Development of a Two-Stage
Facility Location Model for
ConnDOT's Maintenance System,
Phase One -- Model Development

Final Report

August 19, 1993

JHR 93-221 Project 92-5

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This research was sponsored by the Joint Highway Research Advisory Council (JHRAC) of the University of Connecticut and the Connecticut Department of Transportation and was carried out in the Civil Engineering Department of the University of Connecticut.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
JHR 93-221		

4. Title and Subtitle	5. Report Date
Development of a Two-Stage Facility Location Model for ConnDOT's Maintenance System, Phase One -- Model Development	August 19, 1993
	6. Performing Organization Code
7. Author(s) Gerard M. Campbell and Christian F. Davis	8. Performing Organization Report No. JHR 93-221
9. Performing Organization Name and Address The University of Connecticut Department of Civil Engineering 191 Auditorium Road, U-37TI Storrs, CT 02629	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Connecticut Department of Transportation 280 West Street Rocky Hill, CT 06067-0207	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report presents details of the first phase of a two-phase project that is concerned with developing and using an optimization model representing ConnDOT's maintenance system. The two-stage optimization model allows for changes in the locations of equipment repair facilities and roadway maintenance garages. This is a step beyond the model used in a previous study of ConnDOT's maintenance system, where it was assumed that roadway maintenance garage locations would remain fixed.

The first phase of the current project encompasses model development, identification of solution procedures, and specification of data-gathering plans. In addition to discussing these aspects of the project, this report also outlines the steps planned for the project's second phase. Questions that must be addressed early in the second phase are highlighted in the conclusion section of this report. These questions deal with specific aspects of data-gathering plans, but they should be addressed within the broader context of how ConnDOT intends to use the results of this study.

17. Key Words	18. Distribution Statement
Facility location; Roadway maintenance; Equipment maintenance; Optimization model.	No Restrictions

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	55	

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

ACKNOWLEDGEMENTS

The authors acknowledge, with thanks, the considerable assistance given by personnel of the Connecticut Department of Transportation during the course of this study. Particular thanks are due Dr. Charles E. Dougan and Mr. James M. Sime for their assistance in coordinating meetings, Mr. James F. Byrnes, Jr. and Mr. Ernest N. Herrick for their early support and guidance, and Mr. Louis R. Malerba and Mr. Patrick F. Rogers for their thoughtful comments and insight regarding ConnDOT maintenance operations.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
	VOLUME			
fl oz	fluid ounces	29.57	mililitres	mL
gal	gallons	3.785	Litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

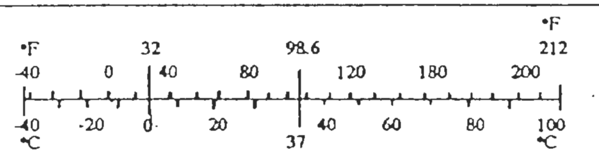
NOTE: Volumes greator than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
	MASS			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

*SI is the symbol for the International System of Measurement

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	MASS			
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
	TEMPERATURE (exact)			
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



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SYMBOLS AND DEFINITIONS

The optimization model's decision variables are as follows:

Y_f = 1 if facility f is kept open, 0 otherwise;

YG_i = 1 if garage i is kept open, 0 otherwise;

A_f = 1 if two work bays are added at facility f, 0 otherwise;

B_f = number of work bays added, above two, at facility f;

AG_i = 1 if two storage bays are added at garage i, 0 otherwise;

BG_i = number of storage bays added, above two, at garage i;

X_{fi} = the proportion of garage i's repair requirements satisfied by facility f;

XS_{ij} = the proportion of roadway sector j's maintenance requirements satisfied by garage i;

T_{fi} = additional equipment going from garage i to facility f due to expansion at garage i (in terms of weighted units of equipment added); and,

TP_{fi} = reduction in equipment going from garage i to facility f due to downsizing at garage i.

The parameters of the optimization model are as follows:

C_{fi} = the total annual cost of transporting all equipment from garage i to facility f for repairs;

D_i = total equipment at garage i;

U_{fi} = the total annual cost of transporting a unit of equipment from garage i to facility f for repairs (this equals C_{fi} divided by D_i);

$TCOST_{ij}$ = the total annual cost of servicing all of sector j requirements from garage i;

K_f = annualized cost of keeping facility f open;

L_i = annualized cost of keeping garage i open;

M = annualized cost of adding two bays at a facility;

N = annualized cost of adding each bay above two at a facility;

MG = annualized cost of adding two bays at a garage;

NG = annualized cost of adding each bay above two at a garage; and

DS_j = the demand in sector j, in terms of equipment required to service that sector;

P_f = repair capacity, in terms of equipment serviceable, if facility f is kept open.

R = repair capacity added by adding two bays;

S = repair capacity added for each bay above two added at a facility;

RG = capacity added by adding two bays at a garage;

SG = capacity added for each bay above two added at a garage;

$XSPACE_i$ = extra space available at garage i.

I. INTRODUCTION

Background

This report presents details of the first phase of a two-phase project. The overall project is concerned with the development and use of a two-stage facility location model representing ConnDOT's maintenance system. The first phase of the project has focused on formulating the model, finding a viable solution procedure, and developing a plan for obtaining required input data. In the second phase of the project, data will be collected and the model will be used to analyze the maintenance system. Although this report focuses primarily on the work done for the first phase of the project, plans for the project's second phase are also discussed in some detail.

This project was undertaken as a follow-up to an earlier study that was completed in 1991. The earlier study, which is detailed in the report by Campbell and Davis (1991), used a single-stage facility location model as the basis for making recommendations regarding the thirteen equipment repair facilities operated by ConnDOT. One of the major shortcomings of the single-stage model was that it did not allow changes to the locations of the fifty-five roadway garages in which equipment is housed. The two-stage facility location model does not suffer from this deficiency.

The two stages in the newly-developed model correspond to the two types of facilities mentioned above -- i.e., equipment repair facilities and roadway maintenance garages. Figure 1 shows the configuration of these facilities in ConnDOT's existing maintenance system. As discussed in Section IV, there are firm plans within ConnDOT to make certain changes to this existing system in the near future, and in the next phase of this study the system shown in Figure 1 will be updated to reflect those changes.

Figure 1 shows thirteen equipment repair facilities and fifty-five roadway garages. It also shows, using triangles, twenty-one other facilities, such as electrical repair and bridge repair buildings, where some equipment is housed. The straight lines in the figure depict the current assignments of equipment to repair facilities. For the purposes of this study, all repair facilities are assumed to perform essentially all types of repairs, and each roadway garage is assumed to be capable of providing all types of roadway maintenance.

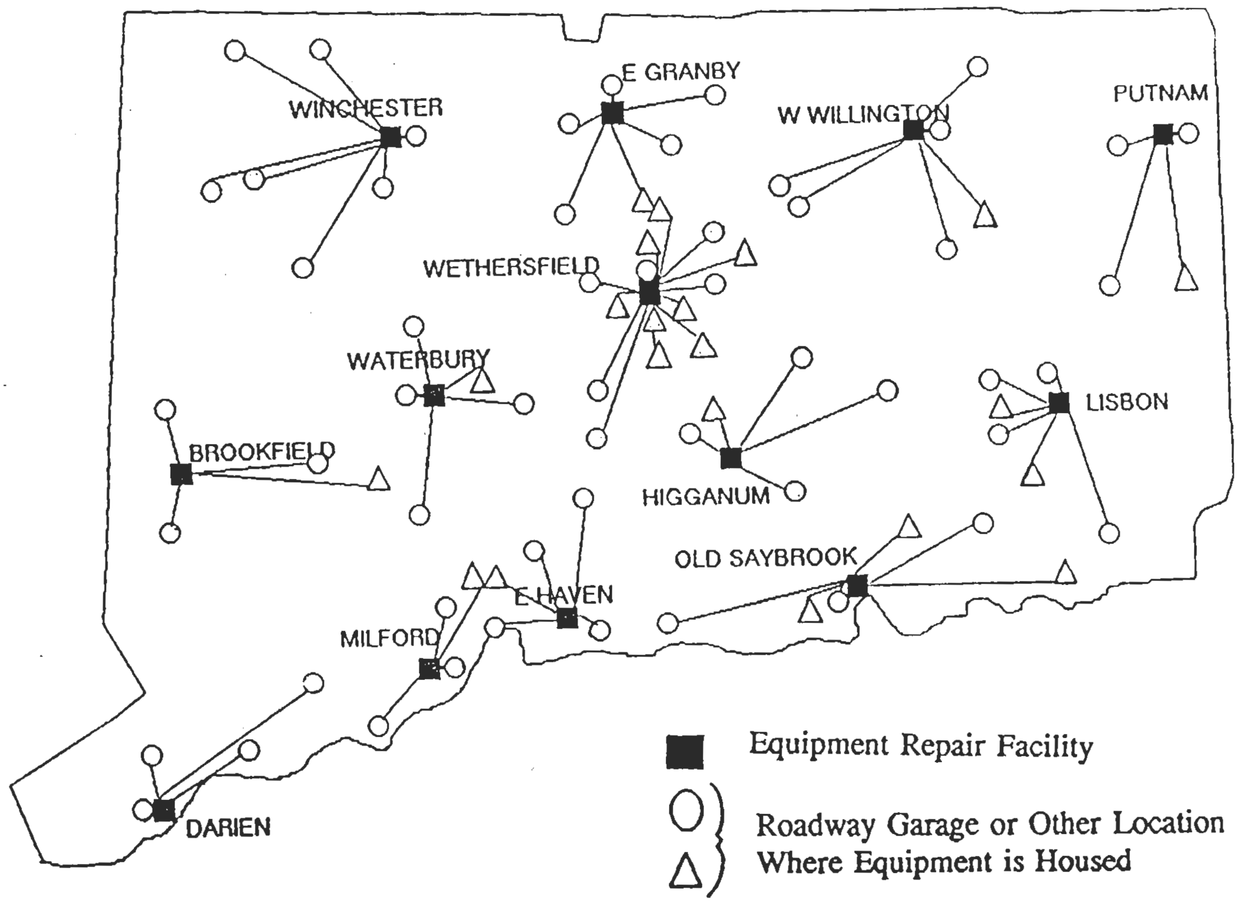

Figure 1. Existing configuration of ConnDOT's maintenance system.

In addition to the two stages represented by the repair facilities and roadway garages, a third level exists within the maintenance system, namely the roadways that require State-provided maintenance. These roadways have been broken down by ConnDOT's Office of Highway Operations into several hundred snow removal "runs". Although snow and ice removal is only one of numerous maintenance activities, it is probably the most important. Therefore, the runs defined for that purpose have been adopted as the basic sectors for this study. In the existing system, each run has a specific truck or trucks associated with it, and these trucks are, in turn, associated with a specific roadway maintenance garage. Thus, the roadways being serviced from each garage in the existing system are well-defined.

Scope and Objectives

For the first phase of the project, the main objective has been to formulate a practical two-stage model of ConnDOT's maintenance system. To be practical, the model must accurately reflect the key cost trade-offs and constraints that are inherent in the system. Practicality also requires that the model be manageable in terms of the data-gathering required to build it and the computational resources required to solve it. Another aspect of practicality is that the model be capable of providing results in a form that is useful for supporting the key decisions that need to be made with respect to the maintenance system.

The main decisions that the model has been designed to address are as follows:
1) which repair facilities to keep open, and which to expand;
2) assignments of equipment to repair facilities;
3) which roadway garages to keep open, and which to expand;
4) assignments of roadway sectors to garages; and,
5) assignments of equipment to garages.

Through various forms of experimentation, the model could also be used to analyze the impact of alternative means of providing services, such as an increased use of subcontracting for roadway maintenance. The model could also be used to investigate the cost implications of system configurations that have been developed by other means (e.g., management intuition). While the possible uses of the model are numerous, its development has been directed primarily toward its use for the second phase of the project, where specific recommendations for the five types of decisions enumerated above will be made.

Overview of Methodology

This section discusses some of the basic principles behind the structure of the model that has been developed to aid in making the five types of decisions discussed above.

Figures 2 and 3, combined, represent a hypothetical maintenance system composed of repair facilities, roadway maintenance garages, and roadways. Figure 2, which is in the same format as Figure 1, shows existing assignments of roadway garages to repair facilities. Figure 3 shows existing service areas for the five roadway garages from Figure 2. Since repair facilities do not have a direct relationship to the roadways, it is not necessary for roadways and repair facilities to be represented in the same figure. The roadway garages, however, are linked to both the repair facilities and the roadways, which is why they are represented in both Figure 2 and Figure 3.

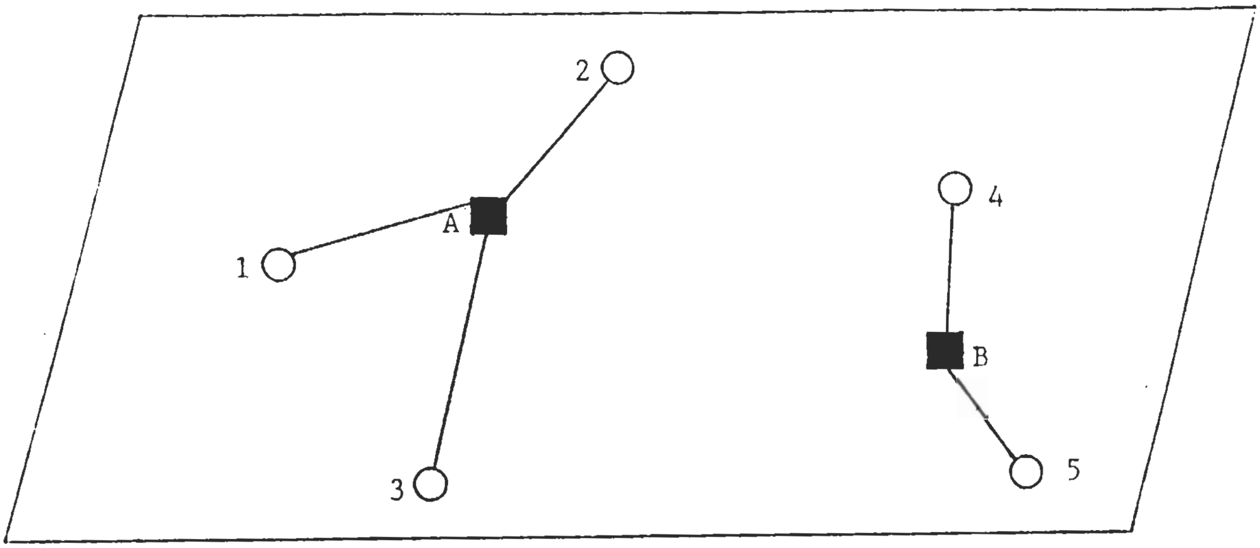

Figure 2. Example of an existing configuration of repair facilities (A & B) and roadway garages (1-5).

