A Prototype Decision Support System
for Two-Stage Facility Location
in ConnDOT's Maintenance System

Final Report

October 12, 1995

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A copy of GAMS optimization software and an input file containing the linear programming model have been delivered to ConnDOT separately.

16. Abstract

This report describes a prototype decision support system (DSS) that has been designed to help ConnDOT investigate alternative maintenance facility configurations. The user of the DSS specifies which repair facilities and roadway garages to keep open, and the DSS determines the optimal assignments of garages to repair facilities and roadway sectors to garages. The engine of the DSS is based on a linear programming model of the two-stage maintenance system. Although the prototype system models only ConnDOT's second maintenance district, there are no technical problems associated with expanding it to include the entire state. To make the DSS more user-friendly, a geographic information system (GIS) interface has been designed. The link between the GIS component and the linear programming model is described, but implementing the link for the prototype system was not part of the current project. Further work that would be required to complete a DSS that covers the entire state and that incorporates a GIS is described.

17. Key Words

Decision Support System;
Facility Location;
Maintenance;
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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

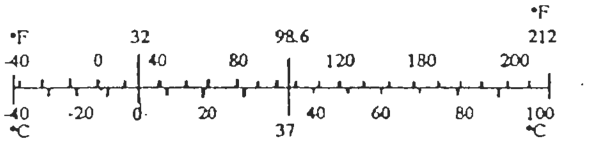
NOTE: Volumes greator than 1000 L shall be shown in m^3.

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

DSS = decision support system.

GIS = geographic information system.

LP = linear programming.

MIP = mixed integer programming.

$\{F\}$ = the set of open repair facilities; and

$\{I\}$ = the set of open roadway garages.

$\{J\}$ = the set of roadway sectors.

$\{K\}$ = the set of other locations having equipment repair requirements (e.g., airports).

P_f = the capacity of repair facility f, in terms of equipment serviceable.

Q_i = the capacity of garage i, in terms of equipment that could be housed there.

U_{fi} = the total annual cost of transporting a unit of equipment from garage i to facility f for repair.

T_{ij} = the total annual cost of serving a unit of sector j demand from garage i.

DS_j = the demand in sector j, in terms of equipment required to serve that sector.

D_k = the demand at other facility k, in terms of equipment requiring repair.

SR_j = snow removal equipment required for sector j.

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

X_{fi} = the amount of garage i equipment served by repair facility j; and

XS_{ij} = the amount of sector j demand served by garage i.

I. INTRODUCTION

Description of the Maintenance System

This research is concerned with a state-wide maintenance system that is composed of two major types of facilities -- equipment repair facilities and roadway garages. Figure 1 depicts ConnDOT's existing system, which consists of thirteen equipment repair facilities and fifty-five roadway garages. The roadway garages house the equipment that is used to maintain the state's roadways, and the repair facilities are where the equipment is transported when it requires repair. The lines on Figure 1 that connect garages to repair facilities represent existing assignments for equipment repair purposes. In addition to the roadway garages, significant amounts of equipment are also housed at other locations such as electrical repair and bridge repair buildings. These other locations are shown as triangles in Figure 1, and their current assignments to repair facilities are also depicted.

