this case

$$TC_i = \sum_{j=1}^{n} P_j C_{i,j}(x_i, y_i) + P_{js}(C_{i,js}(x_{i,js}, y_{i,js}) \tag{4-48}$$

where each of the composite costs for utility j has been multiplied by the probability of installation P_j. Here the probability of installation is actually that attributed to the utility j for which the surrogate has been substituted. The surrogate charges have been combined separately, with the probability of installation identical with the probability of renovation.

SECTION 5: RESULTS

The purpose of this section is to illustrate the application of several programs developed during the investigation, to examine solutions to the types of problems posed previously and discuss results of explorations of the use of the programs to answer fundamental questions concerning the overall problem of facilities placement.

Adding a new facility to an established corridor

The purpose of this subsection is to introduce the principal program developed in conjunction with this work, and to consider an elementary example (for further details of program operation see Appendix A and the Tutorial manual). The following situation is envisioned. Two utilities have been installed along one side of the roadway. For simplicity, it will be assumed that none of these utilities has any above ground component and none has been installed underneath the pavement. A third utility company wishes to install new service and the problem is to determine the best location for this addition. The available corridor extends from the edge of the pavement to the right of way boundary and for practical reasons the maximum available installation depth will be limited to six feet. The previously established utilities have the following characteristics:

Table 5-1: Preexisting Utility Details

NUMBER	TYPE	DIAMETER [IN]	INSTALLATION YEAR	HORIZONTAL LOCATION [IN]	VERTICAL LOCATION [IN]
1	CABLE	3	0	175	42
2	POTABLE	6	0	155	42

There will be more information about each utility than just these five columns, but this data is provided to give a general picture as to what already exists in the corridor. The utility that is to be added is a Reclaimed Water line that is eight inches in diameter. This addition is taking place 10 years after the Cable and Potable lines have been installed. Begin by describing the corridor into which this addition will take place. The Home sheet status can be seen in Figure 5-1.

There are two modes of the placement program operation, “Design” and “Add”. The Design mode (discussed in the next subsection) is to be used when planning new projects to anticipate future installations and lane additions. The Add mode (discussed here) is to be used when adding a utility to an existing corridor.

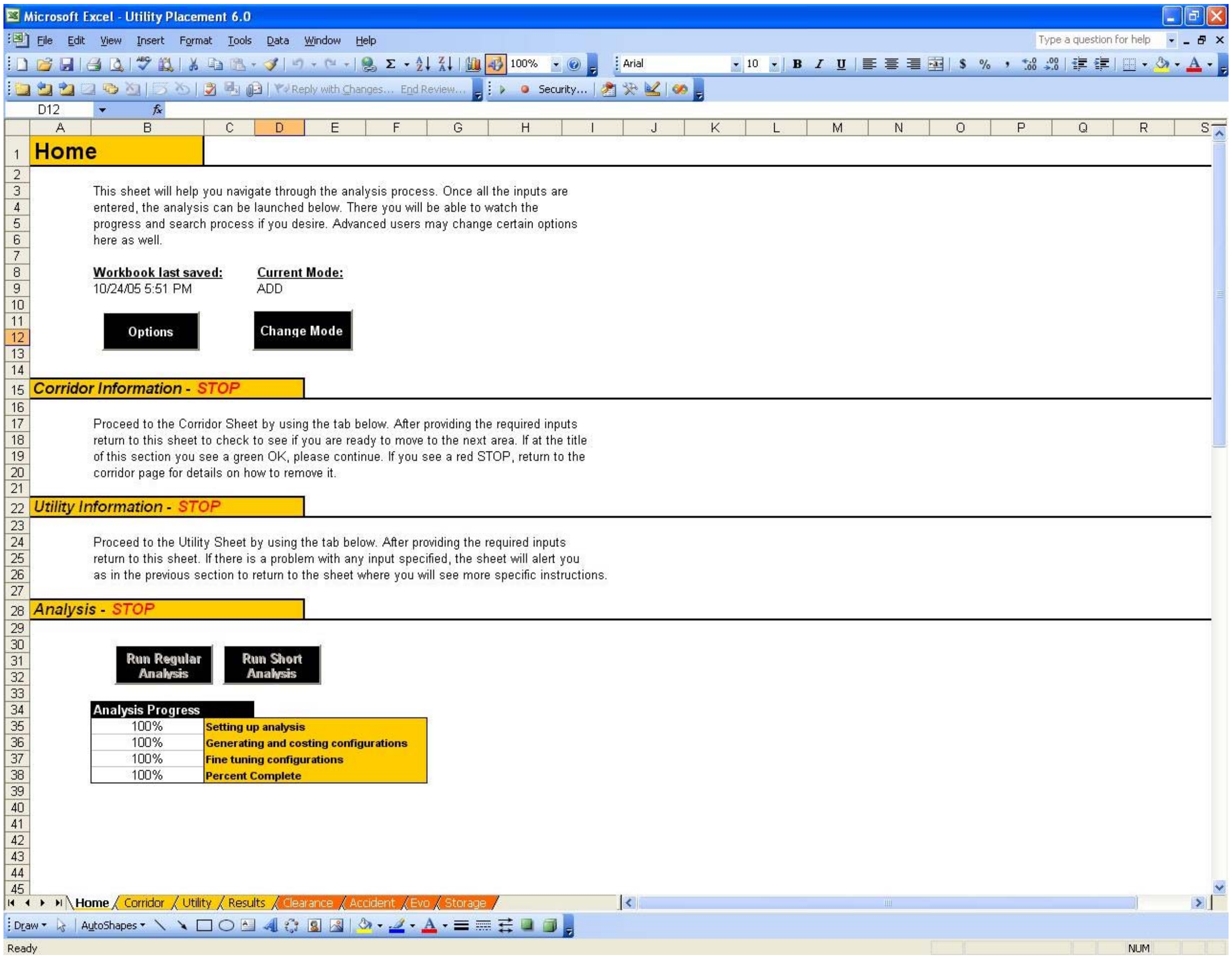


Figure 5-1: Home Sheet at beginning of analysis

The home sheet acts as a base of operations for the entire process. Operations include evaluation of the available input and notification of the user when there is insufficient information or if the data entered has some problem that will cause an error during analysis. There are two main areas of input: Corridor and Utility Information. To navigate to these areas, use the tabs bearing the appropriate name. Clicking on the Corridor tab navigates to the sheet depicted in Figure 5-2. The inputs that will be used in this example are included in this figure. The screen the user initially sees will have zeroes in the input areas.

The corridor used in this example is 15 feet wide measured from the center of pavement out to the edge of the Right of Way. There are two lanes of roadway each 12 feet wide. The program looks at only half the roadway at a time so that this analysis will focus on only one of those lanes. There are additional inputs pertaining to depth and project details that also must be entered. The following are definitions for each input. Data entries shown in the figures illustrate appropriate quantities for this example.

R/W WIDTH: The amount of right of way (in feet) measured from the centerline of the road out. This program solves problems by looking only at one side of the road at a time.

DEFAULT COVER: The minimum amount of cover (in inches) required over installations. This number will also be used as a default value for individual utilities.

MAXIMUM DEPTH: The maximum depth (in inches) for utility installation.

CLEAR ZONE: A distance in feet and measured from the edge of the pavement in which no utilities may be installed.

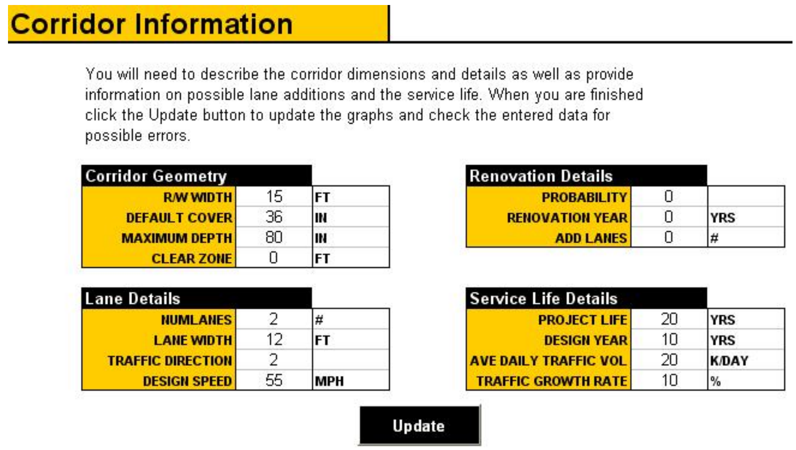


Figure 5-2: Corridor Information Sheet

INITIAL LANES: Although the program solves problems for one side of the roadway only, this is the total initial number of lanes (both ways). The term, “initial number of lanes” is used to contrast and accommodate the possibility of eventual lane additions, which will be called “added lanes”.

LANE WIDTH: The width of the lanes (in feet). Note that this number is a constant for all lanes.

TRAFFIC DIRECTION: There are two possibilities here for either one-way (1) or two way (2) traffic.

DESIGN SPEED: The speed in mph for which the road was designed.

PROBABILITY: The probability expressed as a percentage that a renovation (Lane addition) will occur. The program allows for the anticipation of one renovation and uses probability to weight the costs. This will be further explained in later tutorials.

RENOVATION YEAR: The year relative to the initial installation in which the renovation will take place (not used in this example).

ADD LANES: The number of lanes that are being added in the renovation (not used in this example).

PROJECT LIFE: The number of years that the project is expected to remain in service.

DESIGN YEAR: The year (relative to the design year) at which the road is to be running at the capacity for which it was designed.

AVG DAILY TRAFFIC VOL: The average daily traffic volume for which the project is designed expressed in thousands of cars per day.

TRAFFIC GROWTH RATE: A constant rate expressed as a percentage at which traffic is expected to grow.

After this information is entered, a click on the Update button will cause the graph depicted in Figure 5-3 to appear. This figure is a two dimensional cross-section of the half of the corridor to be analyzed. The black line represents the pavement, and green line represents the ground. The red line shows the minimum cover, defined as DEFAULT COVER above. Individual utilities can be more restricted. Note that the ground profile can be changed to match actual conditions.

On returning to the Home sheet, it will be noticed that the red “STOP” that followed the “Corridor Information” has now changed to a green “GO”. This indicates that enough information has been provided and that the information entered has no flaws that would cause an error. If there is still a red “STOP” next to the “Corridor Information” heading on the sheet, it would be necessary to return to the Corridor sheet for data repair.

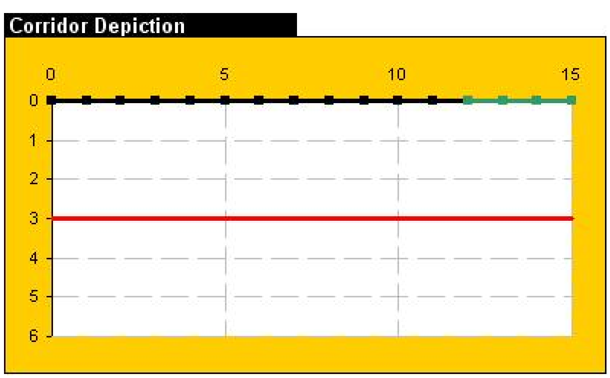


Figure 5-3: Corridor Visualization

A click on the Utility sheet tab at the bottom of the workbook will bring up the utility information input area.

Figure 5-4: Blank Utility List

The Utility sheet is similar in style to the Corridor sheet. The main difference is that multiple utilities can be described. At the top of the sheet, there is a white box with two buttons to the right of it. One button is “Add Utility” and the other is “Delete Utility”, as is shown in Figure 5-4.

It is necessary to click the “Add Utility” button twice to add the two utilities that already exist in the corridor. Error messages will be initially displayed, since the program is trying to catch errors and no data has been entered. After adding the two utilities, Figure 5-4 will change and appear as Figure 5-5. The details for the utilities being added are repeated here for convenience (Table 5-2).

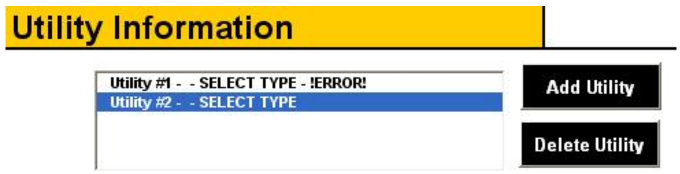


Figure 5-5: Utility List with Two Utilities Added

Table 5-2: Preexisting Utility Details

NUMBER	TYPE	DIAMETER [IN]	INSTALLATION YEAR	HORIZONTAL LOCATION [IN]	VERTICAL LOCATION [IN]
1	CABLE	3	0	175	42
2	POTABLE	6	0	155	42

Clicking on Utility #1 automatically loads all the information for Utility #1 on the screen. A large amount of utility information has been supplied as default. This is to make the input process less cumbersome.