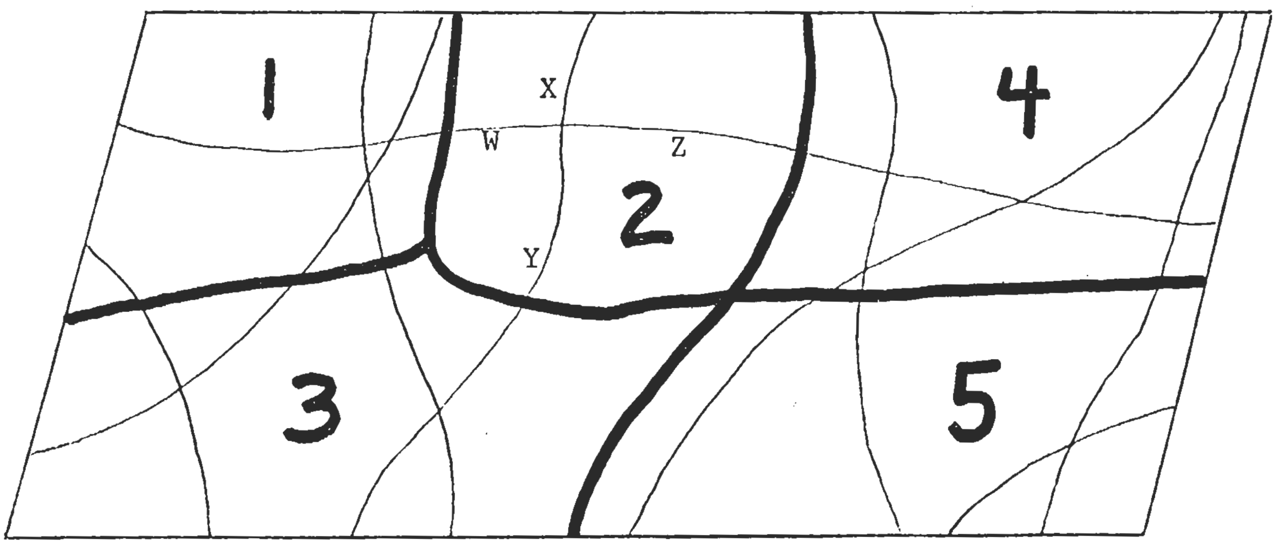

Figure 3. Example of existing roadway garage service areas (area labels correspond to garage labels in Figure 2).

In Figure 3, the four individual roadway sectors served by garage 2 have been labeled W, X, Y and Z. The mathematical model used in this study is based on the assumption that a pre-defined set of such roadway sectors exists. Snow plowing routes form the basis for defining the roadway sectors, as mentioned earlier and discussed more fully in Section IV, but this is not a concern for our example here. For now, let us simply assume that the entire roadway system in the example is broken down into individual sectors for modelling purposes.

Various types of data are input into the model to allow calculation of costs such as the costs of keeping a facility open, the costs of servicing a garage's equipment from a repair facility, and the costs of servicing a roadway sector from a garage. Based on these inputs and others related to capacity constraints, the computer-based optimization model finds the solution that minimizes total costs. The solution consists of specific values of decision variables that relate to the five types of decisions discussed earlier.

Figures 4 and 5 illustrate an alternative configuration of the maintenance system presented in Figures 2 and 3. Compared to the original configuration, the new one has one less repair facility and one less roadway garage. This new configuration will have lower facilities costs, since there are two fewer buildings. However, the new system will have higher transportation costs because some equipment must travel further to receive equipment maintenance and/or perform roadway maintenance. Also, some expansion may be required in the new configuration. For example, work bays may need to be added to repair facility B to enable it to handle the increased amount of equipment that would be sent to it in the new configuration. The optimization model allows for expansions at both repair facilities and roadway garages, at appropriate costs.

The total cost of the maintenance system configuration represented by Figures 4 and 5 may be either higher or lower than that of the configuration represented by Figures 2 and 3, depending on the values of the various cost parameters included in the model. This highlights the importance of obtaining complete and accurate data for the model. Indeed, data collection is expected to constitute the majority of the work that must be done to complete the second phase of this project.

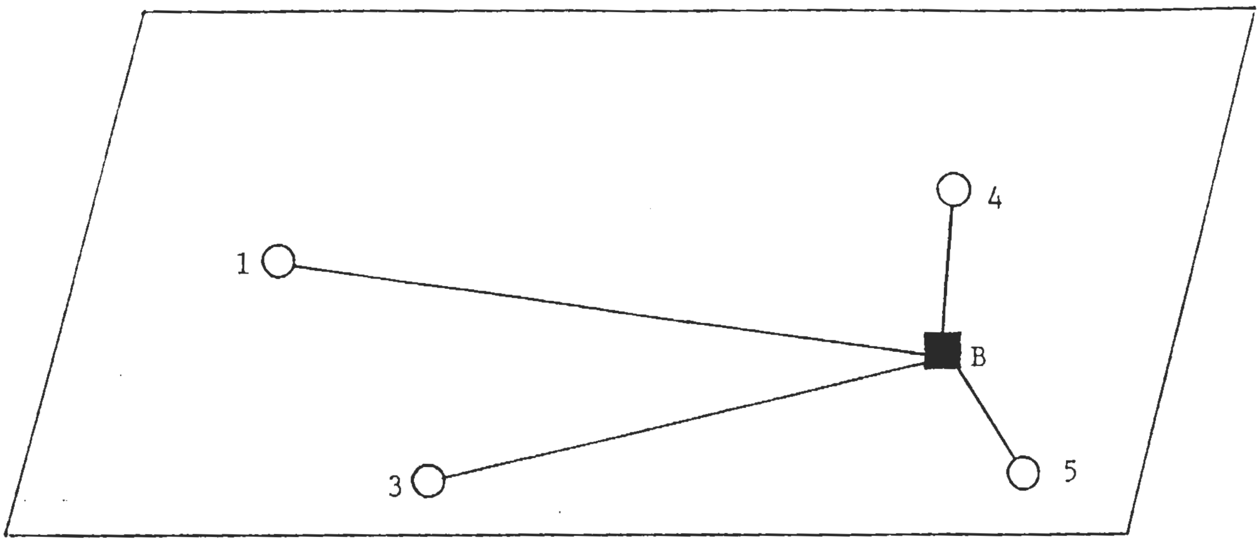

Figure 4. An alternative system configuration.

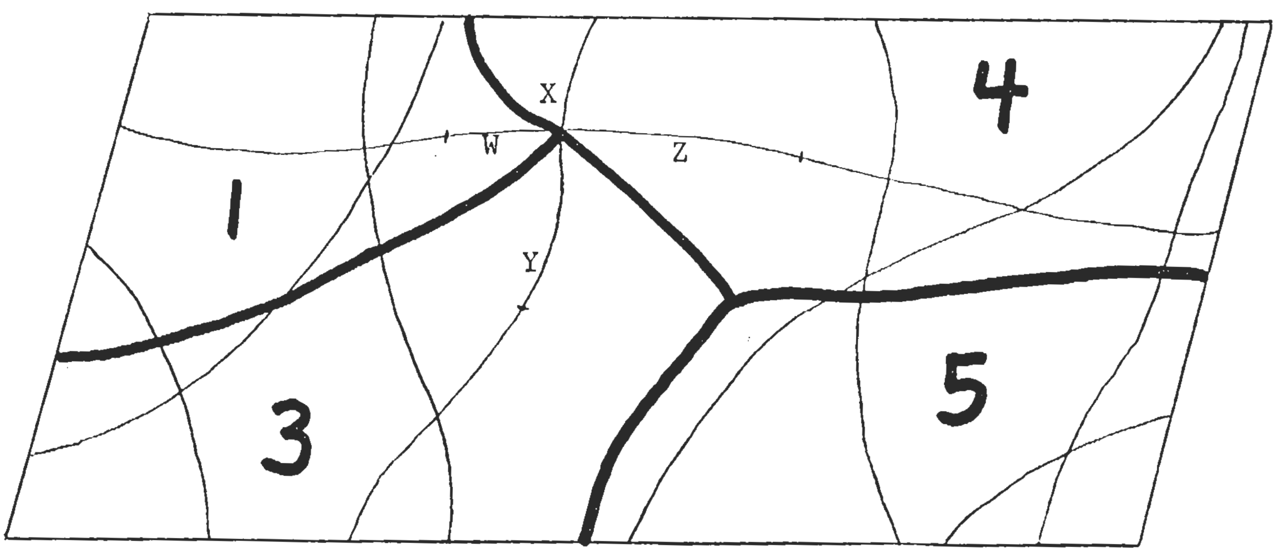

Figure 5. Service areas corresponding to the set of garages shown in Figure 4.

Organization of Report

The mathematical model is described in detail in Section III of this report. Examples of input and output from the optimization software being used for this project are presented and interpreted in Appendices A and B. These appendices are included to illustrate that the mathematical model and the optimization software are working as intended.

Section IV discusses the input data that are needed for the optimization model to accurately reflect the real system. While much of the data has already been collected as part of this project and a previous one, there is still much data collection and analysis yet to be done. Section IV includes an outline of plans for obtaining the data that are still needed.

Section V discusses the anticipated use of the model after all of the required data has been collected. The time-frame for the second phase of the project is outlined in that section.

Section VI concludes this report by highlighting some of the questions that remain open at the project's current stage.

Before proceeding with a discussion of the optimization model in Section III, the next section presents a review of relevant prior research.

II. REVIEW OF LITERATURE

The most relevant piece of prior literature for the current study is the final report from the prior single-stage study by Campbell and Davis (1991). That report included a comprehensive review of the literature on both equipment repair and facility location. The equipment repair literature was broken down into five categories, as follows: 1) productivity standards; 2) equipment maintenance standards; 3) equipment rental rates and downtime costs; 4) roadway maintenance standards; and, 5) contract maintenance. The report also included, in an appendix, the results of a survey of other states and Canadian provinces regarding their equipment repair and roadway maintenance practices. The earlier report's review of the facility location literature emphasized single-stage models, since that study's optimization model was of that type. For the current report, the review of literature from the prior study is used as a point of departure. The presentation here represents an update to the prior report's contents, with an emphasis on material directly relevant to the two-stage facility location model.

The facility location study performed by Bell and Rainer (1980) dealt with the location of roadway garages for the State of Alabama. Although they used a single-stage model, their methods are relevant to the current study because they modelled garages serving roadway sectors, which is the key new feature of the current study's two-stage optimization model. In the Bell and Rainer study, the State of Alabama was divided into nine geographic divisions, and nine separate models were run to determine roadway sector assignments to garages within each division. The State's 11,407 miles of paved roadway were broken down into 1,957 distinct roadway sectors. These sectors were then represented as single points (or nodes) for the purpose of estimating travel times. Travel costs were defined for all garage-sector combinations within a division, and a simple transportation problem of the following type was solved:

$$\text{minimize} \quad \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij}x_{ij} \tag{i}$$

$$\text{subject to:} \quad \sum_{j=1}^{n} x_{ij} \leq a_i \tag{ii}$$

$$\sum_{i=1}^{m} x_{ij} = 1 \tag{iii}$$

$$x_{ij} \geq 0 \tag{iv}$$

where:

c_{ij} = cost of servicing sector j from garage i;

a_i = maximum number of sectors that could be assigned to garage i;

x_{ij} = fraction of roadway sector j assigned to garage i;

m = number of garages; and, n = number of roadway sectors.

The objective function, (i), minimizes total transportation costs, while constraints ensure that garages are not assigned too many sectors [(ii)], and that all sectors are assigned [(iii)]. Compared with the optimization model described in Section III, Bell and Rainer's formulation is much simpler in many respects. In particular, their model is not capable of deciding upon facility closings -- the user must specify the set of open garages, then the model determines sector assignments and reports total transportation costs. The manner in which garage capacities are considered is also not very sophisticated.

The aspect of Bell and Rainer's model that is perhaps most relevant to the current study is the way that they account for lost productive time due to increased travel distances. They did this by modifying the maintenance budget associated with each roadway sector by a factor that reflected travel times to that sector. The standard budget for a sector was based on a one-way travel distance of 45 minutes. If a garage were, say, 75 minutes away from the sector, then the budget for that sector would get multiplied by a factor of 1.2 to reflect the loss in productive work time due to extra travel. Budget multipliers were established based on consultations with experienced maintenance supervisors. The multipliers, combined with the existing sector budgets, formed the basis for the c_{ij} values included in the model.

To evaluate the savings associated with closing garages, Bell and Rainer manually selected garages to close as part of a trial-and-error type of process. The increase in transportation costs associated with closing facilities would then be compared with the savings in overhead that could be realized if the facilities were closed. Interestingly, salvage values of buildings and land were not included in the savings associated with closing a facility because they were considered to be a small part of the total savings. The study resulted in the closing of four roadway garages within the State of Alabama, for an estimated savings of $243,000 per year.

In terms of solvability, the formulation used by Bell and Rainer presented no difficulties whatsoever. Their formulation corresponds to the standard transportation problem, which is even simpler than the standard linear programming problem (of which the transportation problem is a special case). The single-stage optimization model used in the study by Campbell and Davis (1991) is more complicated than a standard linear programming problem because it includes sets of integer variables. Mixed-integer programming formulations are typical for facility location problems.

The basic single-stage facility location problem has been studied by many researchers from the perspective of solvability. Several references pertaining to solution algorithms were made in the literature review in Campbell and Davis (1991), and research on algorithms has continued to appear since that report was produced. Beasley (1993) discusses advances made in the use of Lagrangean relaxation for solving several classes of single-stage facility location problems. The focus for many larger problems of this type is on heuristics that provide solutions that are provably good without necessarily being optimal. Cornuejols, Sridharan and

Thizy (1991) performed a comparison of such heuristics for the single-stage facility location problem. The emphasis placed in the above-mentioned research on obtaining solutions to large problems is different than the emphasis in the current study. The current study is primarily concerned with representing ConnDOT's maintenance system appropriately using a model that can be built and solved at reasonable costs.