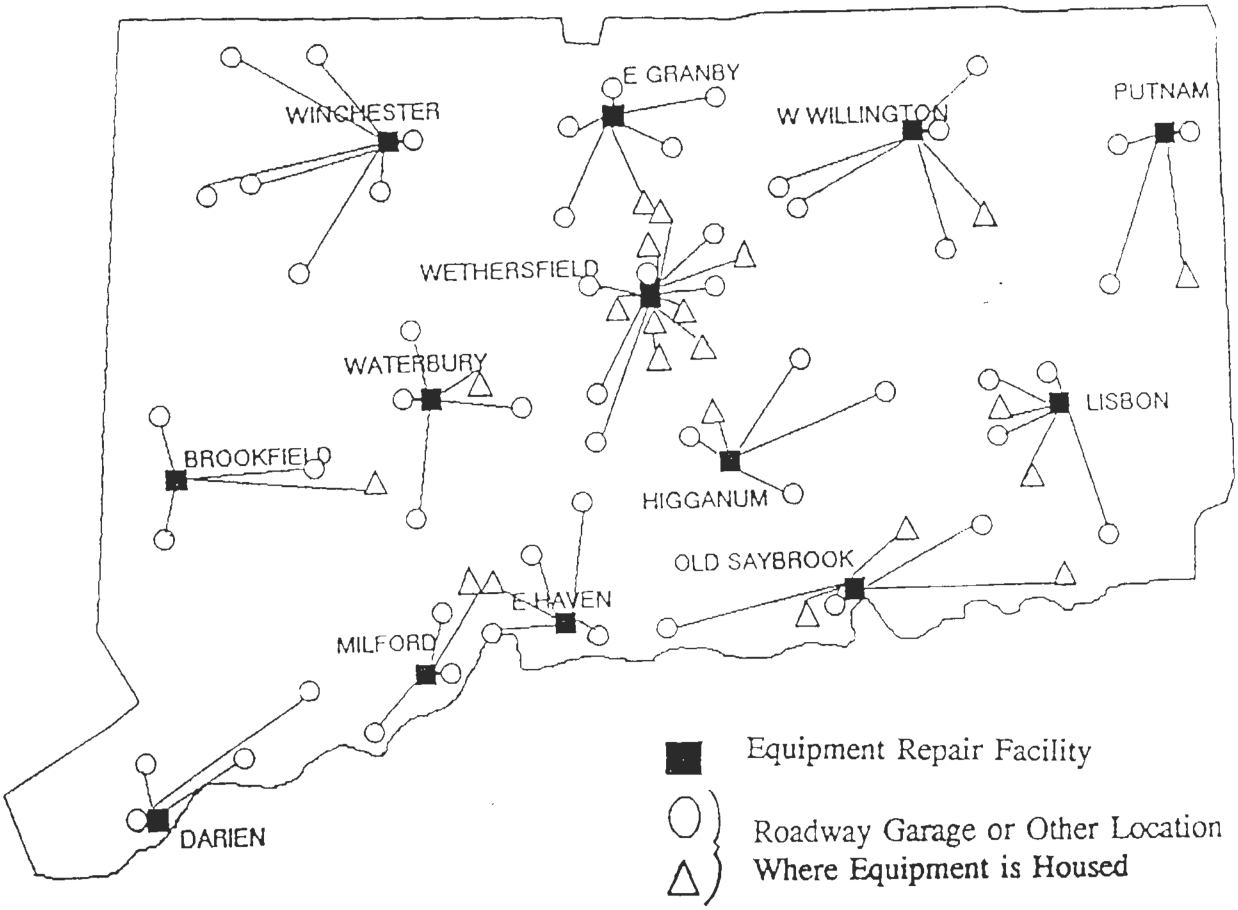

Figure 1. Existing configuration of ConnDOT's maintenance system.

The equipment that is housed in the roadway garages is used to perform roadway maintenance throughout the year. One of the key maintenance functions of the equipment is snow plowing. The area covered by a particular roadway garage can be defined based on the snow plow routes of the equipment assigned to the garage. For example, Figure 2 shows the roadways that are covered by equipment that is housed in the garage located in Mansfield (Garage 39). When summed together, the snow plow routes assigned to all garages represent the entire network of state-maintained roadways. Because snow plowing is a key roadway maintenance function and the snow plow routes are well-defined, it is appropriate to define a garage's area of responsibility based on the snow plow routes that are assigned to it. Redefinition of the snow plow routes themselves is not considered as part of this study. The study is primarily concerned with the assignments of garages to repair facilities and roadway sectors to garages.