An explanation of information for Utility #1, CABLE follows:

NAME: The utility name is not a required field. The purpose of this field was to allow for customization or distinction if more than one utility of a particular type was to be installed. The company installing the utility could be used, but this is purely aesthetic.

UTILITY TYPE: The type of the utility being installed. This information is not typed in, but comes from the dropdown list to the right. Simply choose the type from the list.

INSTALLATION YR: The year of installation relative to the project inception.

INSTALLATION PROB: The probability of installation. For a utility that is already in the ground, this may seem unnecessary as it is 100%.

YEAR PLACED OUT OF SERVICE: The year that a utility is placed out of service relative to the project inception. This entry defaults to the Project Life defined on the Corridor sheet.

DIAMETER: The utility diameter (inches) is the outside diameter, including bells, of the cross section of the pipe to be installed.

COVER: Cover is a utility specific input (inches) that defaults to the minimum set on the corridor page. Increase this if this utility requires additional cover.

OFFSET CENTERLINE: The distance (feet) measured from the centerline of the road which will not be considered for the installation of this particular facility (in this example, facilities will not be installed under pavement).

OFFSET RW: The distance in feet measured from the centerline of the road beyond which a utility will not be considered for installation.

What follows are several questions about this specific utility:

1. This utility has an above ground facility. Check this box if the utility has facilities that extend above the surface. Checking "yes" means that there will be more information to input about that facility.
2. This utility can have others stacked above and below it. This option allows or disallows stacking of utilities.
3. If a renovation occurs and this utility is paved over, it must be relocated. Use this option to force a utility to be moved if a lane addition covers the utility with pavement.
4. This utility is in a fixed location. This option is used to indicate that a utility is already in a specific location or that it will be installed in a specific location. This option allows for more complicated operations not a part of this example.

Under the question area, there is another extensive area for cost data. The program uses a cost basis to determine optimal placement. There are input areas to modify the cost as well. For this example, these numbers will be left at their defaults. Information for Utility #2 is entered in the same way.

Table 5-3: Utility #2 Details

NAME	Potable	OFFSET CL	12
TYPE	POTABLE	OFFSET RW	0
INSTALLATION YEAR	0	ABOVE GROUND FACILITY?	Unchecked
INSTALLATION PROB	100	STACK?	Checked
YEAR OUT OF SERVICE	20	RELOCATE?	Unchecked
DIAMETER	6	FIXED?	Checked (155, 42)
COVER	36		

Thus far the corridor and utilities already installed have been defined. To establish the facility to be added, on the Utility sheet, click "Add Utility". This will add a third utility to the list. Utility information is provided just as before with Utilities #1 and #2. Table 5-4 lists the values to be used in this tutorial.

Table 5-4: Utility #3 Details

NAME	Reclaimed	OFFSET CL	12
TYPE	RECLAIMED	OFFSET RW	0
INSTALLATION YEAR	10	ABOVE GROUND FACILITY?	Unchecked
INSTALLATION PROB	100	STACK?	Checked
YR OUT OF SERVICE	20	RELOCATE?	Unchecked
DIAMETER	8	FIXED?	Unchecked
COVER	36		

The Reclaimed Utility (#3) shares many of the same inputs as the Cable and Potable Utilities (#1 and #2). There are two large differences. The first is that the Installation Year is not zero as before. In this case Utility #3 is being added 10 years after Utilities #1 and #2. Thus the Installation Year is 10 and not 0. The second major difference is that it will not be in a fixed location, so it is necessary to leave this box unchecked. The entire motivation for this analysis is to determine where the additional facility should be installed.

On the Home sheet all the headings with a red "STOP" have now changed to a green "GO" as shown in Figure 5-6. This indicates that the analysis is ready to begin. Clicking on the "Run Regular Analysis" button will start this process.

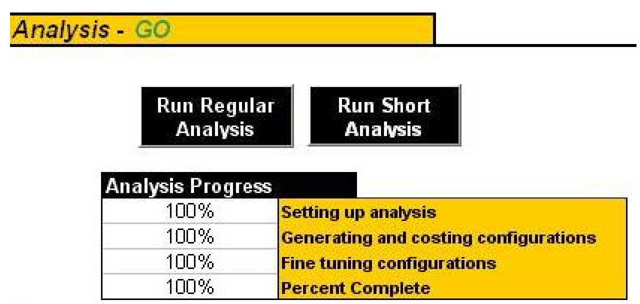
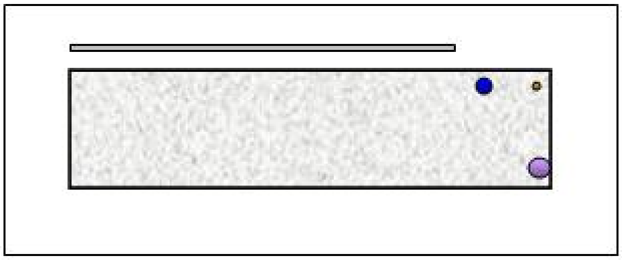


Figure 5-6: Analysis Ready to Proceed

The analysis will take place in three stages. The first is "Setting up analysis". The program makes calculations and adjustments that need to happen before the analysis can take place. A percent completion for each stage is indicated. The second stage is "Generating and costing configurations". This stage is self explanatory and will take place fairly quickly in this case because only Utility #3 is being located and analyzed. The other utility locations are known. Each configuration is priced by a cost function. Again, in this case only Utility #3, the added utility, is being priced. The question being answered when in the add mode is "What does it cost to add this utility?" An optional graphic will appear, showing this search process while it occurs. The third stage is "Fine tuning configurations". Here, the configurations are fine tuned to ensure that an optimal placement has been found. Note that if not enough space within the corridor is available; there will be no solution to the problem. In this example there was indeed a solution. After the analysis is finished, the result will print on the Results sheet and the program will automatically transfer to the output location (Figure 5-7).



Optimal Solution					
Name	Type	Horizontal [in]	Depth [in]	Cost [k$/mi]	Efficiency [%]
CABLE	CABLE	175	42	$0.00	0.00%
POTABLE	POTABLE	155	42	$0.00	0.00%
RECLAIMED	RECLAIMED	176	72.4	$839.98	73.49%
				$839.98	73.49%

Figure 5-7: Results for this example

The conclusion reached for this example is as follows. When proposing an addition to an existing corridor with prior occupancy, two questions may be asked. First, can a specific utility be placed in a location satisfying all constraints (i.e., can one or more feasible solutions be found), and secondly, how expensive will installation be if a location can be found? These two questions address the issue of corridor *flexibility*, which can be defined as a ratio of the absolute minimum cost of installation to the actual cost at some location. A value close to unity indicates a corridor that will easily allow for efficient expansion. Note that the flexibility parameter is specific to a particular corridor and proposed utility.

In this particular example, it was possible to place an additional utility. In fact 72 solutions were found and the best cost solution (i.e. optimal) was $839.98 k$/mi while the absolute minimum cost (if no constraints interfered with placement) was $617.32 k$/mi so that the flexibility was calculated to be 73.49% (note that for the addition of a single new facility, the definition of efficiency and flexibility are identical). Thus in this example it has been determined that while it is possible to install a new facility and an optimal location has been found, preexisting conditions dictate that the new facility is forced into a relatively more expensive location.

A Planning Example

In this subsection, a typical planning example is explored to demonstrate the capabilities of the DESIGN program. Details regarding program data entry and operation are contained in Appendix A and a tutorial manual submitted to the FDOT under separate cover.

Consider a situation where it is desired to install four utilities initially and one additional facility is likely to be installed in five years. The available corridor in this example is small (7 feet horizontally and 4.5 feet vertically) and installation under pavement is not considered. Planning for this corridor involves a relatively complex situation without an obvious solution. Congestion will force some utilities to be installed at a deeper location than would normally be desired.

Figure 5-8 shows the result of inputting data regarding the corridor:

Corridor Geometry		
R/W WIDTH	19	FT
DEFAULT COVER	36	IN
MAXIMUM DEPTH	90	IN
CLEAR ZONE	0	FT

Renovation Details		
PROBABILITY	0	%
RENOVATION YEAR	0	YRS
ADD LANES	0	#

Lane Details		
NUMLANES	2	#
LANE WIDTH	12	FT
TRAFFIC DIRECTION	2	WAY
DESIGN SPEED	55	MPH

Service Life Details		
PROJECT LIFE	20	YRS
DESIGN YEAR	10	YRS
AVE DAILY TRAFFIC VOL	20	K/DAY
TRAFFIC GROWTH RATE	10	%

Figure 5-8: Corridor Data

Next, examine data regarding facilities to be installed (Figure 5-9):

UNUM	TYPE	INST	DIAMETER	TYPE #	COVER	INSTALL YR	INSTALL PRB
1	GAS DIST	OT	5	2	36	0	100
2	POTABLE	OT	8	4	36	0	100
3	TELECOM	OT	7	9	36	0	100
4	POWER DIST	OT	8	5	36	0	100

STACK?	AGFAC?	NMILE	AGFAC D	AGFAC S	AGFAC H	AGFAC F	W	NEVENTS	MACCESS
NO	NO		0	0	0	0	1	1	3
NO	NO		0	0	0	0	1	10	1
NO	NO		0	0	0	0	1	1	1
NO	CYLINDER	20	24	0	0	0	1	1	5

Figure 5-9: Facilities data

Note that one installation (power distribution) involves above-ground facilities. Other than utility types and conduit sizes, the main difference between the facilities lies in the access costs, since the product of the N_{events} and M_{access} is different for each. The four initial installations will be by open trench. The bounding boxes for installation are all set to two feet in each direction for simplicity. It is planned that the facility added later will be installed by trenchless methods. By assumption, no clear zone was imposed in this example and nominal values for the inconvenience surcharge were assumed (inconvenience s_{val}=5 K$/mile/year, ending at two feet from pavement).

The principle objective of this example is to see how preplanning for the added utility can affect the initial placement of the original four utilities. The proposed addition will be for reclaimed water which will include above ground facilities. It is estimated that the probability of installation for this facility is 50% and that the timing for installation will be five years after the initial installations. The specifications for this facility are shown in Figure 5-10:

UNUM	TYPE	NAME	DIAMETER	TYPE #	COVER	INSTALL YR	INSTALL P
5	RECLAIMED	DD	4	6	36	5	50

STACK?	AGFAC?	NMILE	NEVENTS	MACCESS
NO	CYLINDER	40	12	1

Figure 5-10: Data for facility to be added subsequent to initial development.

Two alternative strategies were employed in the search for optimal configurations to better understand the potential of preplanning (for this example a search step size of 0.8 ft was used):

1. Optimal Placement of the four originally installed utilities, then add the remaining utility (Case A-no preplanning). The design program was executed to locate the four initial utilities. An optimal result was then used to anchor the four initial utilities and the analysis was concluded by adding the fifth in the most economical location remaining. The results of this analysis are shown below in Figure 5-11.

Optimal Solution				
Name	**Type**	**Horizontal**	**Depth**	**Cost**
OT	GAS DIST	148.7	38.5	$1,128.52
OT	POTABLE	185.6	40	$1,521.49
OT	TELECOM	205.3	71.9	$715.52
OT	POWER DIST	224	40	$2,188.69
DD	RECLAIMED	174.4	70	$2,661.80
				$8,216.02

Figure 5-11: Program results if no effort at preplanning is made (units are $K/mi). Only one of several optimal configurations is presented.

2. Optimal Placement of all five utilities (Case B). This approach is a more comprehensive strategy, since the installation of all utilities is considered simultaneously, including accounting for the delayed installation. The results of this analysis are shown below in Figure 5-12.