In a comprehensive review of models related to facility location, capacity expansion, and technology selection, Verter and Dincer (1992) discussed the inter-relationships of these models with respect to designing global manufacturing strategies. Although this is clearly beyond the scope of the current study, their review does highlight the important role that facility location models can play in strategic decision-making.

Returning now to the scope of the current study, let us discuss the prior research that has been done to extend single-stage facility location models to represent multiple stages. In the review article by Aikens (1985), two multi-stage facility location formulations are presented for systems without capacity constraints. The formulation by Kaufman, Eede and Hansen (1977) is based on triple-subscripted variables (x_{ijk}) that correspond to the amount of demand in zone k served by plant i through warehouse j. The formulation by Tcha and Lee (1984) is similar in that it requires identification of all paths spanning all levels of the system. They extend the formulation given by Kaufman, Eede and Hansen to allow for any number of stages in the system. The emphasis of both of these multi-stage studies is on efficient solution procedures, not necessarily on modelling any specific application.

The two-stage model developed for the current project is more complex than the multi-stage models mentioned above because it includes capacity constraints at both stages. Consequently, the solution procedures developed for the prior studies cannot be directly applied to solving the optimization problem in the current study. Also, the model developed here is not a straightforward extension of the uncapacitated multi-stage models referenced above. The formulation presented in the next section does not include triple-subscripted variables, nor does it require specification of all paths that span all levels of the system. The new formulation takes certain elements of its structure from previous multi-stage models, but adds some key new features of its own. The way that it simultaneously allows for facility closings, capacity expansions, garage and sector reassignments, and equipment transfers takes it a step beyond previously developed formulations.

In contrast to much of the previous literature, the current study is not concerned with using the fastest possible techniques for obtaining solutions. The model must be kept to a reasonable size, and an appropriate software package and computer system have to be used, but, beyond that, issues of solvability are not key concerns. A work station version of the software package GAMS (Brooke, Kendrick and Meeraus 1988) is used in this study for building and solving the optimization model. GAMS was chosen because it is ideally suited for developing and solving customized mathematical programming models. Geoffrion (1992) discusses some of the advantages that GAMS offers in this respect.

III. OPTIMIZATION MODEL

In this section the two-stage optimization model is presented. The software used to solve the optimization model is also discussed, including reference to the two appendices where detailed examples of input and output are provided.

To begin, let us discuss the decision variables, which are listed and defined on page viii. There are two types of decision variables: 1) continuous; and, 2) binary (i.e., zero/one). Optimization problems that mix variable types in this manner are often referred to as mixed-integer programming problems. Computationally speaking, the presence of binary variables (such as Y_f, A_f, YG_i and AG_i) make problems more difficult to solve. Consequently, we are taking steps to minimize the number of such variables that are required in the model. This is discussed further in Section IV.

The parameters of the model are those elements that are specified at the outset, before the problem is solved. Values for the parameters have been, or will be, obtained through the data-gathering efforts described in Section IV. The parameters of the two-stage optimization model are listed and defined on page ix.

The mathematical programming model of ConnDOT's two-stage maintenance facility location problem is as follows:

$$\text{Min} \sum_{f=1}^{13} (K_f Y_f + M\, A_f + N\, B_f) + \sum_{i=1}^{55} (L_i YG_i + MG\, AG_i + NG\, BG_i)$$

$$+ \sum_{f=1}^{13} \sum_{i=1}^{76} C_{fi} X_{fi} + \sum_{f=1}^{13} \sum_{i=1}^{55} U_{fi}\, (T_{fi} - TP_{fi}) + \sum_{i=1}^{55} \sum_{j=1}^{300} TCOST_{ij} XS_{ij} \qquad (1)$$

Subject to:

$$\sum_{i=1}^{76} D_i X_{fi} + \sum_{i=1}^{55} (T_{fi} - TP_{fi}) \le (P_f Y_f + R\ A_f + S\ B_f) \qquad f=1 \text{ to } 13 \qquad (2)$$

$$\sum_{j=1}^{300} DS_j XS_{ij} \le (D_i + \sum_{f=1}^{13} (T_{fi} - TP_{fi})) \qquad i=1 \text{ to } 55 \qquad (3)$$

$$\sum_{f=1}^{13} T_{fi} \le (RG\ AG_i + SG\ BG_i + XSPACE_i\ YG_i) \qquad i=1 \text{ to } 55 \qquad (4)$$

$$\sum_{f=1}^{13} X_{fi} = 1 \qquad i=1 \text{ to } 76 \qquad (5)$$

$$\sum_{i=1}^{55} XS_{ij} = 1 \qquad j=1 \text{ to } 300 \qquad (6)$$

$$\sum_{j=1}^{300} XS_{ij} \le 20\ YG_i \qquad i=1 \text{ to } 55 \qquad (7)$$

$$A_f \le Y_f \qquad f=1 \text{ to } 13 \qquad (8)$$

$$B_f \le 8\ A_f \qquad f=1 \text{ to } 13 \qquad (9)$$

$$AG_i \le YG_i \qquad i=1 \text{ to } 55 \qquad (10)$$

$$BG_i \le 8\ AG_i \qquad i=1 \text{ to } 55 \qquad (11)$$

$$TP_{fi} \le D_i X_{fi} \qquad i=1 \text{ to } 55,\ f=1 \text{ to } 13 \qquad (12)$$

$$\sum_{f=1}^{13} \sum_{i=1}^{55} T_{fi} = \sum_{f=1}^{13} \sum_{i=1}^{55} TP_{fi} \qquad (13)$$

$$T_{fi},\ TP_{fi},\ BG_i,\ B_f,\ X_{fi},\ XS_{ij} \ge 0 \qquad (14)$$

$$YG_i,\ Y_f,\ A_f,\ AG_i \in \{0,1\} \qquad (15).$$

The objective function, (1), represents a minimization of all relevant costs. The cost components of the objective function are of three types: 1) costs of keeping facilities open; 2) costs of expanding facilities; and, 3) costs of providing service.

The first type of cost has only binary decision variables associated with it. If a repair facility's Y_f value or a garage's YG_i value is set equal to 1, then the entire fixed cost of keeping the associated facility open is incurred. Similarly, if the binary variable is set equal to zero, then none of those costs are incurred. This exemplifies why it is necessary to use binary decision variables in the model. It does not make sense, in the context of the ConnDOT maintenance system, to consider keeping or closing a fractional amount of a facility.

Expansion costs, which are the second type of cost in the model's objective function, also use binary decision variables (i.e., the A_f and the AG_i), but they use continuous variables as well (i.e., the B_f and the BG_i). The use of continuous variables for modelling expansions above two bays is a simplification being made for computational reasons. It obviously does not make sense to call for an expansion of, say, 3.4 bays. However, it has been our experience that expansion cost functions are such that rounding fractional values of bays up to integer values does not introduce serious errors into the analysis. The binary variables (A_f and AG_i) are necessary to accurately represent the non-linear nature of the expansion cost function. In the model, this function reflects the significant fixed costs associated with an expansion, plus variable costs that are proportional to the number of bays added. In essence, the binary variables help to model the fixed expansion costs, and the continuous variables model the variable expansion costs.

The third type of costs in the objective function are the costs of providing service. These costs have only continuous decision variables associated with them. The decision variables representing equipment maintenance are X_{fi}, T_{fi} and TP_{fi}; and those representing roadway maintenance are only the XS_{ij}. There are more decision variables related to equipment maintenance because the model must allow for a variable amount of equipment housed at a garage. Each roadway sector, on the other hand, has a fixed service requirement associated with it.

The constraints of the model ensure that necessary services are provided, and that no logical relationships are violated. There are several types of constraints, including the following: supply constraints, demand constraints, and expansion constraints.

Supply constraints ensure that the total service being provided by a facility does not exceed that facility's capacity. Constraint set (2) represents the capacity of repair facilities. The left-hand side of the inequality is the total equipment being serviced by a facility, and the right-hand side is the facility's capacity, based on its existing number of work bays and any that are being added. Constraint set (3) ensures that the service provided by each garage is less than or equal to the capacity of the equipment at that garage, including any equipment that is being added to (or subtracted from) the garage. With regard to the space available at garages, constraint set (4) ensures that the amount of equipment being added to a garage does not exceed the garage's supply of available space.

Demand constraints are included in the model to ensure that all service requirements are met. Constraint set (5) handles repair of equipment from the garages and constraint set (6) handles roadway maintenance for all sectors. Constraint set (7) states that a sector must be served by a garage that is open. In that constraint set, the value of 20 represents the maximum number of sectors that can be assigned to a single garage. This value was chosen because it appears to be large enough to be non-restrictive for any realistic solution.

Constraint sets (8)-(11) enforce logical relationships amongst expansion variables. Constraint set (8) states that a repair facility cannot be expanded unless it is kept open, and constraint set (9) ensures that expansions above two bays cannot happen unless the initial two-bay expansion occurs. The value of eight in constraint set (9) ensures that the total number of bays added at a repair facility is less than or equal to ten (the initial two, plus eight additional). Constraint sets (10) and (11) are for the garages. They enforce relationships similar to those enforced at the repair facilities by constraint sets (8) and (9), as discussed above. In Section IV of this report, the possibility of obtaining site-specific values for maximum expansion sizes is discussed.

Constraint set (12) is included in the model to ensure that the amount of equipment being subtracted from a repair assignment does not exceed the amount that was assigned. Constraint (13) balances the additions and subtractions associated with reassigned equipment.

The last two constraint sets in the model, constraint sets (14) and (15), are standard non-negativity and binary variable constraints, respectively.

The optimization model, once it has been built, will be solved using standard mathematical programming techniques, as implemented by the software package GAMS (Brooke, Kendrick and Meeraus 1988). Appendix A presents an example of GAMS input, and Appendix B presents an example of GAMS output, including interpretation of decision variable values. The next section of this report discusses the data gathering that must be done to ensure that the model shown in this section (and in Appendix A) will be a good representation of ConnDOT's actual maintenance system.

IV. OBTAINING REQUIRED INPUT DATA

Data Already Collected

As part of the single-stage study described in the final report by Campbell and Davis (1991), much of the data collection required for the current project has already been completed. With respect to the optimization model parameters defined on page ix, values for the following have already been estimated: C_{fi}, D_i, U_{fi}, K_f, M, N, P_f, R and S. These are nine of the seventeen parameter types required to build the model.

For the current project, some updating of the data from the previous project will be required. In particular, the new model will reflect the firm plans that ConnDOT has for closing repair facilities at Higganum, Lisbon and Brookfield, and for building new ones at Colchester and Newtown. Updating of roadway maintenance garage locations and associated travel distances will also be done. Because techniques for estimating the nine parameter types are well-established, based on the previous study, no difficulties are expected in updating the data already obtained. The parameters that present more of a challenge are the eight types that were not included in the previous study's model.

Data Still Needed

The eight new parameter types that require estimation are discussed individually below. Included in the discussion are possible ways of obtaining data and estimating parameter values. For certain cases, the most practical estimation procedures appear to be obvious, whereas others require trade-offs to be considered when deciding which approach to take. For those parameters whose best method of estimation is not obvious, alternatives are outlined and a recommendation is presented.

(i) DS_j -- the demand in sector j, in terms of equipment required to serve that sector.

There is general agreement that the basis for defining roadway sectors should be existing snow plow routes, of which there are several hundred within the State. For each sector, the Office of Highway Operations has already defined the amount of equipment assigned to that sector for snow- and ice-removal purposes. Highway Operations personnel agree that it is reasonable to model the total equipment required to maintain a sector as being proportional to the equipment required to remove snow and ice within that sector. Based on this, the DS_j values of all sectors served by a garage in the existing system configuration can be calculated as follows:

$$DS_j = D_i \; SR_j \; / \sum_{j \epsilon \{S_i\}} SR_j$$

where: D_i = total equipment at garage i;

SR_j = amount of snow removal equipment required for sector j;

$\sum_{j \epsilon \{S_i\}} SR_j$ = total amount of snow removal equipment for all sectors assigned to garage i in the existing system; and,

$\{S_i\}$ = the set of sectors served by garage i in the existing system.

As mentioned above, D_i values have already been estimated for the previous study. Data pertaining to the SR_j and $\{S_i\}$ are readily available based on the information contained in the "snow books" produced by the Office of Highway Operations. Therefore, estimation of DS_j values should present little difficulty.

(ii) $TCOST_{ij}$ -- the total cost of servicing all of sector j requirements from garage i.

This is the largest set of parameters in the model. There are fifty-five existing garages and hundreds of roadway sectors, but, fortunately, an estimate is not required for all possible garage-sector pairs. Based on rules of thumb provided by the Office of Highway Operations, a set of candidate garages will be defined for each roadway sector, so that $TCOST_{ij}$ values will need to be estimated only for garage-sector pairs that correspond to such sets. There is no need, for example, to estimate the cost of servicing a roadway sector in Fairfield County from a roadway garage in the State's northeast corner, because such as assignment is obviously not feasible.

But even with the infeasible assignment possibilities eliminated, the number of $TCOST_{ij}$ parameter values that must be estimated is on the order of 1000. Rather than trying to estimate these individually, a cost function will be developed so that estimates can be calculated systematically by a computer. One of the elements of the cost function will be the travel distances between sector j and roadway garage i. This piece of the function will be estimated using a computer-based roadway network model that has the capability of estimating travel distances (and times).

Another piece of the transportation cost function will be the number of trips made between a roadway sector and a maintenance garage. Based on discussions regarding this aspect of the cost function, it was concluded that estimates can be provided by those most familiar with roadway maintenance operations. However, these estimates will be subject to some degree of error. It will be important, therefore, for the second phase of the study to include a sensitivity analysis that investigates the effects of errors in the $TCOST_{ij}$ estimates.

Besides the accurate reflection of transportation costs, there is also the issue of changes in productive work time due to changes in travel times to and from garages. In the Alabama study referred to in Section II, this was handled by reflecting estimated changes in productive work time in the cost parameters of the model. It is possible to do this for the current study, but this may not be wholly satisfactory because it still does not directly address the issue of reduced time available for roadway maintenance due to increased travel times. One possibility for directly addressing the issue is to add constraints to the model that limit the amount of travel time that could be added. This does not seriously complicate the model, but it does necessitate the definition of new sets of parameters and constraints. Another possibility is to consider added travel times outside of the model when solutions are being translated into specific recommendations. The approach being recommended here is similar to what was done in the Alabama study and in the previous ConnDOT study, which is to design the $TCOST_{ij}$ estimates to reflect a cost for lost productive work time. In the prior ConnDOT study, this was done by using overtime wage rates within the transportation cost functions. Another way of doing it is to have the $TCOST_{ij}$ values reflect the costs of new workers and equipment that would be needed to make up for the loss in productive work time. Either way, increased $TCOST_{ij}$ values would not preclude added travel times from also being considered outside the context of the model as specific recommendations are being developed. Irrespective of how the $TCOST_{ij}$ parameters are calculated, the loss of productivity due to increased travel times is a complicating issue that must be considered when solutions from the optimization model are being used to develop specific recommendations.