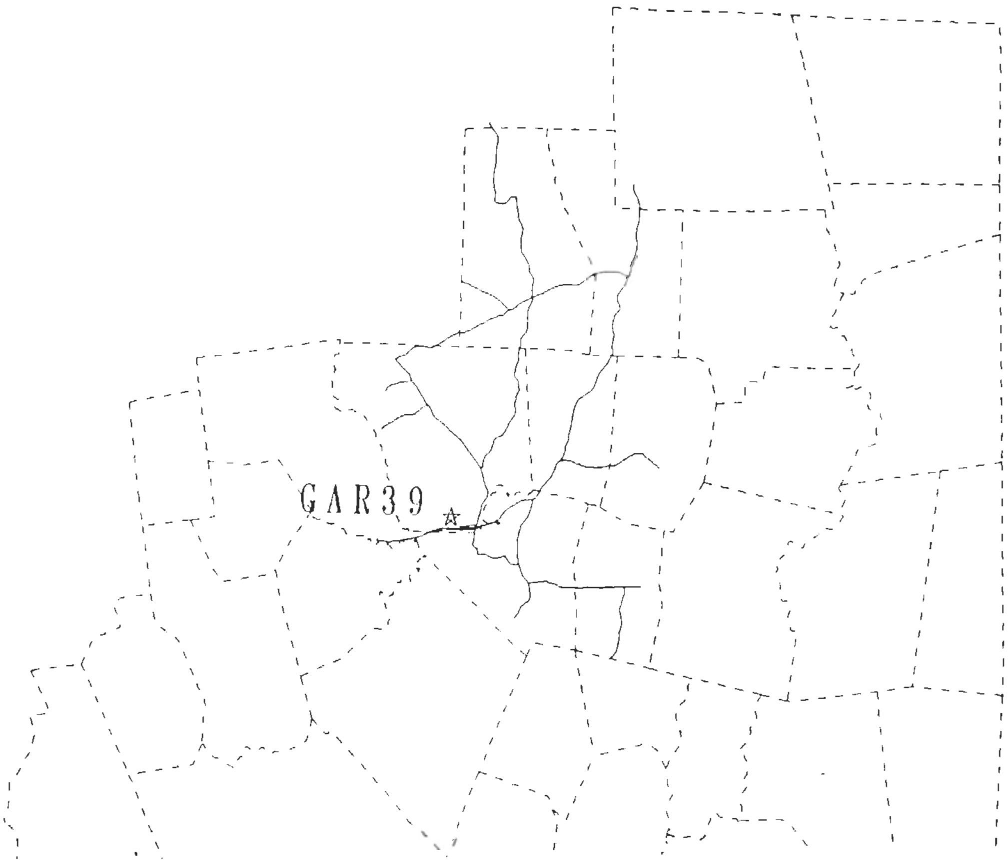

Figure 2. Roadways currently covered by the Mansfield garage.

History of this Research Project

The principal investigators have been studying ConnDOT's maintenance system for several years. Initially, their attention focused strictly on the thirteen equipment repair facilities. An optimization model was built to represent the trade-off between repair facility costs (which increase with the number of facilities) versus costs of transporting equipment to the facilities (which decrease as the number of facilities increases). Use of the optimization model resulted in specific recommendations for reconfiguration of the system, as described in the report by Campbell and Davis (1991). Although the results of that initial study have been useful to ConnDOT, their value is limited by certain assumptions upon which the optimization model is based. A major limiting assumption is that the locations of the 55 roadway garages remain fixed.

In an effort to eliminate the major limiting assumption of the initial model, the principal investigators undertook the development of a two-stage optimization model that allowed for changes in the locations of both repair facilities and roadway garages. The development of this model is described in a second report by Campbell and Davis (1993). This report presents details of the mathematical model and also describes the data-gathering required to complete it. Following this report, discussions with ConnDOT Maintenance revealed that completing the construction of the two-stage optimization model would not be the preferred course of action. It was determined that a model-based decision support system (DSS) that could be used interactively would better suit ConnDOT's needs.

The major difference between the two-stage optimization model and the model-based DSS is that in the former the model specifies which facilities are opened and closed, whereas with the DSS the facility configuration is specified by the user. In terms of development, the DSS is simpler in that costs associated with facilities are not required as inputs to the model. Also, the model for the DSS contains none of the integer decision variables included in the initial two-stage optimization model. This enables solution via linear programming methods, as opposed to more complicated (and slower) mixed integer programming techniques.

Functions of the Decision Support System

Since the model-based DSS is simpler to build and more in line with the preferences of ConnDOT Maintenance, the emphasis of the research shifted towards the development of a prototype DSS. Given prespecified sets of open and closed repair facilities and roadway garages as inputs, the DSS establishes the optimal assignment of roadways to garages and garages to repair facilities. These assignments are established by solving a linear programming problem that minimizes total transportation costs while ensuring that all maintenance requirements are met and that capacity limitations of the facilities are not exceeded.