Optimal Solution				
Name	Type	Horizontal	Depth	Cost
OT	GAS DIST	148.7	38.5	$1,128.52
OT	POTABLE	185.6	40	$1,521.49
OT	TELECOM	166.9	71.9	$1,215.52
OT	POWER DIST	224	40	$2,158.68
DD	RECLAIMED	216.8	70	$2,093.35
				$8,117.57

Figure 5-12: Program results when the addition is included in planning

A small improvement in overall cost for the corridor was obtained by preplanning. It is instructive to recompute these results as efficiencies instead of costs. The absolute minimum total cost (sum costs for least expensive locations irrespective of occupancy) for the five utilities is $6386.57. The efficiency ratios (configuration cost to absolute minimum cost) are then 77.7 % when preplanning is not included and 78.7% for comprehensive planning. Advanced planning is found to be the most efficient (under the current set of assumptions) but also will be more time consuming, computationally. More importantly, a more efficient addition of the last utility to the configuration results from application of preplanning, as can be seen by examining the flexibility parameter in Table 5-5. Since this factor is not a target for optimization, the value of this improvement is open to discussion.

A secondary question to be answered concerns the selection of a step size for the search algorithm. Case B above was recomputed (as Case C) at a smaller step size (0.5 ft) and while another modest improvement was noted, the computational time was excessive and probably not practical. Appropriate non-dimensional parameters applicable to these three cases and two more discussed later are summarized in Table 5-5 below.

Utilizing evolutionary searches

To better understand program operation and also the implications of the selection process, a numerical experiment to model the process of evolutionary corridor development was initiated. This effort led to some surprising and useful results. First, the same problem was posed as before, a group of utilities (including one proposed for later installation) are to be installed in a corridor. Select an order for installation, with the proposed facility last. Instead of overall planning, let the first of these utilities move to the best location possible (on the basis of the same cost function used in the planning model). Next, let the second utility locate in the best location remaining. Then the third is placed, and so forth, until the entire group has been positioned, with the provision that each selection obeys the constraints in place at the time of occupancy (i.e., no conflict with a facility already in place). The proposed additional facility is placed last as before. Then the process is repeated for all installation sequences resulting in a set of feasible and relatively economical solutions can be identified. In a sense this concept represents a third optimization strategy alternative. Unlike the previous strategies, however, there is no guarantee that the entire field of solutions has been searched.

This strategy was pursued for a step size of 0.1 ft. For purposes of discussion, the sequence with the lowest total cost was identified as Case D and that with the highest total cost, Case E. The non-dimensional parameters associated with these solutions are included in Table 5-5, for comparison. These comparisons are very significant since they show that it is possible to obtain a more economical solution than that obtained from the comprehensive design strategy (see above). This improvement is due to the fact that the evolutionary model installs one utility at a time and can do so at a small step size (0.1 feet), much smaller than that used for the complete design model (0.8 feet). The search direction also proceeds so that efficient solutions tend to be found early. The step size used for the design strategies above (Cases A and B) is set much higher because the task of searching all possible combinations of configurations is quite lengthy. Here, the evolutionary approach may often find a very good solution rapidly but the result cannot be guaranteed to be optimum. If the computations were completed by the design method at an equivalent step size a better answer yet might be obtained, but typically time constraints make this approach impractical. The evolutionary method appears to be faster (roughly fifty times faster for the situation described here) and yields better results when compared to overall design method at larger steps. Certainly there is no harm in utilizing both methods (even with different step sizes) and picking the best result obtainable within practical considerations.

Table 5-5: Comparison of five cases for the planning example (NM stands for "not meaningful")

PARAMETER/CASE	A	B	C	D	E
EFFICIENCY	0.65	0.66	0.70	0.83	0.76
CROWDING	0.35	0.34	0.30	0.17	0.24
EFFECTIVENESS	NM	0.09	0.14	NM	NM
FLEXIBILITY	0.76	0.97	0.80	0.77	0.77
BALANCE	0.89	0.81	0.84	0.86	0.86

where

Case A: Plan for four original facilities, then add the fifth
Case B: Plan for five facilities (step size 0.8 ft)
Case C: Plan for five facilities (step size 0.5 ft)
Case D: Evolutionary search – best result
Case E: Evolutionary search – worst result

It should be noted that the evolutionary strategy discussed here does not adequately simulate the manner in which a corridor is likely to develop if left to the "first-come, first-served" approach, since the requirement to opt for the best total societal cost is still imposed. It is unlikely that in the decision making process utilities would include costs over and above those which directly impact their operations. Furthermore, it is not immediately obvious that utilities would employ the resources to select the absolute optimum according to any particular cost model adopted. The modeling of the "first-come, first-served" strategy remains an interesting question left for future research

Before leaving this topic, the following explanation is offered to put the search strategy outlined here into perspective with that used elsewhere in this report. Previously the optimization problem was described in terms of a single target, the total societal cost, which depends on 2n coordinates, corresponding to the set of n x,y pairs that describe the locations of n facilities. Each set of these pairs obeying all imposed constraints (a feasible configuration), denotes a single corridor configuration. The search for feasible configurations consists of an examination of all possible configurations at a resolution of some particular interval of position change ("step"). Once the set of feasible configurations has been identified, the search for an optimum configuration consists of locating the minimum total cost solution. Although other factors may characterize the solution, within the limit of this resolution, locating a minimum is guaranteed. That is not to say that if a smaller resolution in step size was used, that a better solution could not be found.

The evolutionary strategy above is an alternative approach to the problem of finding efficient configurations rapidly (instead of considering a complete analysis based on 2n independent variables). Here the optimization process is restricted to finding the best possible position for each facility in an ordered sequence. This strategy satisfies the imposed constraints and evaluates the cost of each facility separately, involving only one x,y pair of coordinates at a time. In this manner, the best possible location is established by looking at the best cost obtainable for each individual utility where the position of that utility is constrained by the positioning of other facilities earlier in the particular sequence being explored. Thus the problem is reduced to a corresponding sequence of n simple searches in two spatial dimensions using a facility specific target.

The balance parameter

The purpose of this subsection is to comment on the balance (how costs are distributed among the individual utilities) of the optimal solutions found. Recall the definition of the individual cost ratio and the mean cost ratio from Section 2:

$$ICR = \frac{MC_j}{C_j(x_{j,i} y_{j,i})} \qquad (5\text{-}1)$$

$$\frac{\overline{MC}}{C} = \frac{1}{\sum_j P_j} \sum P_j \frac{MC_j}{C_j(x_{j,i}, y_{j,i})} \qquad (5\text{-}2)$$

The balance parameter can then be defined as the mean (absolute) deviation from the average individual cost ratio, respecting the probability of installation for each facility:

$$Q_{effec} = 1 - \frac{1}{\sum_j P_j} \sum_j^n P_j \left| \frac{\overline{MC}}{C} - \frac{MC_j}{C_j} \right| \qquad (5\text{-}3)$$

Inspection of the balance parameter and the individual cost ratios calculated for the results of the evolutionary search (best and worst cases) leads to the following conclusions. While overall the balance is less than one (indicating that some utilities are paying more on a relative basis than others for positions assigned by the program, the parameter by itself does not explain how balance is distributed. In fact, the balance parameter is quite similar for the two sets of results, even though the efficiency (and total cost) differs substantially.

Closer inspection of the distribution of individual cost ratios explains the results more clearly. For the worst evolutionary results (Case E) it was found that the power distribution utility was most out of balance especially in comparison to the telecom utility, but this situation was reversed for the best case (Case D). Since the power distribution facility is the more expensive of the two facilities in terms of individual cost, the total cost is driven up and overall efficiency is reduced, even though the balance parameter is comparable between the two cases.

Further inspection of the results shown in Table 5-5 reveals that in all cases the corridor could be characterized as moderately crowded. Likewise the effectiveness parameter indicates that for this example the difference between an average solution to the configuration problem and an optimal solution is small (but still significant).

Rebalancing individual costs

It is apparent from the previous discussion that optimal configurations are not necessarily well balanced, in the sense that some utilities are forced into less desirable locations. This fact is the consequence of optimizing only for a single target, in this case the total cost. Even though the individual utilities may not be affected by some components of the total cost, it is still true that forcing an expensive location may generate resistance to corridor management.

To rectify this situation, one possibility is to “rebalance” the individual cost components to achieve a uniform distribution.   This concept is demonstrated here for the best evolutionary search example (Case D), using total cost. Extension of this method to other cost models is straightforward. To obtain the same absolute deviation from the average individual cost ratio, the cost attributed to each utility must be divided by the overall efficiency which follows from

$$TC = \sum_j \frac{MC_j}{Q_{eff,\,opt}} = \frac{MTC}{Q_{eff,opt}} \qquad (5\text{-}4)$$

so that the mean ICR is equal to the efficiency. For this condition, the balance parameter is unity and the total cost of the configuration remains the same. The table below shows the differential cost increase or decrease for each utility.

Table 5-6: Results of rebalancing for Case D (Q_{eff}=0.83, ICR_{ave}=0.86)

FACILITY	ICR		BAL COST	OPT COST	DIFF
GAS DIST	1.00	0.16	754.45	628.52	125.93
POTABLE	0.67	0.17	1226.15	1521.49	-295.34
TELECOM	0.74	0.11	632.48	713.19	-80.71
POWER DIST	1.00	0.16	2591.19	2158.68	432.50
RECLAIMED	0.39	0.03	2425.85	2608.23	-182.38
TOTAL COST			7630.12	7630.11	

The intent here is to show that a more equitable distribution of costs can be obtained; recognizing that at present, no means to achieve this goal exists.

Permit program

A logical outgrowth of the ADD program was to explore the construction of an “automated permit program”. Subsequently, additional effort was made in this direction. Two questions are posed: first, can a procedure be developed to optimize the placement of new facilities in existing corridors and second, can an electronic based permitting process be implemented to take advantage of such optimization techniques? The rationale for the second question is not merely to propose ancillary software for the convenience of the permit issuer; rather the ultimate goal is to develop a useful tool which would help assure that permits are granted only after options have been examined along with a consideration of other relevant factors.   If the result of this effort is successful and is adopted, better use of available resources may eventually result.

Starting from ADD module (which already performed most of the necessary computations) an initial input section, consisting primarily of the same data entry as a standard permit application was included. In comparison to the original ADD program additional simplifications and assumptions were imposed so that only a limited amount of user input would be required. Several options for shoulder configurations were allowed, as well as provisions for different installation methods. The optimization routine was set to complete multiple evaluations of several scenarios (using different installation methods for example). Since most utilities propose a location in advance of the application, a section was added to evaluate that suggestion in comparison to the optimal choices. Finally, an output section was added to return a decision to approve or deny the application. In some cases, the need to forward to a higher authority could be recognized and reported. Commentary about the conclusions reached are inserted in the final output, which then becomes a permanent record of the decision making process.

The results of this program are intended to provide a basis for granting or denying permits, by checking physical constraints to installation, safety and total cost. The advantage of such a program lies in the ability to examine a very large set of possible installation configurations. In cases where no basis for a simple decision is apparent, a report of this fact is made so that other steps can be taken. The ability to expand occupancy of a corridor at some later date is yet one more consideration relating to the quality of any proposed solution.

The permit model is the subject of a paper submitted to the Transportation Research board (furnished to FDOT under separate cover) and much of what is reported here is taken directly from that paper. This program is still in a prototype development stage and further effort will be needed to bring it to a fully functional state.

Permit Example 1:

In addition to introducing the concept and application of the permit program, in part this example is intended to illustrate the use of the inconvenience surcharge, as discussed earlier. To review, this cost is an annual charge dependent on horizontal position with respect to the pavement could be imputed by an entity charged with supervision of corridor development, as a method of discouraging installation in areas near the roadway. In this analysis a simple step function model has been assumed, with the transition point located by a constant distance from the pavement edge. Thus a_{reg} is a constant for the region between the edge of the pavement x_{lw} and an ending point at x_r (and zero elsewhere), so that

$$c_{reg}(x) = a_{reg}(x_r, x_{lw}, x) \qquad (5\text{-}5)$$

Not all utilities may be affected by this cost (a_{reg} varies with utility) but the regulatory offset, x_r, is assumed to be constant for all affected utilities. This surcharge will be treated as a recurring expense and must be multiplied by the number of years of service expected for the utility. The concept of an inconvenience surcharge is one unique aspect of this investigation originally suggested by the Florida Department of Transportation.

Suppose an occupied corridor has characteristics given in Table 5-7. It is emphasized that the values chosen here pertain to this illustrative example only and in actual situations parameter values would be changed to represent specific cases of interest.