(iii) L_i-- the annualized cost of keeping garage i open.

Since the model is being constructed to allow for the possibility of closing garages, the savings associated with such closings must be known up-front. Based on discussions with the Office of Highway Operations, there are certain roadway maintenance garages that it would not make sense to close under any circumstances. Those that have been recently constructed or renovated, those positioned at key locations for winter maintenance and incident management, and those that have firm plans for major renovations are the types of garages that will be considered "untouchable." For these, L_i estimates will not be required.

For the 25 to 40 roadway garages that will be candidates for closing, L_i estimates are needed. There are three major components to the L_i values: 1) salvage values of land and buildings; 2) savings in building expenses such as for heat and electricity; and, 3) savings in salaries for support personnel. The K_f values obtained for the repair facilities in the previous study are similar in nature to the L_i values. For the K_f values, the annualized savings in building expenses and personnel represented approximately 75%, on average, of the total estimated savings associated with closing a repair facility. The salvage values of land and buildings accounted for the other 25%.

Estimating salvage values of land and buildings for the roadway garages is a complicated matter. The following three estimation alternatives have been identified: 1) request that Rights of Way assign an appraiser to visit each site and develop estimates, as was done for the repair facilities in the previous study; 2) base estimates on the property values shown on ConnDOT's inventory lists; or, 3) do not include property salvage values in the L_i estimates. For reasons outlined below, the third alternative appears to be the most attractive.

There are two problems associated with the first alternative for estimating property values. First, a significant amount of work is involved. Although Rights of Way has yet to be consulted on this, based on experience in the prior study it is estimated that two to three man-months of labor would be needed for appraising. The second problem is that if the appraisals were developed, they would not include costs of any environmental clean-up that may be required prior to selling the properties. These costs are potentially substantial, but they are difficult to estimate. With the question of environmental clean-up costs left open, any property value estimates obtained would be subject to a high degree of uncertainty. This would cast a serious shadow over any recommendations for facility closings that might be made based on the model.

The second alternative for obtaining property values, which is to base them on values shown on ConnDOT's inventory lists, would result in an even higher degree of uncertainty than the first alternative. Added to the uncertainty introduced by the potential need for environmental clean-ups would be the discrepancies between values on the inventory lists and actual market values. In the previous study, it was observed that such discrepancies are not great for newer facilities, such as that at Darien, but for older facilities, the inventory lists show values that are much lower than appraised market values. Methods for correcting the inventory list values could be developed, and this would certainly require less effort than actual appraisals. However, the estimates obtained by this method would still suffer from a high degree of uncertainty.

The third method, which is to not include property salvage values in the model, may seem overly simplistic at first glance, but upon closer examination it can be seen to offer several significant advantages. One obvious practical advantage is that a large amount of data-gathering is avoided if property values are not required. Also, there would be greater confidence that the estimated savings associated with recommendations based on the model could actually be realized by the State. Another advantage is that relocation of other functions performed at garage sites would not need to be considered. For example, if it were not necessary for garage sites to be sold to achieve savings, then the State would have the option of keeping any sand and salt piles that existed on the properties. All of the above considerations, combined with the fact that salvage values of properties averaged only 25% of the K_f values in the prior study, contribute to the preference for not including property salvage values in the L_i estimates. If this direction is taken for this project, then, for consistency, it would make sense to also not include the property values of the repair facilities. The K_f values from the previous study could be adjusted to reflect this convention if the decision were made to not include property values.

The two other components of the L_i values are much easier to estimate than property values. In the prior study, detailed building expense records for the repair facilities were obtained from ConnDOT's Property and Facilities Services (formerly called Property Control), and, presumably, the same could be obtained for the roadway garages for the current study. With regard to support personnel, the Office of Highway Operations has been, and will continue to be, consulted regarding which positions could be eliminated if a garage were closed, and what the estimated cost savings would be. The types of positions subject to possible elimination are supervisors, crew leaders and clerks. Elimination of maintenance positions is not considered in the model because the total amount of State-provided maintenance work and the number of maintenance workers are assumed to remain fixed. If only the salaries of support personnel and building expenses are included in the L_i, then estimating values for that set of parameters for existing garages should not present a major burden.

L_i values also need to be estimated for new garage sites. For new garages to be considered within the model, their locations must be specified from the outset, and their expected construction and operating costs must be reflected in their L_i values. The Office of Highway Operations will be relied upon for identifying potentially attractive alternative sites, and for helping to develop construction and operating cost estimates. The cost of constructing a new maintenance garage will obviously depend on the facility's size, and also on whether or not State-owned land is available at the location. The optimization model is flexible in that it can allow for the possibility of opening new garages at locations specified by the user, but it is not designed to specify new locations itself. As far as the model is concerned, the decision of whether or not to open a new garage is based largely on the associated L_i estimate. Therefore, these estimates will be essential for all potential new garage sites.

(iv), (v) and (vi):

RG -- capacity added by adding two bays at a garage;

SG -- capacity added for each bay above two added at a garage; and,

$XSPACE_i$ -- extra space available at garage i.

Although the estimation of values for these parameters may appear to be straightforward, it requires clarification of certain assumptions related to policy. In particular, a choice must be made between the following two assumptions: 1) the sizes of existing garages are sufficient for the equipment they house; or, 2) each major piece of equipment requires its own storage bay.

Although certain aspects of the model presented in Section III are based on the first assumption, the Office of Highway Operations has shown a strong preference for the second. They have stated that practically all of the roadway garages are undersized, and many new storage bays must be constructed for the existing system to be sufficient.

Some modifications to the model will be required for it to reflect the second assumption, but this would not be a problem. Also, since the Office of Highway Operations already has information regarding the expansions required at the garages to bring them up to their preferred sizes, the data-gathering associated with basing the model on the second assumption does not present any serious difficulties.

The parameters associated with storage capacity will not be hard to estimate under either of the two assumptions listed above, but the choice of which assumption to go with does affect how data-gathering will proceed. Therefore, it is important for ConnDOT's position on this issue to be understood early in the project's second phase. There is also the option of running two separate models that each reflects one of the two assumptions. Because of the additional work involved in building and running two separate models, this option should only be pursued if it is believed that the results of separate runs could have a direct bearing on ConnDOT's policy regarding whether or not each piece of major equipment should have its own storage bay.

(vii) and (viii):

MG -- annualized cost of adding two bays at a garage; and
NG -- annualized cost of adding each bay above two at a garage.

Because the Office of Highway Operations has cost estimates for expansions of various sizes, developing estimates for these parameters should be straightforward. More difficult than estimating these parameter values will be estimating the maximum number of bays that could be added at each garage. The model, as shown in Section III, allows for a maximum of 10 bays added at each garage. This simple type of constraint may be appropriate for a first-pass analysis, but it would be better if the model could be based on realistic site-specific limitations on expansions. The trade-off, of course, is that it is not a simple matter to estimate the potential for expansion at 55 garage sites. Based on further consultation with the Office of Highway Operations, a plan for how to proceed on this issue will be developed.

This completes discussion of the eight parameter types yet to be estimated and the data-gathering still required to complete the optimization model. The open questions that were raised in this section are summarized and discussed further in the conclusion section of this report.

V. PLAN FOR THE PROJECT'S SECOND PHASE

Phase two of this project consists of five tasks, as outlined below in Table 1.

The schedule for the tasks from Table 1 is shown in Figure 6, and the tasks are discussed individually in further detail below.

Table 1. Tasks for project's second phase.	
Task A --	solidify plans for remaining data collection.
Task B --	perform remaining data collection.
Task C --	run the model and obtain solutions under different scenarios.
Task D --	meet with ConnDOT to review findings of Task C, and run additional scenarios if necessary.
Task E --	write Final Report.

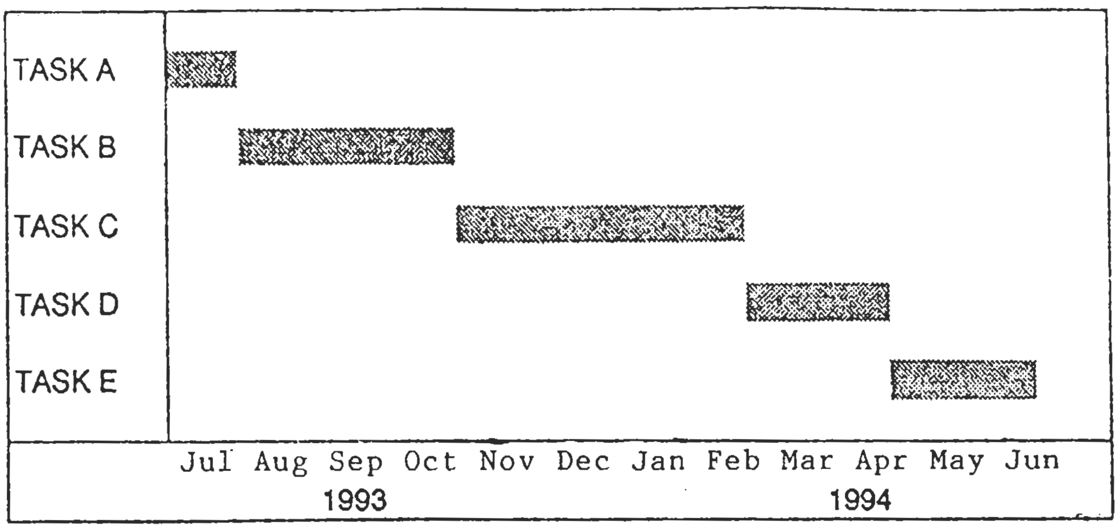

Figure 6. Task schedule for project's second phase.

Task A, which is scheduled to be performed in July, involves answering open questions that have been raised in this report. These questions are summarized in Table 2 shown in Section VI. It is anticipated that distribution of this report will be followed by a meeting between ConnDOT and the principal investigators at which all of these questions will be discussed. When the open questions have been adequately addressed, then Task A will be effectively complete.

Task B, data collection, was the topic of Section IV of this report. Based on the discussion there, it is obvious that this task is going to be a cooperative effort between ConnDOT and the Principal Investigators. If full appraisals of garage property values are required, as discussed in Section IV, then the time frame for Task B will depend largely on how long it would take the Office of Rights of Way to complete them. The three-month time frame on the task may be able to be shortened if full appraisals of all garages are not required. Based on the level of cooperation between the Office of Highway Operations and the Principal Investigators that has been evident so far, most aspects of this task should be easy to accomplish within three months. The Office of Property and Facilities Services is the only other major dependency, and based on their timely cooperation in the previous project, there is unlikely to be a delay associated with obtaining building expense records for the roadway garages.

Task C is where the completed model will be run to obtain solutions that will form the basis for the study's recommendations. At this stage of the project, the principal investigators will remain in contact with the Office of Highway Operations for the purpose of verifying that the model is acting as a fair representation of the actual maintenance system. Potentially, the model could benefit from further refinement at this stage of the project. Examination of initial solutions by those most familiar with the actual system may yield insights into how the model could be improved. Enough time has been allocated to Task C so that several iterations of this type of interaction between the Office of Highway Operations and the principal investigators can occur.

Task D is an extension of the type of interaction described above. The difference with Task D is that it will likely involve a wider range of people within ConnDOT. The findings from Task C will be documented and distributed, and then a review meeting will be scheduled. Based on the discussion at that meeting, additional runs of the model may be required. While more than one iteration of this type of interaction may be required, it is anticipated that after careful consultation with the Office of Highway Operations during the course of Task C, Task D should proceed relatively smoothly.

Task E, writing the Final Report, will involve completely documenting the second phase of the project. This will include: updates on how the model is structured; presentation of solutions obtained from the model; and, discussion of how the solutions were used in developing recommendations. Recommendations will include details of the expected costs and benefits of any suggested changes to the maintenance system. Issues related to implementation of any changes will also be discussed. The final report will also include suggestions for how the research performed for this project might be extended in the future.

Regarding extensions of this research beyond the second phase of the current project, one possibility is the development of a user-friendly decision support system (DSS) that ConnDOT could use on its own to explore alternative maintenance facility configurations. A DSS could be based on the same types of assumptions as the optimization model, and it could use the same input data. However, its function would not be to provide optimal solutions, but rather to evaluate the costs of user-specified configurations. If it were known by November of this year that the development of such a DSS might be desirable, then steps could be taken within the time frame shown in Figure 6 to ensure that the DSS could be completed by, say, December of 1994. This would mean a new project to follow the second phase of the current project.

Certain aspects of the second phase of the current project (and whether or not there will be any follow-on research after that) depend, to a large extent, on how ConnDOT expects to use the project's findings. This point is a major theme that underlies much of the discussion in the next section of this report.

VI. CONCLUSION

The two-stage optimization model and the data gathering required to complete it have been described in this report. Also described were plans for phase two of the project, where the model will be completed, solutions will be obtained, and specific recommendations will be developed. The motivation for pursuing this research is the hope that the study's recommendations will be useful to ConnDOT for maintenance facilities planning purposes. The usefulness of the model will depend upon how accurately it reflects the key aspects of the real system, which will, in turn, depend upon the quality of inputs used to construct it.

The effort that ConnDOT puts into building the model is likely to depend upon how they view it. One view ConnDOT might take is that the model belongs to them. Acknowledgement of ownership implies a high degree of responsibility for the model's validity, both in terms of its underlying structure and the data upon which it is based. An alternative view is that the model belongs to the Principal Investigators. Under this view, ConnDOT cooperates in terms of data gathering and answering questions regarding the model's structure, but a certain degree of distance is maintained as the modelling process unfolds. Considering these alternatives, ConnDOT's view with respect to ownership could affect the quality of the resulting model.

A clear advantage that ConnDOT would gain by "buying into" the model is that they would increase the chances that the study's results would be useful to them for facilities planning. Under this scenario, the model's output could be used as an objective point of reference in support of their decisions. If ConnDOT operated in this manner, then solid answers would be available whenever the maintenance facilities configuration was questioned by outside agents such as the consultants hired by the Thomas Commission.

The advantage of the alternative view, which is to maintain a certain distance from the model, is that ConnDOT might feel less bound to take seriously any of the study's recommendations. Undoubtedly, the recommendations would be easier to ignore if they were developed based on a model that belonged to somebody else.