The user-specified inputs to the DSS are illustrated in Figure 3. The user specifies which garages and repair facilities to keep open. They can also specify facility capacities other than those that currently exist (if, for example, they wanted to see the effects of expanding a facility). Any fixed assignments of garages to repair facilities or roadway sectors to garages can also be specified at this time. Any such assignments that are not made as inputs will be specified as part of the optimal solution displayed in the output of the DSS.

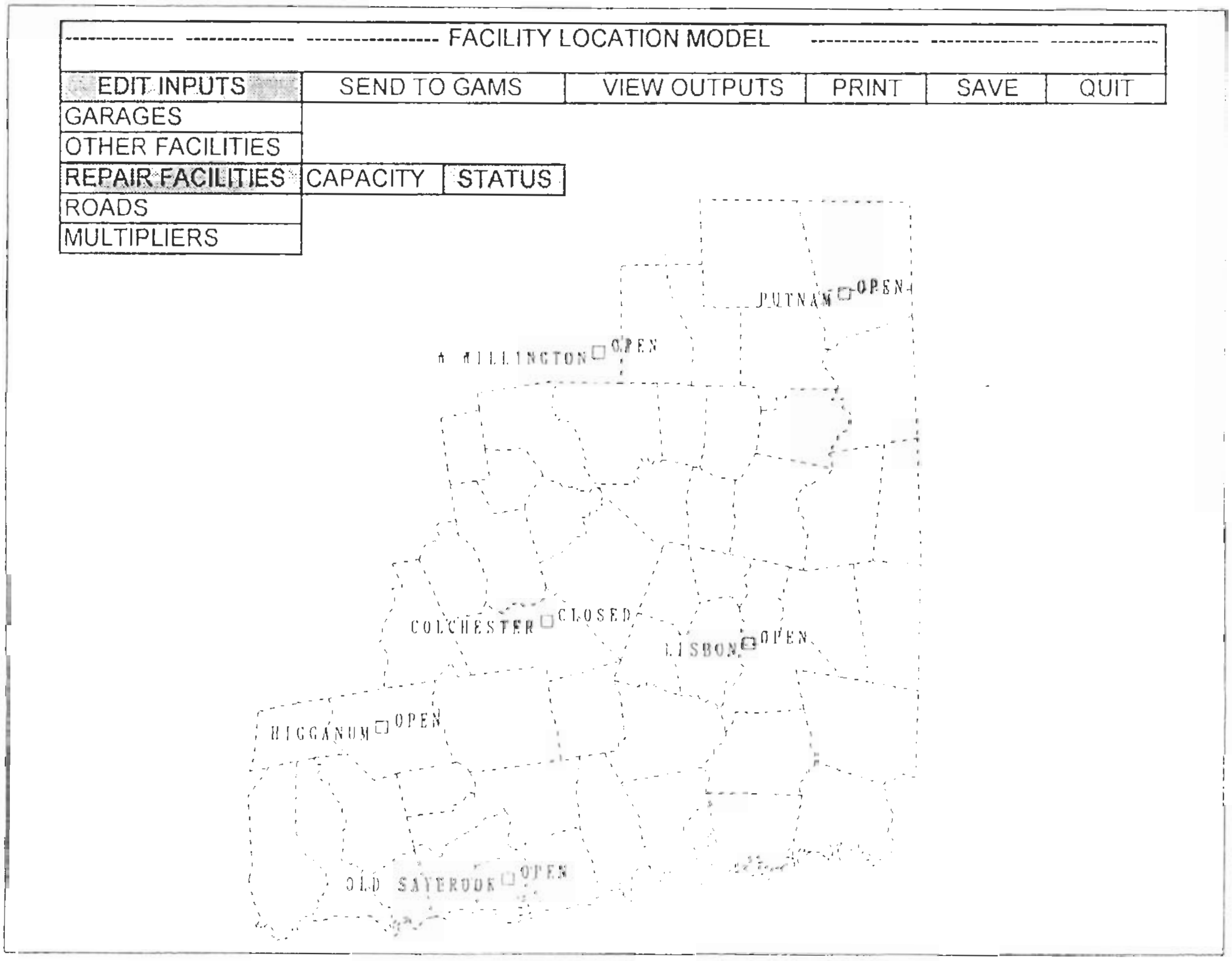

Figure 3. Illustration of inputs required by the DSS.