Table 5-7: Roadway, utility, and cost function adopted for Permit Examples 1 and 2 (horizontal dimensions are from pavement centerline)

PARAMETERS			US		SI
ROADWAY					
	PAVED WIDTH	12	ft	3.7	m
	R/W WIDTH	22	ft	6.7	m
	SERVICE LIFE	20	yr	20	yr
	DESIGN CAPACITY	20,000	veh/day	20,000	veh/day
	DESIGN YEAR	10	yr	10	yr
	DESIGN SPEED	55	mi/hr	88.5	km/h
	TRAFFIC GROWTH RATE	10	%/yr	10	%/yr
	TRAFFIC DIRECTION	2	way	2	way
	LANES (TOTAL)	2		2	
	LANE WIDTH	12	ft	3.7	m
UTILITY					
	MINIMUM COVER	3	ft	0.9	m
	MAXIMUM DEPTH	6.7	ft	2.0	m
COST FUNCTION					
	TRENCH a_{inst}	62.4	k$/mi/ft depth	127.1	k$/km/m depth
	TRENCH b_{inst}	266.7	k$/mi	165.6	k$/km
	TRENCHLESS	982.1	k$/mi/ft diameter	2000.9	k$/km/m diameter
	f_{acc}	1	event/yr/mi/ft	3.3	event/yr/km/m
	L_{eq}	30	ft	9.1	m
	INCONVENIENCE ZONE	12	ft	3.7	m
	A_{dam}	14000	k$/ft	4267	k$/m
	ER	9.14E-08	enc/ft/y/(veh/day)	3.0E-07	enc/m/y/(veh/day)

Current occupancy includes a 3 inch (7.6 cm) diameter gas distribution pipeline installed at a horizontal position of 21.7 ft (6.6 m) and a depth of 3.2 ft (1.0 m) along with an 8 inch (20.3 cm) potable water pipeline installed at 18.8 ft, 3.3 ft (5.7 m, 1.0 m). At year five of service life, a utility company is seeking a permit to install a new 7 inch (17.8 cm) diameter telecom facility and proposes a location of 16.1 ft, 3.3 ft (4.9 m, 1.0 m), installed by a shored trench, with no above ground facilities. Because the corridor is tightly constrained and narrow, there is insufficient space to institute a clear zone requirement. Furthermore, for this example no installation under pavement is permitted. In general clearance rules are complex, depending on both method of installation and type of facility. In both examples presented here a simplified clearance rule has been adopted: in both the vertical and horizontal directions the clearance between outer conduit walls must be at least 2.0 feet (0.61 m).

Although the utility company requested a shored trench installation, horizontal directional drilling is to be considered also, as an alternate. An inconvenience factor a_{reg} =5 k$/mi/yr (3.1 k$/km/yr) was selected initially. The results of submitting this set of conditions for optimization using a search step size of 0.3 ft (9.1 cm) are presented in Figure 5-13a. All positions in the dashed box are equivalent, with a total cost of $593,810/mi ($368,980 /km). Based on the circumstances as presented thus far, the absolute minimum is $518,810/mi ($322,370/km), yielding an efficiency of 87%. Figure 5-13b demonstrates the sensitivity of optimal configuration to the inconvenience factor. By increasing this charge from 5 k$/mi/yr (3.1 k$/km/yr) to 10 k$/mi/yr (3.1 k$/km/yr), the added telecom facility is forced to locate under the previously installed facilities (by directional drilling) at cost of $632,480/mi ($393,000/km) and an efficiency of 82%. It is emphasized that the total costs associated with these configurations do not represent actual construction costs. The example presented here is not sophisticated and the result is fairly obvious. A more complex situation will be explored in Example 2, below.

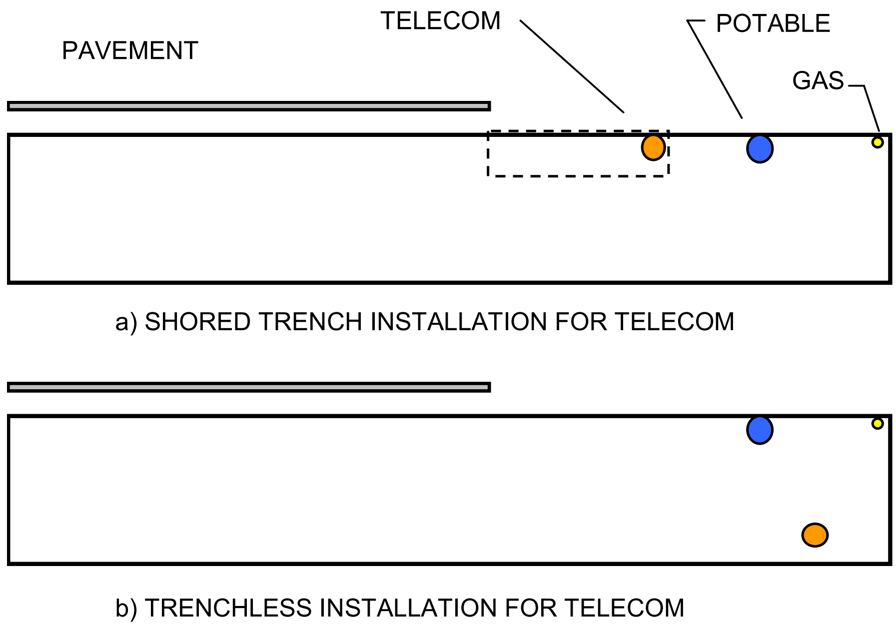


Figure 5-13: Optimal configurations for conditions of Example 1, illustrating the effect of increasing the inconvenience charge a_{reg} from 5 k$/mi/yr for a) to 10 k$/mi/yr for b)

Program implementation of automated permitting

The permitting process usually begins with routine information gathering (application) before an examination and decision making phase can be undertaken. Although at present this stage is often paper-based, the adoption of an electronic format is a relatively straightforward process and it is assumed here that this transformation could be easily accomplished in most jurisdictions, beginning with a permit application form [31]. Subsequent tasks, including the examination of safety and occupancy of the location requested by the utility (as well as the final decision itself) usually remain to be completed manually. Automating many of these operations is a highly desirable step, as for example the determination of the extent of clear zone which is usually made by manual table lookup. In this manner several quantities can be computed directly, following the information gathering step, in preparation for the analysis process.

The intent here is to demonstrate a program that extends the concept of an electronic permit model to include the capabilities of an optimization process as an automatic step, taken prior to a final approval. Thus the task of examining a very large number of alternative configurations is handled by the program and unbiased comparisons to the original proposed location selected by the utility can be made. The development of an automated, electronic based permitting process incorporating an optimization component is illustrated in Figure 5-14 and discussed below.

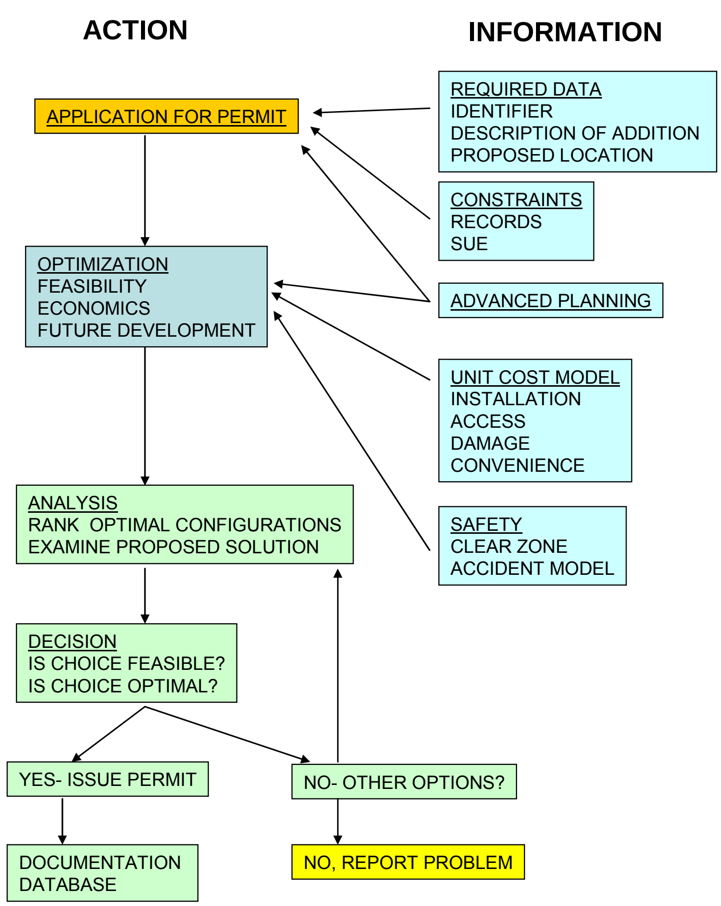


Figure 5-14: Flow chart for permit process including optimization

In addition to the items shown in Table 5-7, a completed permit application also requires information of a general nature (applicant identification, roadway designation and description, extent of proposed work, etc). It is readily apparent from the discussion in the previous section that the data requirements for a computer assisted procedure are more extensive than simple permitting and this information will come from several different sources. Furthermore, the various project stakeholders must agree not only on the parameter values (or accept defaults), but also on the relative importance of the various components of the program output in the final decision process.

Because of the way the optimization process functions, issues of safety, conflicts, and the best use of resources are put into similar economic terms (at least on a relative basis) so that a comparative examination can be made. The output consists of a final report summarizing the findings of the analysis process. This information can become a part of the permanent record [30] of installation and be made available electronically for subsequent retrieval. In cases where the data is incomplete, or a rational decision cannot be made from the information available, the program can inform the user of the problem or refer the decision forward to a higher authority. In some cases the original location suggested by the petitioning utility may prove acceptable, but in other cases better choices may be apparent. In the situation described in Example 1, a permit probably would have been granted. Other issues and questions need to be examined however, as discussed in Example 2 below.

The principal accomplishment at this stage is the investigation of the best use of resources. In constructing a report, the program automates the process of examining a large group of alternatives to compare to the original utility request. Thus a rational basis for decision making has been provided. Furthermore, the opportunity to engage in “what if” explorations of alternate approaches is afforded, since even large searches are relatively fast.

Partitioning of resources

The utility permitting process in the State of Florida requires the examination of five year planning for roadway work due to potential impact on utility placement. The likelihood of addition of other facilities at later times is not necessarily considered however. Especially if the corridor is already congested, it may be true that a place can be found for an applicant facility that is both feasible and economical, but is positioned to preclude any further additions. If the eventuality of later additions can be included in the analysis process, at least to some degree of probability, then further improvement in the use of resources could be achieved. This step represents an enhancement in capabilities, but may not be necessary in all situations.

The optimizing component of the permit program discussed here allows for such consideration as part of the analysis process, as can be illustrated by revisiting the previous example. Suppose that at the time of a permit application it is anticipated that one additional facility might be installed at some time in the future. Instead of planning for the immediate request only, the installation of two utilities is attempted. Assuming that feasible solutions exist for both installations, the best alternatives from this group would be selected as acceptable possibilities. In this manner, space is left open for the future addition, even though cheaper alternatives for the immediate installation might be found if the possibility of a later addition was ignored completely.

It is likely that the exact specifications for any future additions is uncertain and that some assumptions will need to be made. The total cost function can easily be reformulated to include the additional cost of adding a utility at $x_{i,add}$, $y_{i,add}$, where the subscripts i,add designate the coordinates of this potential future addition for a particular configuration i. A probability factor P_{add} is included in the total cost function to allow for weighting the importance of this eventuality. Each of the terms $c_{j,add}$ in the cost function for the added facility the same formulation as that described elsewhere except that the time interval for recurring costs differs for each facility.

$$C_i = \sum_{j=1}^{n} w_j c_j (x_i, y_i) + P_{add} \sum_{j=1}^{n} w_{j,add} c_{j,add} (x_{i,add}, y_{i,add}) \qquad (5\text{-}7)$$

The computation of efficiency must likewise be modified to be the ratio of two sums as in Equation 5-7.

Permit Example 2

As a demonstration of this concept, Example 1 will be reconsidered, assuming that future planning might involve underground relocation of overhead electrics within three years of the telecom permit being sought. To this end, it is anticipated that an 8 inch (20.3 cm) conduit is being considered and that the probability of this installation is 50%. This installation will involve above ground facilities estimated to be 2 feet (0.6 m) in diameter, twenty per mile. The same clearance rules and cost factors as given in Example 1 will be used for computations. Initially, it is assumed that placement of the electric facility beneath the original conduits (stacking) would not be allowed, due to the risers to the above ground facilities. The accident cost function [22] associated with the above ground facility (over a period of 12 years) is shown in Figure 5-15.