Putting aside, for now, the philosophical discussion of model ownership, let us turn back to concrete questions regarding details of the next phase of the project. Table 2 lists five open questions, which are discussed individually below.

Table 2. Open questions at this stage of the project.

1. Is existing roadway garage capacity sufficient, or does each major piece of equipment need its own storage bay?
2. Should property value estimates be included in the savings associated with closing a garage, and, if so, how should the estimates be obtained?
3. How should the model handle the issue of increased travel times between garages and roadway sectors?
4. What subcontracting alternatives, if any, should be explored?
5. Would ConnDOT like to eventually have a model-based decision support system they could use on their own?

The first question was brought up in Section IV under the discussion of the RG, SG and $XSPACE_i$ parameters. If the question is answered by saying that existing capacity is sufficient, then many of the expansions currently being called for at roadway garages will not be supported by the model's solutions. If the question is answered to reflect the policy of housing all major pieces of equipment, then the following two effects can be expected: 1) garages would be less likely to be closed; and, 2) there would be many garage expansions called for by the model. If ConnDOT does plan to go ahead with garage expansions, then the model should be built to reflect the policy of housing all major pieces of equipment. This way, the expansions that would be called for by the model could provide useful insight for future facilities planning.

The second question, which deals with garage property values, was raised in Section IV when the L_i parameters were discussed. Three alternatives for reflecting garage property values were outlined there, and a preference for not including them in the model was indicated. Of course, the effect of not including them is that the model would be less likely to close garages, because the associated savings would be less. If the income that could be obtained from selling properties really is very uncertain due to potential environmental clean-up requirements, then it makes sense to design the model so as to avoid a serious flaw in its underlying assumptions. As pointed out in Section IV, it is preferable to have recommendations that are based on a model that is conservative in how it estimates the savings associated with closing facilities.

The third question shown in Table 2 was raised previously in Section IV under the discussion of the $TCOST_{ij}$ parameters. The question relates to the loss in productive work time that would occur if travel distances between garages and roadway sectors were increased. If we assume that the existing system has just enough equipment and manpower to meet its roadway maintenance requirements, then how should the model handle the issue of lost productive time due to increased travel? One possibility is to base cost estimates on overtime labor rates, which would assume that all extra travel is done on overtime, and, therefore, no additional workers or equipment would be needed. Another alternative is to design travel cost estimates to reflect the need for new hires and more equipment if travel times did increase. This alternative would probably result in higher $TCOST_{ij}$ values than the assumption of overtime pay rates. Under either of these alternatives, the problem of slower response times due to increased travel distances also needs to be considered. Presumably, this will be handled in the model through constraints that restrict the set of garages that could serve a sector based on distances and the types of roads within the sector. Information regarding the added travel time associated with a solution could be calculated outside the model as well. It would be beneficial if all of the issues associated with increased travel times could be settled before phase two of the project is too far underway.

The fourth question shown in Table 2 was not raised before this section of the report. Currently, subcontracting is used for a substantial portion of roadway sector maintenance. If the use of subcontracting is increased, then the model is likely to specify solutions with fewer facilities. If there is a significant cutback in the use of subcontracting, then more equipment, more workers, and more facilities are likely to be required. Modifying the model to accurately reflect alternative levels of subcontracting would not be a trivial matter. The Office of Highway Operations has expressed a preference for having the model reflect the status-quo with respect to subcontracting, and this would obviously be the easiest route to take in terms of the effort required to build the model. However, if ConnDOT decides that a thorough analysis of the effects of alternative levels of subcontracting would be of significant value, then the model will be modified so that this can be included in the study.

The final question was discussed previously at the end of Section V. It raises the possibility of a follow-on project that would package the model from the current study into a decision support system that ConnDOT could use on its own. The decision to go ahead with plans for developing this type of system does not need to be made right away, but at this stage of the current project there would be certain benefits to knowing whether or not ConnDOT would eventually like to have a user-friendly decision support system.

Each of the five questions discussed above should be answered in conjunction with the broader question of how ConnDOT would like to be able to use the results of this study. This broader question relates back to the discussion at the beginning of this section regarding different views that ConnDOT might take with respect to ownership of the model. With the second phase of the project still ahead of us, now is the appropriate time to clarify the project's objectives and to agree upon a course of action that is consistent with meeting those objectives. Hopefully, this report will serve to stimulate discussion on these issues.

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APPENDIX A. EXAMPLE OF INPUT FOR OPTIMIZATION SOFTWARE

The optimization software, GAMS, requires that mathematical models be entered in a specific format. Fortunately, the format for GAMS input is similar in structure to standard mathematical notation. Consequently, there is a close correspondence between the example of GAMS input presented in this appendix and the mathematical specification of the two-stage problem presented in Section III.

Much of the data included in the GAMS input presented in small print starting on the next page is not representative of values that are realistic for the ConnDOT system. The input is being presented to clarify the types of input data that are needed and to illustrate how raw data is translated into a mathematical model like that shown in Section III.

The first part of the GAMS input begins with specification of sets, parameters and scalars. This is followed by several pages of tables containing raw data related to equipment quantities, travel distances, and travel times. On pages A.9 and A.10, this raw data is manipulated through a series of equations so that parameters of the type that are defined on page ix are established. Then, on page A.11, the actual optimization model begins to be specified using variables and equations. There is a direct correspondence between the variables shown on page A.11 and the decision variables defined on page viii. Also, the equations in the GAMS input bear a close resemblance to the objective function and constraints presented in the mathematical formulation given in Section III.

The last six lines of the GAMS input are commands related to the running of the program and the displaying of results. Output from the GAMS software is discussed in Appendix B.

```
*    Full-Sized Two-Stage GAMS Model of ConnDOT's Maintenance System
*    Principal Investigators:  Gerard Campbell and Christian Davis

SET I   set of maintenance garages and other sources of equipment
  /GAR1 * GAR55, OTH1 * OTH21/;

SET F   set of repair facilities
  /WIN,BRO,DAR,WAT,MIL,EGR,WET,EHA,WWL,HIG,OSA,PUTN,LIS/;

SET E   set of equipment types
 /TYPE1A, TYPE1B, TYPE2, TYPE3, TYPE4, TYPE5/;

SET J  roadway sectors
 /S1 * S200/;

PARAMETER K(F)   annual fixed costs of facilities in thousands of dollars
 /WIN 191.6, BRO 281.4, DAR 236.5, WAT 202.6, MIL 208.8, EGR 217.2,
  WET 220.5, EHA 285.5, WWL 178.4, HIG 240.0, OSA 198.7, PUTN 184.2,
  LIS 268.8/;

PARAMETER P(F)   present capacity based on equipment serviceable
 /WIN 120.48, BRO 89.16, DAR 141.36, WAT 78.72, MIL 141.36, EGR 120.48,
  WET 172.68, EHA 120.48, WWL 99.6, HIG 110.04, OSA 130.92, PUTN 110.04,
  LIS 120.48/;

SCALARS      ACAP     capacity added by two bays        /20.88/
             ACOST    cost of adding two bays           /22.15/
             BCAP     capacity added per bay above two  /10.44/
             BCOST    cost per bay above two            /8.075/
             RG       capacity added by two bays at a garage  /5/
             SG       subsequent capacity added at garage     /2.5/
             MG       cost of expanding garage by two bays    /20/
             NG       cost of each bay above two at a garage  /8/;

PARAMETER L(I)   annualized cost of keeping garage i open  ;
    L(I) = 150;

TABLE G(I,E)  quantity of type e equipment at garage i
        TYPE1A  TYPE1B  TYPE2  TYPE3  TYPE4  TYPE5
GAR1       4       1       1      6      2     15
GAR2       4       1       1      4      5     13
GAR3       0       5      37     16     27     83
GAR4      10       9       9     24     15     52
GAR5       5       3       2      9     12     31
GAR6       2       2       1      1      8     11
GAR7       8       1       2     10      9     34
GAR8       6       4       3     14      9     42
GAR9       9       1       1     13      8     33
GAR10      6       7       1     15     19     42
GAR11      6       2       3     12     20     27
GAR12      8       8       1     19     12     35
GAR13      9       6       7     20     17     71
GAR14      5       3       2     12      7     28
GAR15     11       6      11     15     14     61
GAR16      9       4       2     16     13     32
GAR17      6       4       3     10     13     23
GAR18     10       2       1     13      5     32
GAR19     12       2       3     11      6     26
GAR20     11      18      34     32     49    237
GAR21     11       3       5     13     22     33
GAR22      6       3       1     13     10     27
GAR23      8       1       2     13      8     28
GAR24      8       3       2      8     20     31
GAR25     18       7       5     24     26     54
GAR26     11       0       1     14      5     31
GAR27     12       3       2     11     14     27
GAR28      9       2       3     11     17     23
GAR29      9       4       1      9     15     20
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GAR30     7     1     7    13    13    35
GAR31     6     1     4     9     9    21
GAR32     2     2     0     5     8     6
GAR33     2     2     3    12    10    20
GAR34    12     3     2    15    19    34
GAR35    10     1     2     6    15    25
GAR36     6     8     5    17    26    41
GAR37     5     1     0     3     3    18
GAR38     8     3     8    16    11    43
GAR39     3     0     1     5     3     4
GAR40     9     3     1     9     8    27
GAR41     8     4     4     7     5    24
GAR42     8     3     1     8    11    27
GAR43     8     5    16    16    19    86
GAR44    13     1     3    12    13    43
GAR45     7     4     1     6    14    32
GAR46     7     3     3     9    16    47
GAR47    11     4    12    25    20    89
GAR48     6     3     3    12    13    38
GAR49    10     3     2    12    12    36
GAR50     9     4     2     9    12    44
GAR51     7     4     4     8    24    36
GAR52     6     3     1     8     7    37
GAR53     6     4     3     9    24    31
GAR54     7     5     7    20    14    60
GAR55    12    16    15    32    40    62
OTH1      0     3     2     8    10     8
OTH2      0     7     8     1     3    11
OTH3      0     1     6     1     4    17
OTH4      0     1    26     2    24     2
OTH5      0     1    12     6     4    34
OTH6      0     0    12     0     1     0
OTH7      0     2    16     1     8     6
OTH8      1     2     4     8    17     6
OTH9      0    12    29    23    38   120
OTH10     1     1     2     7     7     8
OTH11     0     3     7    15    21    53
OTH12     0     5     6     1     4     7
OTH13     1     4    17     3    12    12
OTH14     0     0    26     1     2     4
OTH15     1     0    31     5     7     7
OTH16     0     0     6     1    42     8
OTH17     0     0    15     0     3     7
OTH18     6     2     6    11     8    12
OTH19     0     2     6    15     2    10
OTH20     3     4     2     4     6    10
OTH21     0     0    17     0     3     6        ;

TABLE SUB(I,E) equipment subtracted from transportation costs
        TYPE1A  TYPE1B  TYPE2  TYPE3  TYPE4  TYPE5
GAR1       0       0      0      0      0      1
GAR2       0       0      0      0      0      4
GAR3       0       0      0      0      0      3
GAR4       0       0      0      0      0      4
GAR5       0       0      0      0      0      1
GAR6       0       0      0      0      0      2
GAR7       0       0      0      1      0      1
GAR8       0       0      0      0      0      1
GAR9       0       0      0      0      0      2
GAR10      0       0      0      0      0      5
GAR11      0       0      0      0      0      2
GAR12      0       0      0      1      0      3
GAR13      0       0      0      1      0      2
GAR14      0       0      0      0      0      0
GAR15      0       0      0      0      0      5
GAR16      0       0      0      0      0      3
GAR17      0       0      0      0      0      1
GAR18      0       0      0      0      0      1
GAR19      0       0      0      0      0      2
```

GAR20	0	0	0	4	0	13
GAR21	0	0	0	0	0	2
GAR22	0	0	0	0	0	1
GAR23	0	0	0	0	0	1
GAR24	0	0	0	0	0	1
GAR25	0	0	0	1	0	5
GAR26	0	0	0	0	0	1
GAR27	0	0	0	1	0	2
GAR28	0	0	0	0	0	1
GAR29	0	0	0	0	0	2
GAR30	0	0	0	0	0	2
GAR31	0	0	0	0	0	1
GAR32	0	0	0	0	0	0
GAR33	0	0	0	0	0	1
GAR34	0	0	0	0	0	2
GAR35	0	0	0	0	0	1
GAR36	0	0	0	1	0	4
GAR37	0	0	0	0	0	1
GAR38	0	0	0	0	0	1
GAR39	0	0	0	0	0	1
GAR40	0	0	0	0	0	1
GAR41	0	0	0	0	0	1
GAR42	0	0	0	1	0	1
GAR43	0	0	0	0	0	2
GAR44	0	0	0	0	0	2
GAR45	0	0	0	0	0	1
GAR46	0	0	0	0	0	3
GAR47	0	0	0	0	0	4
GAR48	0	0	0	0	0	1
GAR49	0	0	0	1	0	0
GAR50	0	0	0	0	0	1
GAR51	0	0	0	1	0	3
GAR52	0	0	0	0	0	1
GAR53	0	0	0	0	0	1
GAR54	0	0	0	0	0	3
GAR55	0	0	0	0	0	0
OTH1	0	0	0	0	0	0
OTH2	0	0	0	0	0	7
OTH3	0	0	0	0	0	0
OTH4	0	0	0	0	0	1
OTH5	0	0	0	0	0	0
OTH6	0	0	0	0	0	7
OTH7	0	0	0	0	0	1
OTH8	0	0	0	0	0	0
OTH9	0	0	0	1	0	2
OTH10	0	0	0	0	0	1
OTH11	0	0	0	1	0	2
OTH12	0	0	0	0	0	5
OTH13	0	0	0	0	0	2
OTH14	0	0	0	0	0	0
OTH15	0	0	0	0	0	0
OTH16	0	0	0	0	0	0
OTH17	0	0	0	0	0	0
OTH18	0	0	0	0	0	2
OTH19	0	0	0	0	0	0
OTH20	0	0	0	0	0	0
OTH21	0	0	0	0	0	0