After all of the inputs have been specified, the DSS uses its linear programming software to obtain an optimal solution. This solution includes specification of the following: assignments of garages to repair facilities; assignments of roadway sectors to garages; and total transportation costs of the system. Figures 4 and 5 show examples of the assignment-related output that is produced by the DSS.

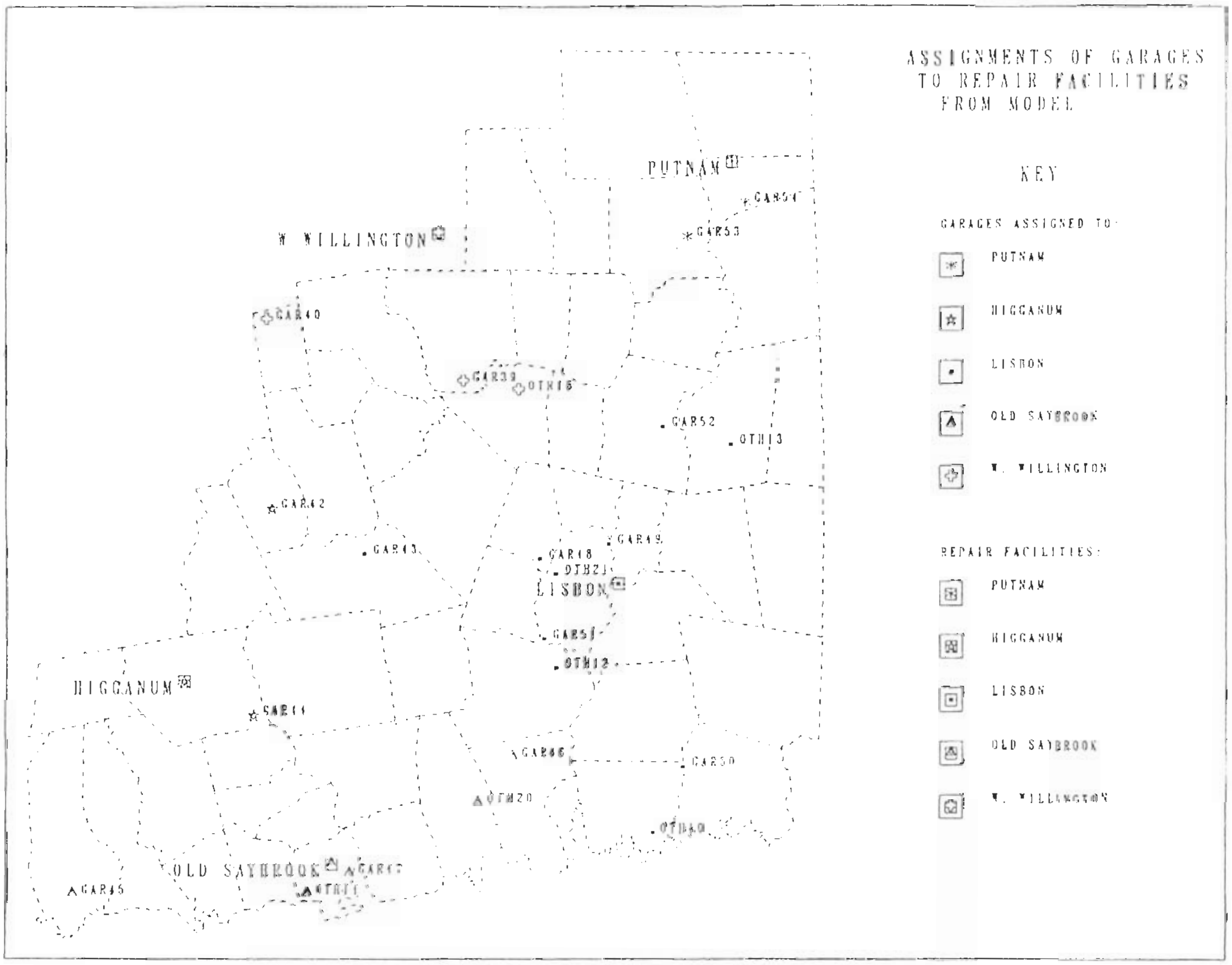

Figure 4. Illustration of garage to repair facility assignments provided by the DSS.