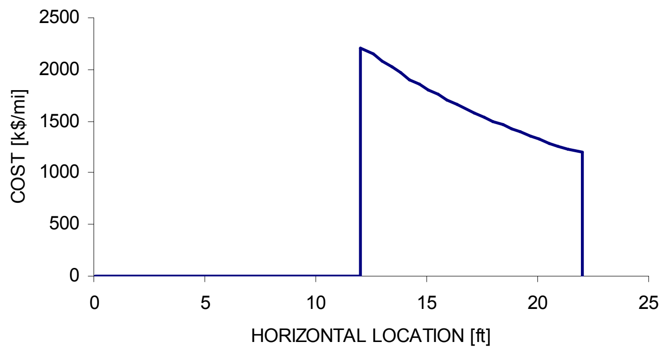


Figure 5-15: The accident function imposed in Example 2 (centerline of pavement corresponds with the origin of the graph)

When the potential addition of the underground electric facility is not considered, installation of the telecom facility could be positioned anywhere in the dashed box region of Figure 5-13a, possibly blocking any further development at minimal cover. The result of optimizing the solution to this problem retaining the opportunity for future placement of an additional facility suggests an optimal location, different than that requested for the applicant facility. As can be seen in Figure 5-16a, by including the electric facility, the telecom installation is forced closer to the pavement leaving the above ground facility as far away as possible. Thus, the available space is effectively partitioned into optimal zones.

A measure of the flexibility, or potential for future placement, may be obtained by calculating the efficiency ratio of the future addition for any particular configuration.

$$Q_{flex,i} = \frac{MC_{add}}{C_{add}(x_{add}, y_{add})} \tag{5-8}$$

For the configuration shown in Figure 5-16a, the flexibility is 76%, indicating that the space can be found but not inexpensively. To complete the discussion, suppose instead that telecom was placed to the right as shown in Figure 5-13a, as originally requested. The best possible placement for the electric line is now adjacent to the pavement in a more expensive position due to the proximity of above ground facilities to the pavement (this configuration is not shown in figure). Although expansion is still possible, the presence of an above ground facility makes this location clearly undesirable, it is logical to reconsider the original constraints in a search for better alternatives.

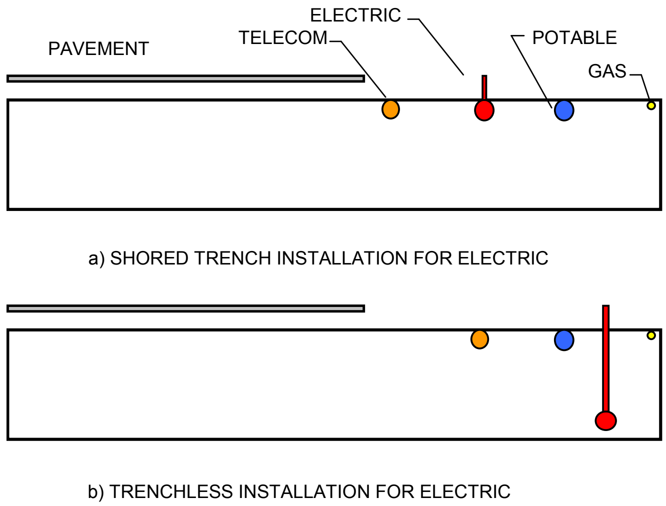


Figure 5-16: Optimal configurations when the possibility of additional electric facilities is included, with a stacking constraint for a) compared to relaxing this constraint for b)

For the corridor configuration examined here, there remains space between the two facilities installed initially. This space is inadequate for trench installation of the underground power line but the riser for the above ground facility could be routed here by relaxing the constraint against stacking facilities. To allow for this possibility, suppose that a clearance rule requiring that the riser separation from adjacent utilities is only 0.5 feet (0.15 meters). The optimization procedure now indicates that a constructible location for the electric facility can be found at 20.2 ft (6.0 m), 6.1 ft (1.8 m) with a flexibility ratio of 81%, if a trenchless installation method is used (Figure 5-16b). In fact, the cost for this configuration is about 93% of the cost of the configuration shown in Figure 5-16a. The imposition of a larger surcharge could be used to further encourage such a solution, as shown previously.

It is emphasized that even small changes in circumstances of the permit application can alter the results obtained. For example, if fewer above ground units are required in the planning for placing electric lines underground the accident costs associated with this addition are reduced. Likewise if the probability of installation is increased, the influence of the proposed future addition on the outcome of the optimization process is increased.

SECTION 6: FINDINGS AND CONCLUSIONS

A modeling method to find optimal configurations for subterranean utility installations in the transportation right of way has been developed and implemented as a PC-based software system. A basic premise of this model is that a “total societal cost” may be defined and calculated, and furthermore that by choosing a corridor configuration minimizing this function allocation of space within the corridor is optimized. As would be expected, the optimal solution represents the smallest possible cost, but this cost is not necessarily the sum of absolute minimal costs for all utilities installed. Crowding may force some utilities to locate in relatively expensive positions, in order to satisfy constraints.

The model and associated software are capable of treating overall corridor design, additional installations and configuration evaluation. Because the optimization process typically identifies a number of solutions with minimal total societal cost, several parameters intended to further describe configuration characteristics have been defined. An important subsidiary component of this work has been the development of a procedure to model the location sensitive costs associated with utility placement. Finally, several example applications have been explored and discussed.

The following observations were made during the course of this research:

- Uncertainty in the location of previously installed utilities (failure to document location, difficulties in maintaining installation accuracy) and the magnitude of the task of quantifying position sensitive costs form two significant barriers to full implementation the methodology described here.

- The importance of obtaining a good model for the cost function cannot be overemphasized. This observation includes the issue of the assumed length for the service life of the corridor since longer spans tend to increase the importance of accident and access costs.

- The stakeholders are responsible for the data input. This fact means that it is the user of the model who must ultimately choose the information input and bears the final responsibility for interpreting the results obtained.

- Agreement among all stakeholders regarding the original modeling assumptions is an important step in the utilization of the program. If agreement is reached successfully then the results of the simulation trials can become a basis for a document of understanding regarding proposed installations, including reimbursements and other considerations.

- Although total societal costs were investigated as the target for optimization, it is possible that individual utilities will not receive equitable treatment under this strategy.

Extended applications for model and programs

Although the intent of the program has always been to find optimal configurations, it should be noted that the program can function equally well to provide an assessment of any configuration (or a group of alternatives) regarding comparative costs and other considerations of interest. In fact, a direct use of the program is to determine whether or not some particular configuration obeys the constraints imposed, without consideration of cost. One example of this type of application is to develop a benefit/cost factor to justify an optimally planned corridor.

Other program applications include:

1. Growth of corridor by evolution

A question of practical interest to this investigation concerns the cost savings that may accrue from application of the program. By comparing a "first come-first served" approach to planned corridor development, an assessment of potential savings can be obtained. Suppose a group of utilities has been scheduled for occupancy of a new corridor. Given the opportunity, the first of these would be installed in the best location, specific to that facility. It is noted that this location will not necessarily be optimal in the sense of this report. A utility might choose to look for the location involving least installation expense and ignore other considerations (this discussion is continued under "Alternative search methods" below).

The next utility to be installed will have to be located at the best available position, but not conflicting with the first. This location can be determined by the same procedure as discussed above. This logic extends to each successive utility in the group scheduled for installation. As long as the corridor is not heavily occupied, there is some possibility of finding low cost locations, even for the last utilities to be installed. Very dense occupation is likely to result in limited opportunities for optimal installation, however. In much the same way, the program can be used to compare the advantages of planning versus not anticipating later additions.

2. Candidates for relocation

A possible application for the program developed here is to select the most logical utility candidate for relocation in situations where multiple opportunities exist. This task (which was not examined during this investigation) would involve setting up several relocation problems and comparing the results obtained. Here, as in all such “what if” questions, the use of non-dimensional ratios is extremely important to develop valid comparisons between different situations. It is noted that the alternative to not relocate anything should also be considered along with the possibility of relocating several facilities simultaneously.

3. Sensitivity studies

In most modeling efforts, the challenge of calibrating the model – determining exactly the influence or importance of parameters that may not be well known- can be overwhelming. One alternative is to first investigate how sensitive the results are to a particular parameter, so that no effort is wasted in accurately determining quantities with minimal influence. Several questions were explored using this technique during the conduct of this research project (for example, the influence of the “inconvenience” factor). It should be noted that the program can be used at anytime to help answer this type of question as uncertainties arise.

4. Reimbursements

A logical application for the programs developed here is in the assessment of reimbursements. Although regulations may necessitate reformulation of the cost function (societal cost is not meaningful here), examining optimal relocation strategies may be useful in minimizing reimbursement charges.

5. Alternate search methods

It was observed when pursuing the planning model in Section 5, that an evolutionary type search can be a highly efficient method of configuring the corridor under some circumstances. This method was expanded by considering all possible ordering for the installation group, and it was found that the minimum total cost for the corridor configuration could be substantially reduced for some selection sequences. Furthermore, in some cases, feasible configurations could be found for a group of utilities that were not identified by the planning program, because much smaller step sizes can be used without consuming a large amount of computational time. While it may be possible to obtain better results with this evolutionary approach, there is no guarantee that a still better solution could not be obtained by using very small step sizes with the planning program. There is however a practical limitation to this argument, not only do small step sizes require more computation time but also the overall accuracy of placement is limited. It should also be noted that the evolutionary model may well produce configurations which lack balance, in that the last facilities added are placed in very disadvantageous positions. Resolution of the issues raised here appears to be a suggestion to treat the evolutionary program as an alternative method, complimenting the planning program. If the evolutionary program finds a better configuration, by employing a smaller step size, then this result warrants further consideration. Finally, in some situations a user could potentially ask the program to search an extremely large corridor, in which case a conventional search may be very time consuming. Here, the evolutionary search could provide a rapid and effective alternative.

6. The PERMIT program

At the request of the FDOT and as a direct consequence of the first programs developed as a part of this investigation, a program strategy has been implemented to make an optimization capability available to a permitting agency during examination of the permit application, which is assumed to be filed electronically (discussed in Section 5). The results of this program are intended to provide a basis for granting or denying permits, by checking physical constraints to installation, safety and total cost. The advantage of such a program lies in the ability to examine a very large set of possible installation configurations. In cases where no basis for a simple decision is apparent, a report of this fact is made so that other steps can be taken. The ability to expand occupancy of a corridor at some later date is yet one more consideration relating to the quality of any proposed solution, and this concept is explored as well. The program and examples presented here represent a prototype effort with sufficient generality to be applicable in widely varying circumstances.

An electronic based data gathering and formatting component has been combined with an optimizing function and a prototype program has been furnished to the Department under separate cover. The program capabilities were demonstrated by an elementary example and then extended to include allowances for future installations. The final analysis obtained consists of a set of solutions, ranked according to economic efficiency and flexibility, to facilitate the final permit decision.

The principal benefit of automating the permitting process in combination with an optimization step derives from the ability to examine a large set of possible configurations. Not only are safety and conflict issues considered, but also it was demonstrated that the introduction of information regarding future planning may reveal the desirability of retaining some space for later additions. Furthermore, the ability to assess a large number of cases rapidly means that alternative scenarios for the same problem could be investigated. For example, while a utility may express a preference for one type of installation, it is possible to examine a number of different methods.

As with any software tool of this nature, there exist some operational limitations. Because a large amount of data is required initially, it would be highly desirable to expand the program to include automated access to databases containing relevant information. It appears that access and availability of these sources is narrow at present, but may expand in the future. Another serious limitation is concerned with the accuracy of data regarding location of existing facilities within the corridor. Subsurface utility engineering (SUE) is a rapidly developing discipline, and will certainly affect the predictive capabilities of the program demonstrated here.

Recommendations for future research

As a result of this investigation, several recommendations for further study have been developed.

1. <u>It is recommended several potential improvements to the existing programs be considered for future expansion of effort:</u>

a) It is likely that other software packages could be identified that contain relevant data as well as computational capabilities. Direct linkage to these packages may prove desirable and should be explored. Likewise, there may be databases that are directly accessible (presently or in the future), containing useful information, as for example archived unit cost data.

b) Other investigations may offer information and techniques relative to the present effort. For example, an area currently being explored is automated data storage regarding facilities locations.

c) As the software capabilities for optimal placement grow, it may be profitable to explore moving to a web based service for performing calculations. In addition to allowing more oversight of the type of work being requested, an in-house computational facility would also allow data capture and archiving.

d) Initial attempts to construct a permit program were successful but this effort will require further improvements and modifications. It is recommended that this effort receive high priority. Obviously, the development of such a package would include substantial testing, verification and documentation. Provisions should be made for long term maintenance and upgrades.

e) During the course of this investigation several issues were identified as potential problem areas and examined, but left unresolved, to be the subject of continued investigation. Some of the issues (which have not been mentioned elsewhere) include:

Inclusion of shoring slope angle (function of soil type)
Maintenance of traffic (modeling function required)
Non-circular facility conduits.