TABLE DIST(I,F)   distance between facility f and garage i

	WIN	BRO	DAR	WAT	MIL	EGR	WET
GAR1	15.13	9999	9999	35.60	9999	34.75	9999
GAR2	8.39	9999	9999	28.64	9999	28.01	37.86
GAR3	3.8	32.93	9999	16.6	9999	24.46	30.36
GAR4	0	9999	9999	24.00	9999	19.62	29.47
GAR5	16.0	28.04	9999	23.91	9999	36.89	9999
GAR6	23.01	25.58	9999	27.09	9999	9999	9999
GAR7	14.0	22.12	9999	14.85	9999	33.5	30.88
GAR8	33.33	6.0	38.26	26.5	9999	9999	9999
GAR9	31.07	16.54	9999	12.5	26.04	9999	32.21

GAR10	9999	6.0	27.33	26.92	27.39	9999	9999
GAR11	9999	26.42	5.03	9999	23.56	9999	9999
GAR12	9999	31.26	0	9999	26.71	9999	9999
GAR13	9999	25.14	8.4	9999	18.46	9999	9999
GAR14	9999	27.15	14.74	34.2	11.43	9999	9999
GAR15	24.0	28.55	9999	0	27.86	34.69	23.02
GAR16	18.71	28.9	9999	5.29	33.15	30.72	19.05
GAR17	29.79	34.58	9999	13.13	27.61	29.31	14.92
GAR18	36.28	23.51	36.69	12.28	15.61	9999	31.66
GAR19	9999	23.41	31.24	21.94	5.79	9999	33.19
GAR20	9999	29.02	26.17	27.86	0	9999	38.01
GAR21	9999	25.99	21.56	29.43	5.35	9999	9999
GAR22	9999	38.21	9999	32.93	16.34	9999	28.9
GAR23	9999	29.67	32.83	25.04	6.73	9999	32.23
GAR24	9999	34.65	9999	21.6	15.71	9999	22.59
GAR25	42.07	39.19	9999	22.29	20.63	38.39	18.33
GAR26	20.28	9999	9999	17.41	38.84	17.57	9.19
GAR27	29.04	9999	9999	31.05	9999	17.7	10.18
GAR28	29.75	9999	9999	30.62	9999	18.41	7.6
GAR29	35.34	41.53	9999	20.08	26.41	31.66	11.6
GAR30	34.91	40.1	9999	19.65	28.68	29.09	9.26
GAR31	15.67	9999	9999	23.49	9999	11.49	15.27
GAR32	19.15	9999	9999	29.45	9999	5.24	19.89
GAR33	19.62	9999	9999	34.69	9999	0	20.35
GAR34	26.58	9999	9999	37.43	9999	6.96	18.21
GAR35	27.28	9999	9999	32.27	9999	7.66	13.05
GAR36	34.29	9999	9999	36.30	9999	17.39	15.43
GAR37	9999	9999	9999	9999	9999	30.29	33.84
GAR38	9999	9999	9999	9999	9999	29.22	28.52
GAR39	9999	9999	9999	9999	9999	38.83	31.31
GAR40	35.52	9999	9999	37.53	9999	24.18	16.66
GAR41	9999	9999	9999	28.36	33.5	31.16	14.76
GAR42	9999	9999	9999	38.68	9999	27.60	16.79
GAR43	9999	9999	9999	9999	9999	33.88	23.07
GAR44	9999	9999	9999	37.94	39.49	9999	24.34
GAR45	9999	9999	9999	38.59	22.03	9999	32.27
GAR46	9999	9999	9999	9999	9999	9999	39.69
GAR47	9999	9999	9999	9999	37.55	9999	35.05
GAR48	9999	9999	9999	9999	9999	9999	35.0
GAR49	9999	9999	9999	9999	9999	9999	9999
GAR50	9999	9999	9999	9999	9999	9999	9999
GAR51	9999	9999	9999	9999	9999	9999	39.77
GAR52	9999	9999	9999	9999	9999	9999	9999
GAR53	9999	9999	9999	9999	9999	9999	9999
GAR54	9999	9999	9999	9999	9999	9999	9999
GAR55	29.47	9999	9999	23.02	9999	20.35	0
OTH1	36.55	17.82	9999	12.55	18.92	9999	31.93
OTH2	29.14	31.93	9999	10.48	31.24	29.68	17.3
OTH3	9999	31.28	38.14	22.89	12.69	9999	25.32
OTH4	9999	31.28	38.14	22.89	12.69	9999	25.32
OTH5	28.63	9999	9999	31.01	9999	19.49	4.59
OTH6	9999	9999	9999	28.02	9999	14.67	6.44
OTH7	9999	9999	9999	31.05	9999	17.7	10.18
OTH8	19.15	9999	9999	29.45	9999	5.24	19.89
OTH9	25.26	9999	9999	27.27	9999	13.92	7.19
OTH10	9999	9999	9999	9999	9999	9999	9999
OTH11	9999	9999	9999	9999	34.44	9999	35.98
OTH12	9999	9999	9999	9999	9999	9999	9999
OTH13	9999	9999	9999	9999	9999	9999	9999
OTH14	29.37	9999	9999	21.38	9999	21.99	1.64
OTH15	33.38	9999	9999	29.05	9999	22.06	6.57
OTH16	29.47	9999	9999	23.02	9999	20.35	0
OTH17	33.38	9999	9999	29.05	9999	22.06	6.57
OTH18	9999	9999	9999	9999	9999	9999	34.33
OTH19	9999	9999	9999	29.12	33.31	30.24	20.6
OTH20	9999	9999	9999	9999	9999	9999	9999
OTH21	9999	9999	9999	9999	9999	9999	39.75

+	EHA	WWL	HIG	OSA	PUTN	LIS
GAR1	9999	9999	9999	9999	9999	9999
GAR2	9999	9999	9999	9999	9999	9999
GAR3	9999	9999	9999	9999	9999	9999
GAR4	9999	9999	9999	9999	9999	9999
GAR5	9999	9999	9999	9999	9999	9999
GAR6	9999	9999	9999	9999	9999	9999
GAR7	9999	9999	9999	9999	9999	9999
GAR8	9999	9999	9999	9999	9999	9999
GAR9	29.77	9999	38.00	9999	9999	9999
GAR10	33.85	9999	9999	9999	9999	9999
GAR11	37.1	9999	9999	9999	9999	9999
GAR12	9999	9999	9999	9999	9999	9999
GAR13	32.45	9999	9999	9999	9999	9999
GAR14	24.97	9999	9999	9999	9999	9999
GAR15	28.46	9999	32.63	9999	9999	9999
GAR16	33.75	9999	33.48	9999	9999	9999
GAR17	20.49	9999	20.52	37.2	9999	9999
GAR18	17.95	9999	33.18	9999	9999	9999
GAR19	12.32	9999	34.22	36.67	9999	9999
GAR20	13.61	9999	39.07	38.21	9999	9999
GAR21	18.89	9999	9999	9999	9999	9999
GAR22	6.92	9999	29.9	21.87	9999	9999
GAR23	6.88	9999	32.34	31.48	9999	9999
GAR24	7.52	9999	23.24	31.47	9999	9999
GAR25	11.3	9999	18.44	30.12	9999	9999
GAR26	31.72	32.77	26.47	9999	9999	9999
GAR27	39.52	18.34	25.26	9999	9999	35.44
GAR28	33.34	25.37	18.35	35.03	9999	34.40
GAR29	18.03	39.83	13.79	30.47	9999	9999
GAR30	20.37	37.26	14.89	31.57	9999	9999
GAR31	37.80	31.71	31.1	9999	9999	9999
GAR32	9999	33.59	34.97	9999	9999	9999
GAR33	9999	29.22	35.43	9999	9999	9999
GAR34	9999	23.52	33.29	9999	9999	9999
GAR35	9999	25.18	28.13	9999	9999	9999
GAR36	9999	13.09	30.51	9999	36.26	33.92
GAR37	9999	7.25	9999	9999	22.51	32.69
GAR38	9999	0	42.48	9999	23.17	27.7
GAR39	9999	12.94	30.76	35.39	24.44	16.21
GAR40	9999	15.03	31.74	9999	34.49	28.96
GAR41	21.9	39.33	4.27	20.95	9999	37.19
GAR42	37.87	24.64	19.51	26.84	38.73	25.21
GAR43	39.77	26.62	18.66	23.58	9999	18.93
GAR44	26.6	38.21	5.49	11.96	9999	29.79
GAR45	10.27	9999	23.26	17.27	9999	9999
GAR46	39.2	36.71	28.91	13.75	9999	14.2
GAR47	25.79	9999	16.7	0.66	9999	27.61
GAR48	9999	25.39	28.28	27.25	30.41	7.0
GAR49	9999	26.78	34.36	28.77	25.65	0.92
GAR50	9999	9999	39.26	24.1	36.14	16.43
GAR51	9999	27.98	33.05	22.48	31.31	7.21
GAR52	9999	25.3	9999	39.81	16.34	11.91
GAR53	9999	16.05	9999	9999	8.35	23.18
GAR54	9999	23.17	9999	9999	0	25.44
GAR55	29.63	28.52	19.03	35.71	9999	9999
OTH1	22.65	9999	38.08	9999	9999	9999
OTH2	26.17	9999	26.68	9999	9999	9999
OTH3	9.42	9999	26.35	35.74	9999	9999
OTH4	9.42	9999	26.35	35.74	9999	9999
OTH5	30.20	27.66	15.94	32.63	9999	39.54
OTH6	35.78	22.08	21.52	38.2	9999	38.14
OTH7	39.52	18.34	25.26	9999	9999	35.44
OTH8	9999	33.59	35.42	9999	9999	9999
OTH9	36.53	22.12	22.27	38.75	9999	9999
OTH10	9999	9999	35.52	20.36	9999	15.51
OTH11	22.68	9999	17.63	4.01	9999	31.68
OTH12	9999	9999	35.29	22.35	31.26	5.82
OTH13	9999	26.79	9999	9999	14.85	12.67

OTH14	29.48	30.16	18.88	9999	9999	9999
OTH15	28.24	30.23	13.51	9999	9999	9999
OTH16	29.63	28.52	19.03	35.74	9999	9999
OTH17	28.24	30.23	13.51	9999	9999	9999
OTH18	9999	12.5	27.96	31.99	28.02	20.0
OTH19	22.18	39.59	9.5	25.0	9999	36.24
OTH20	6.34	9999	26.05	10.89	9999	17.19
OTH21	9999	27.25	33.00	22.6	31.53	7.13 ;

TABLE TIME(I,F) travel time between facility f and garage i

	WIN	BRO	DAR	WAT	MIL	EGR	WET
GAR1	0.33	9999	9999	0.72	9999	0.75	9999
GAR2	0.18	9999	9999	0.57	9999	0.60	0.82
GAR3	0.07	0.59	9999	0.29	9999	0.50	0.59
GAR4	0	9999	9999	0.43	9999	0.42	0.64
GAR5	0.33	0.62	9999	0.50	9999	0.77	9999
GAR6	0.48	0.57	9999	0.57	9999	9999	9999
GAR7	0.28	0.51	9999	0.31	9999	0.71	0.64
GAR8	0.71	0.14	1.08	0.66	9999	9999	9999
GAR9	0.61	0.35	9999	0.28	0.56	9999	0.63
GAR10	9999	0.14	0.80	0.49	0.60	9999	9999
GAR11	9999	0.57	0.1	9999	0.45	9999	9999
GAR12	9999	0.66	0.00	9999	0.47	9999	9999
GAR13	9999	0.55	0.15	9999	0.35	9999	9999
GAR14	9999	0.59	0.26	0.61	0.21	9999	9999
GAR15	0.43	0.53	9999	0.00	0.54	0.75	0.46
GAR16	0.34	0.62	9999	0.09	0.63	0.68	0.39
GAR17	0.64	0.65	9999	0.24	0.56	0.63	0.28
GAR18	0.64	0.46	0.66	0.21	0.33	0.92	0.57
GAR19	9999	0.49	0.57	0.41	0.13	9999	0.65
GAR20	9999	0.64	0.47	0.54	0.00	9999	0.74
GAR21	9999	0.58	0.39	0.55	0.10	9999	9999
GAR22	9999	0.80	9999	0.63	0.31	9999	0.62
GAR23	9999	0.63	0.59	0.48	0.13	9999	0.63
GAR24	9999	0.69	9999	0.44	0.30	9999	0.45
GAR25	0.89	0.78	9999	0.46	0.38	0.68	0.38
GAR26	0.45	0.85	9999	0.37	0.79	0.36	0.19
GAR27	0.64	9999	9999	0.63	9999	0.35	0.19
GAR28	0.65	9999	9999	0.61	9999	0.36	0.15
GAR29	0.73	0.77	9999	0.36	0.49	0.59	0.25
GAR30	0.75	0.76	9999	0.35	0.54	0.59	0.20
GAR31	0.35	9999	9999	0.51	9999	0.25	0.33
GAR32	0.41	9999	9999	0.64	9999	0.11	0.43
GAR33	0.42	9999	9999	0.75	9999	0.00	0.40
GAR34	0.56	9999	9999	0.74	9999	0.14	0.34
GAR35	0.59	9999	9999	0.65	9999	0.17	0.25
GAR36	0.73	9999	9999	0.72	9999	0.37	0.28
GAR37	9999	9999	9999	9999	9999	0.68	0.62
GAR38	9999	9999	9999	9999	9999	0.61	0.53
GAR39	9999	9999	9999	9999	9999	0.79	0.63
GAR40	0.75	9999	9999	0.74	9999	0.46	0.30
GAR41	9999	9999	9999	0.52	0.60	0.58	0.28
GAR42	9999	9999	9999	0.77	9999	0.52	0.31
GAR43	9999	9999	9999	9999	9999	0.64	0.43
GAR44	9999	9999	9999	0.73	0.82	9999	0.48
GAR45	9999	9999	9999	0.74	0.42	9999	0.69
GAR46	9999	9999	9999	9999	9999	9999	0.77
GAR47	9999	9999	9999	9999	0.69	9999	0.64
GAR48	9999	9999	9999	9999	9999	9999	0.64
GAR49	9999	9999	9999	9999	9999	9999	9999
GAR50	9999	9999	9999	9999	9999	9999	9999
GAR51	9999	9999	9999	9999	9999	9999	0.73
GAR52	9999	9999	9999	9999	9999	9999	9999
GAR53	9999	9999	9999	9999	9999	9999	9999
GAR54	9999	9999	9999	9999	9999	9999	9999
GAR55	0.64	9999	9999	0.46	9999	0.40	0.00
OTH1	0.67	0.34	9999	0.24	0.41	9999	0.60
OTH2	0.58	0.61	9999	0.20	0.62	0.65	0.35
OTH3	9999	0.64	0.68	0.47	0.24	9999	0.50