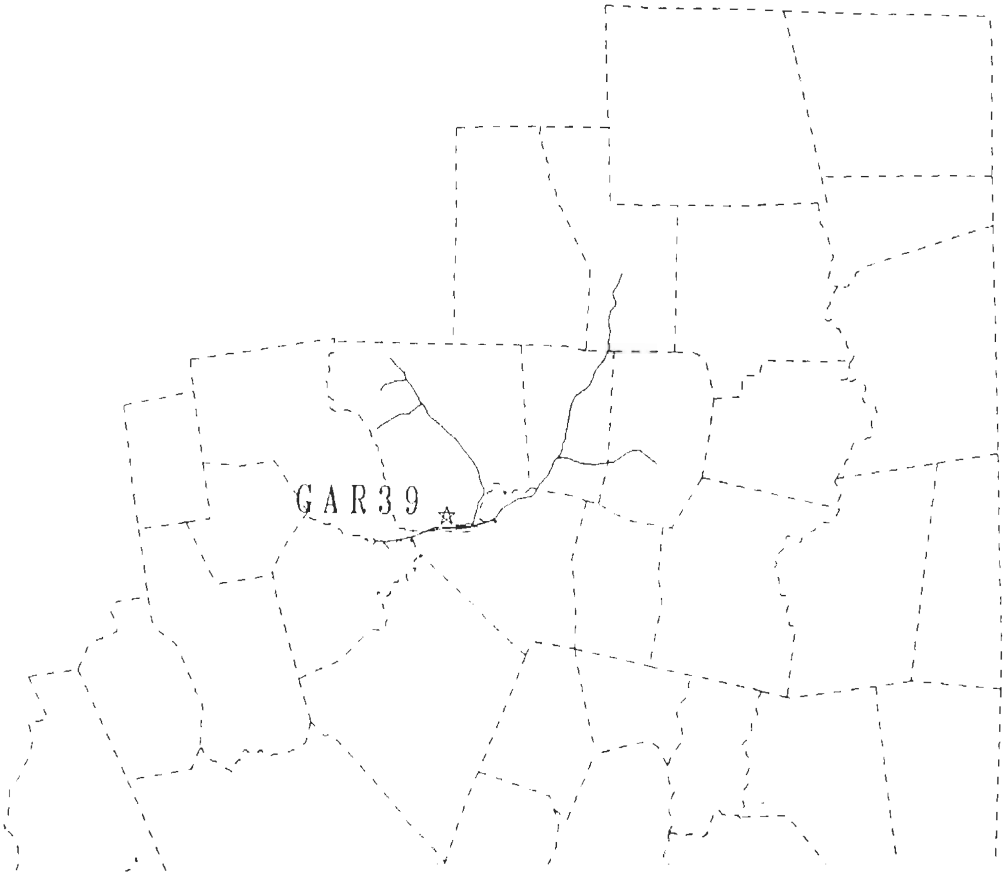

Figure 5. Illustration of roadway sector to garage assignments provided by the DSS.

Scope of the Prototype System

Ideally, it would be beneficial for ConnDOT Maintenance to have a user-friendly DSS that enables analysis of the entire state's maintenance system. However, the prototype DSS built for the current project falls short of this ideal in two significant ways:

1) it encompasses only one of the state's four maintenance districts; and

2) the linear programming software has not been tied to a GIS (geographic information system) to enable a more user-friendly interface.

Despite these limitations, the prototype is useful for illustrating the feasibility of developing a complete state-wide system. The expansion from a single district to a four-district system is straightforward, and the linking of the linear programming software to a GIS is a matter of programming (although the programming effort involved should not be understated). The nature of the GIS interface is defined in this report, but the programming itself is beyond the scope of the current project.

The software provided to ConnDOT for the current project consists of a linear programming software package and the digitized text of a model that can be solved using the package. Instructions for using the software, modifying model inputs and interpreting output are included in appendices of this report.

The remainder of the main body of this report is organized into sections that review the literature, describe the mathematical model, and discuss the GIS interface. The conclusion section discusses the steps required to complete a user-friendly DSS that would be useful for analyzing the maintenance system of the entire state.

II. REVIEW OF LITERATURE

The piece of prior literature that is most relevant to the current project is the report by Campbell and Davis (1993), which describes the development of a comprehensive two-stage facility location model. The contribution of the current project beyond what appears in that prior report is primarily related to the use of the model as part of an interactive DSS. This literature review includes discussion of decision support systems, and it is structured based on the three main DSS components -- i.e., the data base, the engine, and the human interface.