Default data for frequency of access
Relationship between search step size and installation tolerance
Vertical riser costs for above ground facilities

2. Investigation of advanced techniques for optimization

At several points in this report it was noted that one direction for the research had been chosen over another, especially regarding optimization and the methods of evaluating the cost function. There are several alternative methods that could be explored further. These methods are included in the general topics of advanced optimization algorithms (simulated annealing, Monte Carlo techniques, genetic algorithms, etc). Furthermore, there exist methods for handling uncertainty in the available data, including decision-making strategies, application of fuzzy logic, game theory and data mining. It is not obvious that these methods will lead directly to better methods for the current project but nonetheless the potential application of each should be considered. Any promising methods could also be incorporated into the user package described above. It should be noted that one step in this direction has already been taken by the investigators and that this effort has resulted in a Master's thesis (as mentioned earlier).

3. Accidental damage data for cost function

As was pointed out in the body of this report, one of the least certain components of the cost modeling was that associated with the part of the cost function devoted to damage due to excavation. This part of the model could be improved by a separate study of incidence rates and cost associated with such damage and revisiting the underlying modeling assumptions. It is possible that better types of models could be developed, using statistical techniques. Before proceeding however, it would be wise to devote more effort in a sensitivity study of this parameter.

4. Constructability

One issue considered only briefly during this investigation is that of *constructability*, ensuring that the method and the timing of installation of a particular utility is compatible with other ongoing work as well as with previously installed facilities. Included in this issue are questions concerning

a) Location constraints: To what extent is stacking of facilities permitted? Can vertical risers be rerouted when stacking is allowed? Is joint trenching encouraged and how is the cost function modified? How does flexibility in clearance constraints affect the final outcome?

b) Construction limitations: How are construction clearance rules modified by shoring? What is the effect of local obstructions on overall planning? What are the consequences of installation in medians or under sidewalks? How does the order of installation affect the attainment of optimal configurations?

c) Uncertainty of location of installed facilities: As discussed elsewhere, once a utility has installed facilities the location of these conduits is to a degree uncertain. Thus, during future construction events there exists a possibility of increased damage events. Furthermore, installation of additional facilities at planned locations may not be possible due to unplanned occupancy. The current approach to this problem is to enforce a zone of no construction, but such action may be wasting valuable resources. A combination of advanced locating techniques (subsurface utility engineering) and improved record keeping may reduce costs and improve corridor configurations.

5. Advanced strategies for installation

Although it may be possible to use the current software to approximate cost saving approaches to installation, the possibilities of common trenching or the benefits of undergrounding aerial electrical transmission lines has not been extensively considered here. Construction of the cost function including these and similar ideas will need to be reconsidered. Similar issues apply to totally specified configurations, in order to ensure that an optimum is attained.

6. Decomposition of overall installation into smaller sections

The software package as currently constituted can address sections of installation work along linear portions of the roadway. Modest horizontal curvature is allowed, but no provisions are made for intersections, conflicts or other situations that call for abrupt changes in the installation configuration (some consideration of routing around large conflict boxes was attempted). Unfortunately most projects have at least some instances of these limitations. Thus it is not possible to optimize the entire installation but only to sum the results for individual sections. Consideration should be given to this particular issue to ensure that an overall optimal configuration results.

REFERENCES AND REVIEW OF LITERATURE

A review of the literature pertaining to the accommodation of utilities in the transportation R//W yielded very few references to work directly related to optimal organization of facilities.   A detailed review of the entire field of utility accommodation was not attempted; rather a brief discussion of recent work closely related to this study is given below, broken down by subject area

1. Utility accommodation [1-17]

The involvement of governmental agencies in managing utility use of right of way corridors has a long history. Much of the background for these policies is the result of efforts to develop effective utility accommodation policy, supported by the federal government. The states have been asked by the federal government to have some form of utility accommodation policy in effect (here, the FDOT Utility Accommodation Manual is of particular interest [16]). Accompanying these policies are appropriate statutory references, and a variety of systems involving permits and fee structures, unique to each state. No attempt will be made to review statutory authority here (policy varies from state to state).

1. A Policy on the Accommodation of Utilities on the National System of Interstate and Defense Highways, American Association of State Highway and Transportation Officials, Washington, D.C., 1959.

2. A Guide for Accommodation Utilities on Highway Rights-of-Way, American Association of State Highway and Transportation Officials, October 1969.

3. Accommodation of Utility Plant Within the Rights-of-Way of Urban Streets and Highways State-of-the-Art, Special Report No. 44, American Public Works Association, July 1974.

4. Policy for Accommodation of Utilities on Highway Rights-of-Way, NCHRP Synthesis No. 34, Transportation Research Board, Washington, D.C., 1976.

5. Utility Relocation and Accommodation: A History of Federal Policy Under the Federal-aid Highway Program, Part I: Utility Relocation, FHWA, 1981

6. Joint Usage of Utility and Transportation Corridors, C. H. Klohn, ed., ASCE, Sept 1981

7. A Policy on the Accommodation of Utilities Within Freeway Right-of-Way, American Association of State Highway and Transportation Officials, Standing Committee on Highways, 2005.

8. Federal-Aid Highway Program Manual, Volume 6, Engineering and Traffic Operations, Chapter 6, Railroads and Utilities, Section 3, Utilities, Subsection 2, Accommodation of Utilities Transmittal 389, HNG-12, published in 23 CFR 645 B, U.S. Department of Transportation, September 6, 1985.

9. Report of the AASHTO Task Force on Corridor Preservation, July 1990

10. Highway /Utility Guide, Office of Technology Applications, U.S. Department of Transportation, Pub. FHWA-SA-93-049, June, 1993

11. Highway Utility Guide, FHWA, 1993

12. AASHTO Task Force on Fiber Optics on Transportation Rights-of-Way, Guidance on Sharing Freeway and Highway Rights-of-Way for Telecommunications, American Association of State Highway and Transportation Officials, Washington, D.C., 1996.

13. Shared Resources: Sharing Right-of-Way for Telecommunications Guidance on Legal and Institutional Issues, Report FHWA-JPO-96-0015, U.S. Department of Transportation, Federal Highway Administration, 1996.

14. R.L. Williams, Longitudinal Occupancy of Controlled Access Right-of-Way by Utilities, Synthesis of Highway Practice 224, National Cooperative Highway Research Program, National Academy Press, Washington, D.C., 1996.

15. Federal Aid and Design Division, Utility Adjustments and Accommodation on Federal-Aid Highway Projects, Fourth Edition, Federal Highway Administration, Washington, D.C., March 1998.

16. Utility Accommodation Manual, Florida Department of Transportation, Jan, 1999.

17. Program Guide: Utility Relocations Adjustments, and Accommodation on Federal-Aid Highway Projects Fifth ed. FHWA-IF-01-006, Jan 2001

2. Cost information [18-21]

Cost information relevant to this study includes methods for developing aggregated unit cost estimates. In addition to the references mentioned here, there are numerous sources of archived data available from various agencies including the FDOT (see, for example, *Average Low Bid Unit Price - Construction – (Statewide)*, TxDOT, http://www.dot.state.tx.us/business/Avgd.Htm)

18. Understanding and Using Unit Costs, Chpt. 44 Montana Right-of–Way Utilities Manual (undated)

19. Understanding the Unit Cost Process for Utility Relocation Projects
Joseph Eve & Company, CPA, (undated)

20. Zhao, J.Q. and Ranjani, B., Construction and Rehabilitation Costs for Buried Pipe with a Focus on Trenchless Technologies, Institute for Research in Construction, Research Report No 101, National Research Council of Canada, June, 2002.

21. RSMeans Heavy Construction Cost Data, E.R. Spencer, ed., 19th Annual Edition, Reed Construction Data, 2005.

3. Accidents [22-25]

An important area for consideration in the present study is the cost analysis of traffic accidents with above ground utility facilities. Although it is difficult to attach a value to liability claims arising from death, injury or property damage, several models for analyzing cost benefits associated with moving hazards have been formulated. A comprehensive review of modeling for crashes has been presented in [23]. The RSAP program is an advanced probabilistic model utilizing Monte Carlo simulations to evaluate cost/ benefits for hazard removal. In the present research, the methods of a predecessor model to the RSAP program were utilized [22], because a direct computational algorithm was required for the programs developed.

22. Task Force for Roadside Safety of the Standing Committee on Highways Subcommittee on Design, Roadside Design Guide, AASHTO Appendix A: A Cost-Effectiveness Selection Procedure, Jan 1996

23. Roadside Safety Analysis Program (RSAP) - Engineer's Manual, NCHRP Report 492, Transportation Research Board of the National Academies, 66p., 2003,

24. A Policy on Geometric Design of Highways and Streets – 2001, American Association of State Highway and Transportation Officials, Washington, DC, 2001

25. Roadside Design Guide 2002. American Association of State Highway and Transportation Officials, Washington, DC, 2002

4. Damage due to excavation [26-31]

Although often discussed, there is little data to support cost estimates incurred when excavation damages a preexisting utility. Even the rate at which such accidents occur is not well established and only anecdotal evidence is available.

Considerable effort is made to avoid damage incidents, primarily through one-call services and subsurface utility engineering.

Once facilities have been installed in underground locations, it is important to be able to determine at later times this position with reasonable accuracy. This problem has received considerable attention and many companies have emerged to provide this specialized engineering service. A number of techniques can be employed to find and map buried lines including tracers, ground penetrating radar and other similar methods. Typically this operation is performed in advance of excavation around a probable location to avoid accidental damage or conflicts. Most states utilize a "one-call" service so that information regarding the intent to excavate may be passed to potentially interested parties. Additionally many underground facilities are indicated above ground with permanent markers.

The importance of SUE to the current investigation is primarily to gain information about the accuracy of positioning of specific facility conduits. In the research reported here, an important parameter is a differential spatial unit characterizing the smallest significant position increment describing the location of a specific facility, which relates in a complex fashion to the smallest search step size during optimization computations. In this regard, it has been reported that many states required marking an 18 inch zone on either side of a conduit to indicate a region for hand excavation only. Secondly, the accuracy of location of underground lines would be expected to have some influence on the frequency of accidental damage to existing facilities during excavation.

a) One-call

26. Common Ground: Study of One-Call Systems and Damage Prevention Best Practices, U.S. Department of Transportation, August 1999

b) Subsurface utility engineering (SUE)

27. Zembillas, N., Subsurface Utility Engineering (SUE). Proceedings of the Ninth National Highway/Utility Educational Conference, 2001

28. Cost Savings on Highway Projects Utilizing Subsurface Utility Engineering, Purdue University, Publication No. FHWA-IF-00-014. 1999 (Executive summary is available on the Web at:www.fhwa.dot.gov/programadmin/PUS.html)

c) Data needs

29. Quiroga, C., and R. Pina. Utilities in Highway Right of Way: Data Needs and Modeling. In *Transportation Research Record: Journal of the Transportation*

Research Board, No. 1851, TRB, National Research Council, Washington D.C. , 2003, pp. 133-142.

30. Quiroga, C., C.D. Ellis, and S.Y. Shin. Integrated Platform for Managing Utilities Along Highway Corridors. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1768*, TRB, National Research Council, Washington D.C. , 2001, pp. 233-241.

31. Quiroga, C., and R. Pina. Issues in Automating Utility Permits at Transportation Agencies. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1890, TRB, National Research Council, Washington D.C. , 2004, pp.143-151.

5. Alternative methods of installation [32-44]

While the burial of utility facilities can be accomplished by excavating and developing trenches, numerous trenchless alternatives have been proposed. Currently, several installation methods do not require opening the ground including directional drilling, jack and bore, microtunneling, pipe burst, etc. The literature in this area is large and no comprehensive review will be attempted here.

Along with these conventional schemes for burying utility facilities along the road way several alternative modes for locating facilities have been proposed. A comprehensive review of these ideas was undertaken by Kuhn [32] in 2002 (the source of many references mentioned here). Several concepts are noteworthy.