OTH4	9999	0.64	0.68	0.47	0.24	9999	0.50
OTH5	0.64	9999	9999	0.55	9999	0.38	0.10
OTH6	0.58	9999	9999	0.57	9999	0.29	0.12
OTH7	9999	9999	9999	0.63	9999	0.35	0.19
OTH8	0.41	9999	9999	0.64	9999	0.11	0.43
OTH9	0.57	9999	9999	0.56	9999	0.28	0.13
OTH10	9999	9999	9999	9999	9999	9999	9999
OTH11	9999	9999	9999	9999	0.64	9999	0.68
OTH12	9999	9999	9999	9999	9999	9999	9999
OTH13	9999	9999	9999	9999	9999	9999	9999
OTH14	0.62	9999	9999	0.43	9999	0.43	0.03
OTH15	0.71	9999	9999	0.52	9999	0.42	0.13
OTH16	0.64	9999	9999	0.46	9999	0.40	0.00
OTH17	0.71	9999	9999	0.52	9999	0.42	0.13
OTH18	9999	9999	9999	9999	9999	9999	0.69
OTH19	9999	9999	9999	0.53	0.61	0.56	0.25
OTH20	9999	9999	9999	9999	9999	9999	9999
OTH21	9999	9999	9999	9999	9999	9999	0.74

+	EHA	WWL	HIG	OSA	PUTN	LIS
GAR1	9999	9999	9999	9999	9999	9999
GAR2	9999	9999	9999	9999	9999	9999
GAR3	9999	9999	9999	9999	9999	9999
GAR4	9999	9999	9999	9999	9999	9999
GAR5	9999	9999	9999	9999	9999	9999
GAR6	9999	9999	9999	9999	9999	9999
GAR7	9999	9999	9999	9999	9999	9999
GAR8	9999	9999	9999	9999	9999	9999
GAR9	0.61	9999	0.75	9999	9999	9999
GAR10	0.70	9999	9999	9999	9999	9999
GAR11	0.69	9999	9999	9999	9999	9999
GAR12	9999	9999	9999	9999	9999	9999
GAR13	0.59	9999	9999	9999	9999	9999
GAR14	0.45	9999	9999	9999	9999	9999
GAR15	0.57	9999	0.61	9999	9999	9999
GAR16	0.66	9999	0.65	9999	9999	9999
GAR17	0.42	9999	0.41	0.68	9999	9999
GAR18	0.36	9999	0.68	0.82	9999	9999
GAR19	0.25	9999	0.69	0.71	9999	9999
GAR20	0.25	9999	0.78	0.71	9999	9999
GAR21	0.34	9999	9999	9999	9999	9999
GAR22	0.14	9999	0.64	0.40	9999	9999
GAR23	0.12	9999	0.65	0.58	9999	9999
GAR24	0.14	9999	0.49	0.62	9999	9999
GAR25	0.21	9999	0.40	0.60	9999	9999
GAR26	0.65	0.62	0.50	9999	9999	9999
GAR27	0.72	0.34	0.46	9999	9999	0.77
GAR28	0.65	0.47	0.38	0.68	9999	0.63
GAR29	0.34	0.72	0.27	0.57	9999	9999
GAR30	0.39	0.72	0.30	0.60	9999	9999
GAR31	0.79	0.63	0.61	9999	9999	9999
GAR32	9999	0.68	0.70	9999	9999	9999
GAR33	9999	0.62	0.67	9999	9999	9999
GAR34	9999	0.48	0.61	9999	9999	9999
GAR35	9999	0.51	0.52	9999	9999	9999
GAR36	9999	0.25	0.55	9999	0.75	0.76
GAR37	9999	0.14	9999	9999	0.50	0.72
GAR38	9999	0	9999	9999	0.50	0.60
GAR39	9999	0.28	0.67	0.74	0.50	0.36
GAR40	9999	0.30	0.57	9999	0.75	0.66
GAR41	0.49	0.71	0.09	0.39	9999	0.75
GAR42	0.77	0.54	0.42	0.53	0.85	0.47
GAR43	0.87	0.59	0.41	0.46	9999	0.35
GAR44	0.58	0.76	0.12	0.26	9999	0.60
GAR45	0.22	9999	0.48	0.32	9999	9999
GAR46	0.73	0.76	0.52	0.25	9999	0.30
GAR47	0.49	9999	0.31	0.02	9999	0.54
GAR48	9999	0.54	0.58	0.51	0.54	0.14
GAR49	9999	0.58	0.70	0.53	0.45	0.02

```
GAR50  9999   9999   0.73   0.46   0.72   0.37
GAR51  9999   0.59   0.67   0.42   0.56   0.15
GAR52  9999   0.55   9999   0.77   0.30   0.26
GAR53  9999   0.35   9999   9999   0.17   0.50
GAR54  9999   0.50   9999   9999   0.00   0.46
GAR55  0.59   0.53   0.36   0.66   9999   9999
OTH1   0.46   9999   0.73   9999   9999   9999
OTH2   0.54   9999   0.53   9999   9999   9999
OTH3   0.17   9999   0.54   0.68   9999   9999
OTH4   0.17   9999   0.54   0.68   9999   9999
OTH5   0.55   0.51   0.29   0.59   9999   0.73
OTH6   0.65   0.41   0.39   0.69   9999   0.70
OTH7   0.72   0.34   0.46   9999   9999   0.77
OTH8   9999   0.68   0.70   9999   9999   9999
OTH9   0.66   0.41   0.40   0.70   9999   9999
OTH10  9999   9999   0.64   0.37   9999   0.35
OTH11  0.44   9999   0.35   0.09   9999   0.61
OTH12  9999   9999   0.69   0.42   0.59   0.13
OTH13  9999   0.59   9999   9999   0.26   0.24
OTH14  0.59   0.56   0.36   9999   9999   9999
OTH15  0.52   0.55   0.25   9999   9999   9999
OTH16  0.59   0.53   0.36   0.66   9999   9999
OTH17  0.52   0.55   0.25   9999   9999   9999
OTH18  9999   0.26   0.62   0.62   0.61   0.46
OTH19  0.47   0.73   0.23   0.44   9999   0.76
OTH20  0.68   9999   0.47   0.20   9999   0.36
OTH21  9999   0.57   0.66   0.42   0.54   0.14    ;

PARAMETER XCORD(I)  x coordinate of garage i
 /GAR1 2, GAR2 4, GAR3 5, GAR4 6, GAR5 3, GAR6 2, GAR7 4, GAR8 2, GAR9 5,
GAR10 2, GAR11 2, GAR12 2, GAR13 4, GAR14 5, GAR15 6, GAR16 6, GAR17 8,
GAR18 6, GAR19 7, GAR20 7, GAR21 6, GAR22 10,GAR23 8, GAR24 9, GAR25 10,
GAR26 9, GAR27 12,GAR28 12,GAR29 10,GAR30 10,GAR31 9, GAR32 9, GAR33 10,
GAR34 11,GAR35 11,GAR36 13,GAR37 16,GAR38 15,GAR39 16,GAR40 13,GAR41 12,
GAR42 13,GAR43 15,GAR44 14,GAR45 12,GAR46 17,GAR47 15,GAR48 17,GAR49 18,
GAR50 19,GAR51 17,GAR52 19,GAR53 19,GAR54 20,GAR55 11,
OTH1 99, OTH2 99, OTH3 99, OTH4 99, OTH5 99, OTH6 99, OTH7 99, OTH8 99,
OTH9 99, OTH10 99, OTH11 99, OTH12 99, OTH13 99, OTH14 99, OTH15 99,
OTH16 99, OTH17 99, OTH18 99, OTH19 99, OTH20 99, OTH21 99/;

PARAMETER YCORD(I)  y coordinate of garage i
 /GAR1 10,GAR2 10,GAR3 8, GAR4 9, GAR5 8, GAR6 8, GAR7 7, GAR8 5, GAR9 5,
GAR10 4, GAR11 2, GAR12 1, GAR13 1, GAR14 2, GAR15 5, GAR16 6, GAR17 5,
GAR18 4, GAR19 3, GAR20 2, GAR21 1, GAR22 2, GAR23 2, GAR24 3, GAR25 4,
GAR26 7, GAR27 7, GAR28 6, GAR29 4, GAR30 5, GAR31 8, GAR32 9, GAR33 9,
GAR34 9, GAR35 8, GAR36 8, GAR37 9, GAR38 8, GAR39 7, GAR40 7, GAR41 4,
GAR42 5, GAR43 4, GAR44 3, GAR45 2, GAR46 2, GAR47 2, GAR48 4, GAR49 4,
GAR50 2, GAR51 3, GAR52 6, GAR53 8, GAR54 8, GAR55 6,
OTH1 99, OTH2 99, OTH3 99, OTH4 99, OTH5 99, OTH6 99, OTH7 99, OTH8 99,
OTH9 99, OTH10 99, OTH11 99, OTH12 99, OTH13 99, OTH14 99, OTH15 99,
OTH16 99, OTH17 99, OTH18 99, OTH19 99, OTH20 99, OTH21 99/;

PARAMETER XCOR(J)  x coordinate of sector j;
   XCOR(J) = MOD((ORD(J)-1),20)+1;

PARAMETER YCOR(J)  y coordinate of sector j;
   YCOR(J) = FLOOR((ORD(J)-1)/20) +1;

PARAMETER DISTANCE(I,J)  distance between garage i and sector j;

DISTANCE(I,J) = SQRT(SQR(XCORD(I)-XCOR(J)) +
SQR(YCORD(I)-YCOR(J)));

PARAMETER W(E)  weight for equipment type e based on work bays
 /TYPE1A 1, TYPE1B .59, TYPE2 .33, TYPE3 .38, TYPE4 0, TYPE5 0/;

PARAMETER DEM(I)   total weighted demand at garage i;
 DEM(I) = SUM( E, ( W(E)*G(I,E) ));
```

```
PARAMETER CALL(E)   identifier for equipment types
 /TYPE1A 1, TYPE1B 10, TYPE2 2, TYPE3 3, TYPE4 4, TYPE5 5/;

PARAMETER DCHECK(F,I,E)  special identifier for type 3 equipment;

DCHECK(F,I,E)$(CALL(E) EQ 3) = 1$(DIST(I,F) LE 9.17) + 2$(DIST(I,F) GT 9.17) ;

PARAMETER PARTC(F,I,E)  partial annual transportation costs;

PARTC(F,I,E)$(CALL(E) EQ 1) = (DIST(I,F)*1.09*4.68
   + TIME(I,F)*1.09*250.72)*9.4*G(I,E)/1000 ;

PARTC(F,I,E)$(CALL(E) EQ 10) = (DIST(I,F)*1.09*6.00
   + TIME(I,F)*1.09*250.72)*9.4*G(I,E)/1000 ;

PARTC(F,I,E)$(CALL(E) EQ 2) = (DIST(I,F)*1.09*3.56
   + TIME(I,F)*1.09*263.16)*5.2*G(I,E)/1000 ;

PARTC(F,I,E)$(DCHECK(F,I,E) EQ 1) = (DIST(I,F)*1.09*5.56
   + TIME(I,F)*1.09*398.16)*3.4*(G(I,E)-SUB(I,E))/1000 ;

PARTC(F,I,E)$(DCHECK(F,I,E) EQ 2) = (68.20 + DIST(I,F)*1.09*10.24
   + TIME(I,F)*1.09*136.40)*3.4*(G(I,E)-SUB(I,E))/1000;

PARTC(F,I,E)$(CALL(E) EQ 4) = (DIST(I,F)*1.09*2.00
   + TIME(I,F)*1.09*131.60)*1.4*G(I,E)/1000 ;

PARTC(F,I,E)$(CALL(E) EQ 5) = (DIST(I,F)*1.09*2.00
   + TIME(I,F)*1.09*131.60)*0.7*(G(I,E)-SUB(I,E))/1000  ;

PARAMETER C(F,I)   annual transportation costs in thousands of dollars;

C(F,I) = SUM(E,PARTC(F,I,E)) + (DIST(I,F)*1.09*1.00
         + TIME(I,F)*1.09*65.80)*26/1000 ;

PARAMETER GF(I)  distinguishes garages from other equipment locations;
   GF(I)$(ORD(I) LE 55) =1;

PARAMETER MAP1(I,J)  greater than zero if gar i and sector j are within a
                     specified distance and i is a maintenance garage;

   MAP1(I,J) = GF(I) * (6-DISTANCE(I,J));

PARAMETER MAP(I,F)  greater than zero if t and tp can be other than zero;

  MAP(I,F)$(DIST(I,F) LE 40) = GF(I);

PARAMETER U(F,I)   cost of transporting a unit from garage i to facility f;

U(F,I)$(GF(I) EQ 1) = C(F,I)/DEM(I);

U(F,I)$(GF(I) NE 1) = 999;

PARAMETER RLIMIT(I)  maximum reduction at garage i, based on equipment;

RLIMIT(I)$(GF(I) EQ 1) = DEM(I)*.5;

PARAMETER DS(J)  demand in sector j, based on equipment;

DS(J) = SUM(I$(GF(I) EQ 1),DEM(I))/200;

PARAMETER TCOST(I,J)  total annual cost to service sector j from garage i;

TCOST(I,J)=DISTANCE(I,J)*6;

PARAMETER XSPACE(I)   extra space at garage i, based on equipment;

   XSPACE(I) = 0;
```

```
VARIABLES
   A(F)       binary variable indicating if two bays are added
   B(F)       number of bays added above two
   AG(I)      binary variable for two bay expansion at garage i
   BG(I)      number of bays above two added at garage i
   X(F,I)     shipment percentages
   Y(F)       binary variable indicating if facility is kept open
   XS(I,J)    proportion of sector j served by garage i
   T(F,I)     additional equipment going to facility f from garage i
   TP(F,I)    reduction in equipment going to f from i
   YG(I)      binary variable indicating if garage i is kept open
   Z          total cost;

POSITIVE VARIABLES X, B, XS, T, TP, BG;

BINARY VARIABLES A, AG, Y, YG;

EQUATIONS
   COST           objective function
   DEMAND(I)      all of garage i demand must be met
   SUPPLY(F)      capacity of facility f cannot be exceeded
   EXPAND1(F)     first expansion not allowed unless facility is open
   EXPAND2(F)     additional expansions not allowed without first
   EXG1(I)        first expansion at garage i
   EXG2(I)        additional expansion at garage i
   SMALL(I)       fixes binary variable for oth facilities
   TIGHTEN(F,I)   extra constraints added to tighten l.p. bounds
   JDEM(J)        all of sector j demand must be met
   ISUPPLY(I)     capacity of garage i cannot be exceeded
   SASSIGN(I)     assign sector to an open garage
   TIGHT2(I,J)    another set of extra constraints to tighten lp bounds
   IEXPAND(I)     limit on expansion at garage i
   REDUCE(F,I)    limits extent of reduction in what garage i sends facility f
   BAL2           overall equipment balance
   TOTFAC         constraint on total number of facilities ;

COST ..   Z =E= SUM(F,(K(F)*Y(F)+ACOST*A(F)+BCOST*B(F)))
          +SUM((F,I)$(DIST(I,F) LE 40),(C(F,I)*X(F,I)))
          +SUM((I,F)$(MAP(I,F) GT 0),(U(F,I)*(T(F,I)-TP(F,I))))
     +SUM((I,J)$(DISTANCE(I,J) LT 6),TCOST(I,J)*XS(I,J))
     +SUM(I$(GF(I) EQ 1),(L(I)*YG(I)+MG*AG(I)+NG*BG(I)));

DEMAND(I)..   SUM(F$(DIST(I,F) LE 40),X(F,I)) =E= 1;

SUPPLY(F)..  SUM(I$(DIST(I,F) LE 40),(DEM(I)*X(F,I)))
            +SUM(I$(MAP(I,F) GT 0),(T(F,I)-TP(F,I))) =L=
             P(F)*Y(F)+ACAP*A(F)+BCAP*B(F);

EXPAND1(F).. A(F) =L= Y(F);

EXPAND2(F).. B(F) =L= 8*A(F);

EXG1(I)$(GF(I) EQ 1)..  AG(I) =L= YG(I);

EXG2(I)$(GF(I) EQ 1)..  BG(I) =L= 8*AG(I);

TIGHTEN(F,I)$(DIST(I,F) LT 20)..   X(F,I) =L= Y(F);

JDEM(J)..  SUM(I$(MAP1(I,J) GT 0), XS(I,J)) =E= 1;

ISUPPLY(I)$(GF(I) EQ 1)..  SUM(J$(MAP1(I,J) GT 0), (DS(J)*XS(I,J))) =L=
                    (DEM(I)+SUM(F$(MAP(I,F) GT 0),(T(F,I)-TP(F,I))));

SASSIGN(I)$(GF(I) EQ 1)..  SUM(J$(MAP1(I,J) GT 0),XS(I,J)) =L= 20*YG(I);

SMALL(I)$(GF(I) NE 1).. YG(I) =E=0;

TIGHT2(I,J)$(DISTANCE(I,J) LE 1).. XS(I,J) =L= YG(I);
```

```
IEXPAND(I)$(GF(I) EQ 1)..  SUM(F$(MAP(I,F) GT 0),T(F,I)) =L=
                           RG*AG(I) + SG*BG(I) + XSPACE(I)*YG(I);

REDUCE(F,I)$(MAP(I,F) GT 0)..  TP(F,I) =L= DEM(I)*X(F,I);

BAL2..  SUM((I,F)$(MAP(I,F) GT 0),T(F,I)) =E=
        SUM((I,F)$(MAP(I,F) GT 0),TP(F,I));

TOTFAC ..  SUM(F,Y(F)) =L= 13 ;

MODEL CONNDOT /ALL/;

OPTION OPTCR = 0.40;

OPTION ITERLIM= 200000 ;

OPTION RESLIM= 1000000 ;

SOLVE CONNDOT USING MIP MINIMIZING Z;

DISPLAY YG.L, AG.L, BG.L, Y.L, A.L, B.L, X.L, XS.L, T.L, TP.L;
```