32. Kuhn, B. et al, Utility Corridor Structures and Other Utility Accommodation Alternatives in TXDOT Right of Way, Texas Transportation Institute, FHWA/TX-03/4149-1 Sept 2002

Some schemes are directly concerned with the manner of organization of the configuration as a strategy.

a) Common trenching

In some circumstances, several utilities may opt to cooperate during initial installation by excavating a <u>common trench</u> and jointly laying their facilities in specific positions. Obviously, cost savings are achieved by this action and furthermore the location of each utility with respect to others in the common trench is better known. With regard to the present study, common trenching is of interest as one form of interaction in the cost function to be defined, since how the various facilities are organized with respect to one another affects the cost of access.

33. M. Tubb, “Joint Trench Construction, Solves Utility Dilemma in High-Tech Corridor,” Underground Construction, Volume 54, Number 9, Pages 27-32, Oildom Publishing Company of Texas, Houston, Texas, September 1999.

34. W. J. Boegly, Jr., W. L. Griffith, and A. L. Compere, “Common Trenching-State of the Art,” Transportation Research Record 571, Transportation Research Board, National Research Council, Washington, D.C., 1976.

35. R. Murray, “Joint trenching,” *Municipal News*, Union Gas, March 2002, p. 2.

36. “Benefits of a Joint Trenching System,” *The Conduit*, TXU Electric & Gas, Vol. 1, Issue 1, May 2000, p. 3.

37. “Enbridge Consumers Gas Joint Utility Construction in Residential Subdivision,” Builder’s Technical Bulletin, Enbridge Consumers Gas, December 2001.

38. OUCC Joint Trench Examples, Oregon Utility Notification Center Website, http://www.digsafelyorgon.com/digsafe/ds/ds_joint_trench.htm, 3 July 2002.

39. “Joint Trenching: Construction Facts,” Gas Utility Manager, James Informational Media, Inc., Des Plaines, IL, September 1999.

b) Utilidors

Another alternative to arbitrary location is for a regulatory body to specify a particular configuration. A variation of this method is to place the utilities in underground structures (utilidors).

40. Boegly, W. J. and Griffith, W. L., Underground Utility Tunnels, Mechanical Engineering, p27-32, Sept. 1971

41. Departments of the Army and the Air Force, Arctic and Subarctic Construction Utilities, Technical Manual, Army TM 5-285-2, Air Force AFR 88-19, Volume 5, US Department of Defense, Washington, D.C., August 1987.

42. T. R. Shaw, Under the Magic Kingdom, The Hidden Mickey Website, http://www.hiddenmickey.org, 2001.

43. Perma-Pipe, Heating and Cooling Services; Tunnels; Utilidor, Perma-pipe a subsidiary of MFRI, Inc., Website www.permapipe.com, 2001.

c) Undergrounding electric utilities

In contrast to facilities which are always located underground, electric utilities have traditionally used aerial utility poles to convey power. Often other telecommunication facilities share space so that an above ground corridor is formed. Early in the history of the distribution of electric power, Thomas Edison advocated buried electric service, for practical as well as aesthetic reasons. At present many utilities are considering underground existing facilities. Although costly, this alternative is widely debated today. In many new installations, electric utilities are initially placed underground.

44. Report on Cost-effectiveness of Underground Electric Distribution Facilities, Florida Public Service Commission, Dec. 1991

APPENDICIES

Appendix A: Operation of facility placement program

This subsection is intended to summarize briefly the operation of the program. A more detailed account may be found in the Tutorial (provided to the FDOT under separate cover). The Excel/Visual Basic package can be easily run on most current PC machines and requires no special add in packages. The program begins with a splash screen as an introduction. The following pages are included. Sheets intended for user access:

1. HOME- This is the main page, intended to guide the user through the process of completing a project. Near the top is an indication of the current status of the workbook. In order to proceed, the work book must be "unlocked and ready for data entry". The user will also notice an OPTIONS command button. This button will bring up a user form to allow certain changes in the overall operation of the work book (discussed further below under Advanced Features). A sequence of three subtitle boxes appears, referring to the corridor data entry, the utilities data entry and the analysis phase of the computations. A "READY" or a "NOT READY" status indicator is included in each box so that the user can tell at a glance if more information is required to proceed in these areas. The first two of these selections require data entry on the CORRIDOR and UTILITIES sheets, as described below. The Analysis section can be started from the HOME page, but the final output is directed to the RESULTS page.

2. CORRIDOR – On this sheet a number of parameters are entered as initial data and checked for consistency. The command button UPDATE will initiate a record, but also this sheet will be updated on exit. Only when this sheet is adequately filled out will the appropriate section on the HOME page indicate this with a READY status.

3. UTILITIES – This sheet permits the entry of information regarding specific utilities and will ultimately determine the constraints and costs for each. There are a number of points where direction is provided if the sheet does not register as ready for computations.

4. RESULTS – On this sheet is presented the results and accompanying analysis of the characteristics of the problem solution.

Sheets not generally intended for user modification:

5. CLEARANCE – This page contains the clearance rules for separation distances between utilities. The current default values are those imposed by Pinellas County, Florida county (simplified conditions have been used in some of

the programs however). The default values can be easily modified and then restored by a command button on the page.

6. ACCIDENT - This page contains data and parameter determination procedures extracted from Reference 22. There is no part of this page that requires user input. Should another accident package be desired for application, a compatible, direct substitution of the entire page would be required.

7. STORAGE - On this page provisions are made to store the most important values acquired by the program. Other than for possible reference, the user should not need to consult this page and normally nothing should be modified here by any direct action. There are exceptions, in that this page also contains the universal constants required by the program, which could conceivably require modification at some later date.

Appendix B. Provisional Database

While the best results from the programs will be obtained when the most realistic values for various parameters are employed, it is clear that at least some of these values are uncertain. The point has already been made that the stakeholders themselves come to eventual agreement on the various parameters necessary to construct the cost function. Initially however, some values are required to utilize the program, even on a trial basis. To remedy this deficiency, a tentative set of default values can be obtained from a provisional database included as part of the software. This extension includes the simplifying assumptions discussed earlier. The purpose of this appendix is to provide insight into the structure of the cost function based on current understanding and information. It is likely that the information used to develop this representation will change and improve with experience.

In addition to fundamental constants, adjustment parameters etc., four types cost information have been identified and can be described as follows:

1. Initial subsurface installation costs: For trench type installations this cost will be primarily a function of vertical position (trenchless installations are much less dependent on position but cost must still be included). Factors to consider include proximity to pavement, presence of subsurface water, the need for shoring, savings due to common trenching or stacking, and cost of a vertical riser (including material costs), if any. This cost is immediate and one time only. Renovation costs can be addressed in much the same way except that this event is in the future.

2. Routine access to installed utility: Excavation to access an installed line is treated much like open trench installation, and so will be a function of both vertical (excavation cost with depth) and horizontal position (presence of pavement cover – expected to be a step function variation). Access costs are expected to be recurring, with some specified annual rate. If the installation is initially free from pavement cover but later paved over, the access cost may increase, but for only a portion of the service life.

3. Accidental damage during routine excavation: A charge for damage incidents occurring during excavation around existing facilities should be included with both access and installation events. In addition to dependence on the rate of these events, this cost is primarily a function of excavation depth relative to location of existing lines. Unfortunately little information regarding frequency or severity of such accidents exists, as discussed in Section 2.

4. Accidental damage due to traffic encroachments with impact: The program requires a deterministic function of horizontal position, pertaining only to above ground facilities.

Sources of information

During this investigation, several attempts were made to gather necessary information, including interviews, surveys and research of the literature. While all methods yielded some information, very little useful data was obtained directly from the industry. It should be noted that there exist several types of commercial estimators [21].

Use of consultants

The methodology of this research effort requires the definition and evaluation of an overall cost function. The need for valid cost information was established early in the conduct of this research, along with the problems attendant in obtaining such information. Once this information is available, it is relatively easy to incorporate into any of the various programs developed here. The results of many discussions with practitioners as well as the disappointing return of information from survey attempts leads to the following reasoning:

> 1. There exists at least a limited body of qualitative information regarding installation/maintenance/access costs, which can be found in reports, and estimating guides, or developed by inquiry. Furthermore, the literature contains some useful data regarding the incidence and importance of accident costs.
>
> 2. Although difficult to develop, there exists a substantial amount of detailed information regarding installation and access costs. Unfortunately, this information is widely dispersed and is very difficult to obtain. In some cases, such information is considered to be proprietary and furthermore some entities possessing information are reluctant to share, due to suspicions as to ultimate use.
>
> 3. Each project will be unique, thus the cost function will be specific to that project. Those entities (stakeholders) involved in the design and planning process should be expected to provide (and justify) the required data.
>
> 4. The facility owners may not be the best sources of cost information; rather the firms performing engineering services related to such projects may actually have the best information.

Accordingly, the following concept could be used to generate a provisional data base of information. One or more engineering firms which normally provide design services to utilities anticipating new facility development could be contracted for the task of "estimating" particular scenarios as specified by the group managing the program operation (in a realistic format closely resembling an actual request for services). From the results of these service contracts, cost function data can then be extracted for use in the general data base. In this manner, a practitioner wishing to utilize the methods of this report would have access to a generalized data base. At any time more accurate or specific data becomes available such information could be directly substituted.

A portion of the work reported here was an attempt to try this method, and this approach met with some success. A local engineering firm was engaged by subcontract to provide pricing for several scenarios. Deliverables included a report (furnished separately to FDOT) with accompanying spread sheets analyzing costs for each scenario, along with general commentary and explanations. From this work it was possible not only to generalize costs to several representative functions but it was also possible to derive subsequent spreadsheet analyses for various situations. The overall advantage of this approach is that costs developed for estimating purposes are likely to be very realistic. Obviously, maintenance of the data for currency and experience is essential.

Spreadsheet formulation of installation costs

As an example of application of the data obtained from the consultant, a prototype version spread sheet version of an installation calculator was developed (including trenchless installations), in part to satisfy the needs of the automated permit model. A sample page from this work is shown below. Because of space limitations, only three parts of the sheet are shown. At present this work is promising but has not been fully implemented, and should be viewed as tentative. An attempt was made to develop several simple empirical formulas to represent installation costs for open trench techniques for several different circumstances (units of K$/mile) using this spreadsheet formulation. Two empirical formulas were generated for open trenches assuming both sides shored:

installation unit cost =4.317*y+725.95 (under pavement, y in inches)
installation unit cost =4.313*y+604.08 (not paved, y in inches)

While this result is useful, it is cautioned that considerably more effort will be needed to ensure the validity of this information.

INSTALLATION COST WORKSHEET

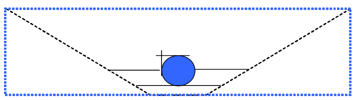
DATA ENTRY				
		Xp=	15.00	ft
		Yp=	3.00	ft
		COVER=	3.00	ft
		D=	0.58	ft
		RATIO=	2.00	:1
		SLOPE=	0.50	ft
		EDGE=	11.00	ft
		R/W=	21.00	ft
		R=	0.29	ft
	SIDE OF PIPE	b1=	1.00	ft
CUT	BASE-STRUC	b2=	1.50	ft
CUT	STRUC-FRICT	b3=	2.00	ft
CUT	LAP	b4=	0.50	ft
END	ADD AT EDGE	b5=	0.50	ft
	DEPTH FOR SHORE		5.00	ft
	BED	v1=	0.50	ft
	BASE	v4=	1.00	ft
	STRUCT	v3=	0.50	ft
	FRICTION THICK	v2=	0.25	ft
	SHORE ADD 3+1	v5=	4.00	ft

OFFSET FROM R/W 20.71

POSITION	**FULL L**	**VERT L**	**FULL R**	**VERT R**
TOP X	7.71	13.71	22.29	16.29
TOP Y	0.00	0.00	0.00	0.00
LOW X	13.71	13.71	16.29	16.29
LOW Y	3.79	3.79	3.79	3.79

TRENCH CUT

CASE I SLOPE BOTH SIDES



TRENCH IS DIVIDED INTO LEFT AND RIGHT HALVES

POSITION	**FULL L**	**FULL R**
TOP X	7.71	22.29
TOP Y	0.00	0.00
LOW X	13.71	16.29
LOW Y	3.79	3.79
PAVE	PAVE	CLEAR
Y SHORE	FALSE	FALSE
R/W SHORE	NA	CONFLICT
VALID	FALSE	FALSE
X BASE LEN	NA	NA
X STRU LEN	NA	NA
X FRICT LEN	NA	NA

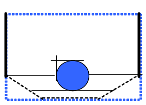
MEANS	6"	
EXCAV	9.40	
BED	4.38	
	13.78	
(BACKFILL FROM STOCK)		
FOR COMPARATIVE PURPOSES ONLY		
COST	**19.83**	$3.30 per inch
NRC		$20.09 per inch

QUANTITY	**FULL L**	**VERT L**	**FULL R**	**VERT R**	**UNITS**	**UC**	**COST**	**UNIT**
MOT					0	0.31	0.00	EA
Y SHORE LE	0.00		0.00		0.00	5.00	0.00	LF
BED	0.90		0.90		0.07	7.30	0.48	CY
HAUNCH	0.75		0.75		0.06	12.19	0.68	CY
EXCAV	14.52		14.52		1.08	6.54	7.04	CY
BACKFILL	12.88		12.88		0.95	12.19	11.63	CY
BASE	NA		NA		0.00	11.22	0.00	SY
STRUC	NA		NA		0.00	6.11	0.00	SY
FRICTION	NA		NA		0.00	8.25	0.00	SY
						TOTAL	**NA**	**PER FOOT ALONG R**

IF "NA" THEN CANNOT INSTALL BY THIS ME

a) open trench installation

CASE II SHORE BOTH SIDES



TRENCH IS DIVIDED INTO LEFT AND RIGHT HALVES

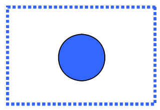
POSITION	**FULL L**	**VERT L**	**FULL R**	**VERT R**
TOP X		13.71		16.29
TOP Y		0.00		0.00
LOW X		13.71		16.29
LOW Y		3.79		3.79
PAVE		CLEAR		CLEAR
Y SHORE		TRUE		TRUE
R/W SHORE		NA		CLEAR
VALID		TRUE		TRUE
X BASE LEN		0.00		0.00
X STRU LEN		0.00		0.00
X FRICT LEN		0.00		0.00

QUANTITY	**FULL L**	**VERT L**	**FULL R**	**VERT R**	**UNITS**	**UC**	**COST**	**UNIT**
MOT						0.31		EA
Y SHORE LEN		7.79		7.79	15.58	5.00	77.92	LF
BED		0.90		0.90	0.07	7.30	0.48	CY
HAUNCH		0.75		0.75	0.06	12.19	0.68	CY
EXCAV		5.52		5.52	0.41	6.54	2.68	CY
BACKFILL		3.88		3.88	0.29	12.19	3.50	CY
BASE		0.00		0.00	0.00	11.22	0.00	SY
STRUC		0.00		0.00	0.00	6.11	0.00	SY
FRICTION		0.00		0.00	0.00	8.25	0.00	SY
						TOTAL	**85.26**	**PER FOOT ALONG R**

IF "NA" THEN CANNOT INSTALL BY THIS ME

b) shored trench installation

JACK AND BORE, TUNNEL, DIRECTIONAL DRILL



POSITION	VERT	
TOP X	15.00	
TOP Y	2.71	
LOW X	15.00	
LOW Y	3.29	
PAVE	FALSE	
Y SHORE	FALSE	
R/W SHORE	NA	
DIAMETER	7.00	INCHES

	FACTOR(NCR)
MICRO TUNNEL	49.67
H DIRECTIONAL DRIL	15.50
JACK AND BORE	22.38

TOTAL	347.68	PER FOOT ALONG R
TOTAL	108.47	PER FOOT ALONG R
TOTAL	156.68	PER FOOT ALONG R

CURRENTLY, ALWAYS VALID

c) trenchless installations

Figure A2-1: Spreadsheet demonstration of installation cost calculation for three alternative methods.

Constraint information

Vertical Separation - BB

BURDEN	TYPE	CABLE	GAS DIST	GAS TRANS	POTABLE	POWER DIST	RECLAIM	SANITARY	STORM	TELECOM	POLE
CABLE	1	12	12	12	12	12	12	12	12	12	24
GAS DIST	2	12	12	12	12	12	12	12	12	12	24
GAS TRANS	3	12	12	12	12	12	12	12	12	12	24
POTABLE	4	12	12	12	6	12	6	18	18	12	24
POWER DIST	5	12	12	12	12	12	12	12	12	12	24
RECLAIMED	6	12	12	12	6	12	6	6	6	12	24
SANITARY	7	12	12	12	18	12	6	12	12	12	24
STORM	8	12	12	12	18	12	6	12	12	12	24
TELECOM	9	12	12	12	12	12	12	12	12	12	24
POLE	10	24	24	24	24	24	24	24	24	24	24

Horizontal Separation - BB

BURDEN	TYPE	CABLE	GAS DIST	GAS TRANS	POTABLE	POWER DIST	RECLAIM	SANITARY	STORM	TELECOM	POLE
CABLE	1	12	24	24	12	12	12	12	12	12	24
GAS DIST	2	24	36	36	36	36	36	36	36	36	24
GAS TRANS	3	24	36	36	36	36	36	36	36	36	24
POTABLE	4	12	36	36	12	30	24	36	24	12	24
POWER DIST	5	12	36	36	30	12	30	30	12	12	24
RECLAIMED	6	12	36	36	24	30	12	24	24	12	24
SANITARY	7	12	36	36	36	30	24	12	12	12	24
STORM	8	12	36	36	24	12	24	12	24	12	24
TELECOM	9	12	36	36	12	12	12	12	12	12	24
POLE	10	24	24	24	24	24	24	24	24	24	24

Figure A2-2: Matrix illustrating the clearance rules imposed for utilities for Pinellas County, FL.

Table A2-1: Program constants

The encroachment rate for crashes	ENCR - 0.0003 - #/YR/MI/(CARS/DAY)
The swath width for crashes	SW - 3.6 - FT
Maximum damage for excavation	MAXDAM - 1000 - k$
Frequency of damage for excavation	FDAM - 0.01
Length of access trench	Leq - 30 - FT
Clearance for stacking	STACK CLEARANCE - 6 -IN

Spreadsheet formulation of clear zone computation

As a part of this investigation, the imposition of clear zone requirements in the context of the program was studied. In some circumstances, waiving or omitting the requirement may be necessary to obtain any solution. If however the clear zone is to be imposed, either the user must supply this information or the program must automatically choice the appropriate value. Obviously, it is highly desirable that the latter feature be included in a final software package but the options to enter manual or ignore completely should be retained.

To accomplish the task of computing the clear zone according to standards, a supplemental worksheet was constructed. Because this particular sheet is generally useful, it has been separately submitted as stand alone software and furnished separately to FDOT. At present this sheet is not attached to the software, but could be at a later date. Clear zone dimensions should be entered manually.

Appendix C. Contact effort

During the course of this investigation, a number of different attempts were made to develop source information through letters of inquiry and survey. In general these contacts produced very little useful information and were abandoned in favor of face-to-face interviews and telephone contacts. For the record the first letter below was sent to state utility engineers and the second to a large, diverse group selected from the membership list of the Florida Utilities Coordinating Committee, along with a survey, also included below.

Letter sent to various state Utility officers

January 10, 2002

The Florida Department of Transportation has begun an exploratory study entitled "Optimal placement of utilities within the FDOT R/W" and has asked the University of South Florida to conduct this research, focusing primarily on new construction. The goal of this study is to suggest a location strategy so that each utility sharing the joint use, right-of-way corridor will be accommodated with minimal interference and sufficient access. Ultimately, we will be interested in renovation and rehabilitation of existing corridors. We are contacting appropriate agencies throughout the U.S. regarding the philosophy and methodology employed to satisfy the needs of each utility as well as the public interest. We would be interested in any insights you might be able to provide, or suggestions as to where we might find information. It would be very helpful to us if you could provide some examples (with diagrams) of the organization of utility corridors along roads in your jurisdiction. These could be typical situations or special problems you have encountered. Permit applications and location studies would also be particularly interesting as we are currently engaged in preliminary information gathering.

We are very interested in understanding constraints and costs associated with the installation, maintenance, renovation and damage of various utilities. If you have any studies related to strategic or optimal organization of utilities that would be extremely helpful. In this regard we are also interested in costs or valuation associated with the following:

- Costs to install utilities
- Closing roads during utility installation
- Traffic control at site during utility installation
- Cutting or other damage to pavement
- Cost of review and permitting
- Safety issues
- Other costs

Perhaps there are other contacts at your agency or appropriate individuals and organizations within your region that might be able to provide useful information for our study. If you could suggest other individuals for follow up questions, please do so. Although time consuming for all involved, studies such as this can eventually lead to more efficient and economical use of resources, benefiting all parties. As this study progresses we will be presenting our findings and soliciting responses. We thank you for your time and effort.

Sincerely,

Stanley C. Kranc
Professor of Civil Engineering
kranc@eng.usf.edu

William A. Miller
Professor of Industrial Engineering
miller@eng.usf.edu

Survey for FDOT Study (sent to select group from FUCC)

Dear

The Florida Department of Transportation has begun a study entitled "Optimal placement of utilities within the FDOT R/W" and has asked the University of South Florida to conduct this research, focusing primarily on new construction. The goal of this study is to suggest a location strategy so that each utility sharing the corridor will be accommodated with minimal interference and sufficient access. As part of this effort, we are conducting a preliminary survey to better understand the needs and constraints of all interested parties. We would appreciate your cooperation in helping us obtain this basic information. Attached is a list of questions that we think are appropriate to your particular group. It may be that more than one type of utility is involved, if so please provide separate information for each type. If you or someone in your group cannot respond to a particular question please indicate the reason or respond "not applicable".

A very important aspect of this investigation is to identify costs specifically resulting from choice of location for particular lines. We recognize that it is difficult to separate or differentiate these expenses by please try to quantify costs as accurately as possible. Any information you can supply will be useful

We are asking also for details regarding contacts at your organization. If you would like to suggest other individuals for follow up questions, please do so. Also if you wish to suggest other contacts outside your organization we would definitely appreciate your help. It would be very useful if you have any internal documents, manuals or standards relevant to utility placement you could share with us. Finally, we solicit your suggestions regarding the questions we are asking. It is highly likely that there exist relevant issues that should be considered further.

Although time consuming for all involved, studies such as this can eventually lead to more efficient and economical use of resources, benefiting all parties. As this study progresses we will be presenting our findings and soliciting responses. We thank you for your time and effort.

Sincerely

S. C. Kranc
Professor

William A. Miller
Professor

OPTIMAL PLACEMENT OF UTILITIES WITHIN THE FDOT R/W

Fall 2001

Conducted by University of South Florida for the Florida Department of Transportation

S.C. Kranc and W. Miller, Principal Investigators (813) 974-5821
Gordon Wheeler, FDOT Project Manager, (850) 414-4366

1. Physical description of your utility:

Utility type- describe completely (ie electric, voltage, gas, pressure, etc)
Location (above or below ground
Exterior Diameter range
Circular or rectangular
Material (PVC, etc)
Is color coding or other tracing used?

2. What type of installation is required?

Underground

Depth of cover requirements
Requirements for separation from other utilities
Lateral or other clearance
Is under pavement location acceptable or desirable?
Vibration constraints
Loading constraints
Minimal radius of curvature
How fragile is this utility (ie puncture, cracking etc)
Is shielding or jacketing utilized?
Are external supports or thrust blocks used?
Environmental constraints (humidity, soil conditions)
Is corrosion a problem (is cathodic protection employed)
Signage
Are there any other constraints on installation?

Above ground

Vertical clearance
Lateral or other clearance
Requirements for separation from other utilities
Vibration constraints
Loading constraints
Minimal radius of curvature
How fragile is this utility (ie puncture, cracking, lightning etc)
Is shielding or jacketing utilized?
Are external supports or guy wires used?
Environmental constraints (humidity, soil conditions)
Signage
Are there any other constraints on installation?

3. What type of access is required

Horizontal (branch connections)
Vertical access (manholes?)
Are there any other access requirements?

4. Costs of installation

Installation method
Installation cost (state basis) as a function of vertical and horizontal position
Expected lifetime
Maintenance costs
Costs associated with relocation
Costs associated with damage
Summarize other costs associated with right of way installations

5. Regulation

Legal or regulatory
Liability or insurance issues?
Safety issues
Security issues

6. Summarize any other constraints or requirements not covered above

7. What would be the optimal location for your utility? (horizontal and vertical position, other factors)