APPENDIX B. EXAMPLE OF OUTPUT FROM OPTIMIZATION SOFTWARE

The example of GAMS output presented in this appendix is based on input similar to that shown in Appendix A, except the model is on a smaller scale. Rather than encompassing the entire State, the example in this appendix includes only the State's southeast quarter, as shown in Figures B.1 and B.2.

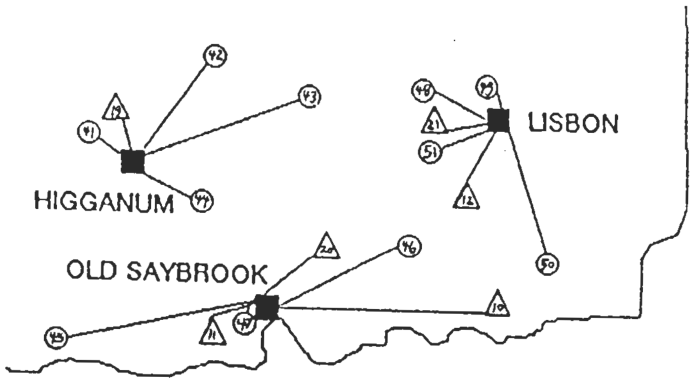

Figure B.1. Existing configuration of facilities in example problem.

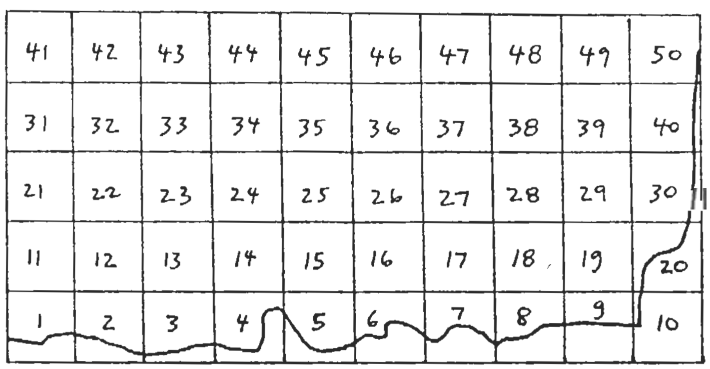

Figure B.2. Arbitrarily-defined roadway sectors for example problem.

The actual model to be used for Phase Two of this project will have roadway sectors that are defined in a more sophisticated manner than what is presented in Figure B.2. Section IV discusses how roadway sectors are defined for the actual model.

The input associated with this example problem is not shown here, just the output. The output, which is shown in fine print beginning on page B.5, corresponds to the system configuration shown in Figures B.3 and B.4.

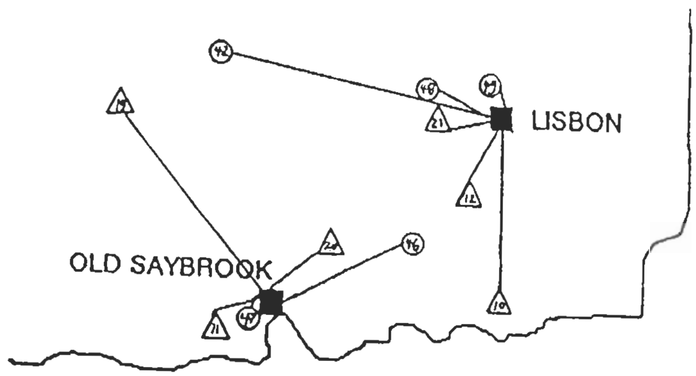

Figure B.3. Facility configuration based on GAMS output.

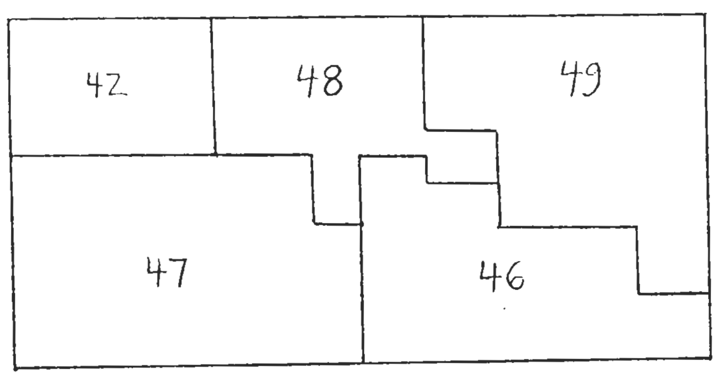

Figure B.4. Roadway sector assignments, based on GAMS output.

Looking at the first three sets of variables specified in the output beginning on page B.6 (YG, AG and BG), we see that only five of the original eleven garages are kept open in the GAMS solution, and those five are being expanded by the following amounts:

Garage #:	42	46	47	48	49
Expansion (bays):	3.4	10	10	5.4	10.

The next three sets of variables (Y, A and B) indicate that two of the original three repair facilities remain open, and neither of these requires expansion.

The set of X variables specifies the assignments of garages to repair facilities that was represented in Figure B.3. Note, however, that the Higganum facility, which is closed in this solution, has garages being assigned to it based on the X variable values shown on page B.6. Also, the garages that are closed (i.e., 41, 43, 44, 45, 50 and 51) all have been assigned to repair facilities. These characteristics of the X variables can be explained by the fact that all of the equipment assigned to a closed repair facility or from a closed garage is subsequently reassigned using the T and TP variables. As an example, consider the closed garage #45, which is assigned to the closed repair facility at Higganum based on the X variables. Looking at the TP variables, which are shown on page B.7, we see that 11.97 units of equipment are subtracted from the GAR45-HIG assignment. The value of 11.97 represents the total amount of equipment currently housed at garage 45 in the existing system. Therefore, the TP value for the GAR45-HIG pair cancels the assignment of GAR45 to HIG, based on the value of the associated X variable. Constraint sets (2) and (4) in the optimization model ensure that equipment will not remain assigned to a closed facility.

But if garage 45 is closed, what happened to the equipment that was housed there? To answer this, we must look at the values of the T variables to see which garages are picking up additional equipment and where that equipment will be going for repair. Constraint (13) in the mathematical model ensures balance amongst reassigned equipment. Based on the values of the T and TP variables, we cannot say where the equipment being picked up by a garage has come from, but from the standpoint of the model this is not important information, as long as the system-wide total amount of equipment remains the same. Once assignments of roadways to garages have been sorted out and compared with what the assignments were previously, then the details of how pieces of equipment are to be reassigned can be established.

The XS variables, which begin on page B.6, show the assignments of roadway sectors to garages. Based on these variables, only open garages are assigned sectors, so there are none of the complications that exist with the X variables. The values of XS variables shown in the output correspond to the garage coverage areas shown in Figure B.4. Note that fractional values of the XS variables do occur, but not very often -- it happened for only three roadway sectors out of fifty in this example. Although fractional XS values do present some questions related to how a roadway sector should be split up, they are not expected to be a major source of error for solutions based on this optimization model. It is anticipated that any inconsistencies caused by fractional values of XS or X variables can be resolved outside the model by rounding fractional values up or down, based on the judgement of those using the output as a basis for recommendations.

This completes the interpretation of the sample output from the GAMS software package. In the final report for the second phase of this project, maps in the formats of those shown in Figures B.3 and B.4, supplemented by relevant cost information, will be used to represent solutions. Therefore, details such as those presented in small print below will not be necessary to present for all of the solutions obtained using the optimization model.

---- VARIABLE YG BINARY VARIABLE INDICATING IF GARAGE I IS KEPT OPEN

GAR42 1.000, GAR46 1.000, GAR47 1.000, GAR48 1.000, GAR49 1.000

---- VARIABLE AG BINARY VARIABLE FOR TWO BAY EXPANSION AT GARAGE I

GAR42 1.000, GAR46 1.000, GAR47 1.000, GAR48 1.000, GAR49 1.000

---- VARIABLE BG NUMBER OF BAYS ABOVE TWO ADDED AT GARAGE I

GAR42 1.402, GAR46 8.000, GAR47 8.000, GAR48 3.366, GAR49 8.000

---- VARIABLE Y BINARY VARIABLE INDICATING IF FACILITY IS KEPT OPEN

OSA 1.000, LIS 1.000

---- VARIABLE A BINARY VARIABLE INDICATING IF TWO BAYS ARE ADDED

(ALL ZERO)

---- VARIABLE B NUMBER OF BAYS ADDED ABOVE TWO

(ALL ZERO)

---- VARIABLE X SHIPMENT PERCENTAGES

	GAR41	GAR42	GAR43	GAR44	GAR45	GAR46
HIG					1.000	
OSA	1.000		1.000	1.000		1.000
LIS		1.000				

+	GAR47	GAR48	GAR49	GAR50	GAR51	OTH10
HIG					1.000	
OSA	1.000					
LIS		1.000	1.000	1.000		1.000

+	OTH11	OTH12	OTH19	OTH20	OTH21
OSA	1.000		1.000	1.000	
LIS		1.000			1.000

---- VARIABLE XS PROPORTION OF SECTOR J SERVED BY GARAGE I

	S1	S2	S3	S4	S5	S6
GAR46						1.000
GAR47	1.000	1.000	1.000	1.000	1.000	

+	S7	S8	S9	S10	S11	S12
GAR46	1.000	1.000	1.000	1.000		
GAR47					1.000	1.000

+	S13	S14	S15	S16	S17	S18
GAR46				1.000	1.000	1.000
GAR47	1.000	1.000	1.000			

+	S19	S20	S21	S22	S23	S24
GAR46	1.000					
GAR47			1.000	1.000	1.000	1.000
GAR49		1.000				

+	S25	S26	S27	S28	S29	S30
GAR46		1.000	0.584			
GAR47	0.365					
GAR48	0.635		0.416			
GAR49				1.000	1.000	1.000

+	S31	S32	S33	S34	S35	S36
GAR42	1.000	1.000	1.000			
GAR48				1.000	1.000	1.000

+	S37	S38	S39	S40	S41	S42
GAR42					1.000	1.000
GAR48	0.360					
GAR49	0.640	1.000	1.000	1.000		

+	S43	S44	S45	S46	S47	S48
GAR42	1.000					
GAR48		1.000	1.000	1.000		
GAR49					1.000	1.000

+	S49	S50
GAR49	1.000	1.000

---- VARIABLE T ADDITIONAL EQUIPMENT GOING TO FACILITY F FROM GARAGE I

	GAR42	GAR46	GAR47	GAR48	GAR49
OSA		25.000	25.000		
LIS	8.504			13.416	25.000

---- VARIABLE TP REDUCTION IN EQUIPMENT GOING TO F FROM I

	GAR41	GAR43	GAR44	GAR45	GAR50	GAR51
HIG				11.970		13.720
OSA	14.340	22.310	19.140			
LIS					15.440	

**** FILE SUMMARY

INPUT C:\GAMSLIB\SUM93.GMS
OUTPUT C:\GAMSLIB\SUM93.LST

EXECUTION TIME = 22.800 SECONDS VER: 386-EK-009