Campbell and Davis (1994) presented an overview of decision support systems as part of their evaluation of management tools that might be of use to ConnDOT. Three basic components of a DSS were identified, as shown in Figure 6.

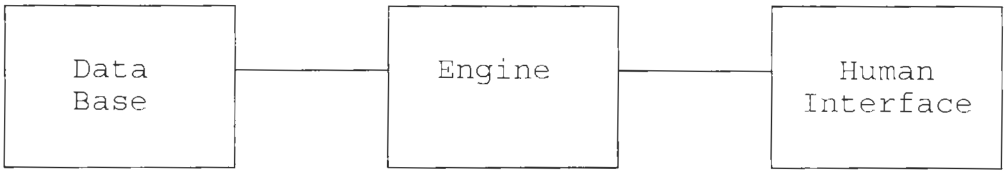

Figure 6. Basic components of a decision support system.

The three-part DSS structure shown in Figure 6 provides a useful framework for discussing the prototype DSS that has been developed for ConnDOT. The rest of this literature review is structured around these three components.

The DSS Data Base

Much of the data for the prototype DSS was gathered as part of prior studies. For the single-stage study described in Campbell and Davis (1991), travel distances and costs between garages and repair facilities were obtained using a computer-based network of Connecticut's roadways. The same methodology was used in the current project for obtaining travel distances between roadway sectors and garages.

Campbell and Davis (1991) also describes the techniques used for establishing the capacities of repair facilities. Based on the numbers of work bays and the amounts of equipment served at the thirteen facilities, an "efficient frontier" was identified and used to establish the capacities of the facilities. These capacities have been carried over to the current project.

Other data from Campbell and Davis (1991) regarding equipment quantities at roadway garages has also been used for the current study. This has been supplemented with data regarding roadway sectors that has been obtained from the "Program for Winter Snow Removal" provided by ConnDOT Maintenance (ConnDOT 1992-1993). Table 1 summarizes the roadway sector information from the program for District 2, which is the district that the prototype DSS has been set up to model.

Table 1. District 2 roadway sectors, based on existing snow plow routes.

Sector No.	ConnDOT Route No.	No. of ConnDOT Trucks	No. of Rentals	Current Garage
1	14 14A 49 667	1	1	Canterbury (52)
2	12 14 664	1	1	Canterbury (52)
3	14 97 426	1	1	Canterbury (52)
4	6 14A 169 205	1	1	Canterbury (52)
5	138 169 600 668	1	1	Canterbury (52)
6	I-395	2	1	Canterbury (52)
7	138 I-395 629 630	1	0	Canterbury (52)
8	6 12 435	2	0	Canterbury (52)
9	I-395	2	1	Putnam (54)
10	I-395	1	0	Putnam (54)
11	I-395	2	1	Putnam (54)
12	I-395 618	2	1	Putnam (54)
13	6 I-395 695	2	1	Putnam (54)
14	12 21 193 200	1	1	Putnam (54)
15	12 44 171 438	2	0	Putnam (54)
16	12 131 197	2	0	Putnam (54)

Sector No.	ConnDOT Route No.	No. of ConnDOT Trucks	No. of Rentals	Current Garage
17	171 198	2	0	Pomfret (53)
18	169 197	2	0	Pomfret (53)
19	44 97 244 644	2	0	Pomfret (53)
20	44 97	1	1	Pomfret (53)
21	6 44 169	1	1	Pomfret (53)
22	12 101 607 618	2	0	Pomfret (53)
23	195 275 430	1	1	Mansfield (39)
24	44 89 198	1	1	Mansfield (39)
25	14 97 203	1	1	Mansfield (39)
26	6 198	2	0	Mansfield (39)
27	44 74 89	2	0	Mansfield (39)
28	6 SR632 SR633	3	1	Mansfield (39)
29	85 94 316 603	2	0	Bolton (40)
30	6 31 44 85 533 534	2	0	Bolton (40)
31	31 32 275	2	0	Bolton (40)

Sector No.	ConnDOT Route No.	No. of ConnDOT Trucks	No. of Rentals	Current Garage
32	32 44 195	1	1	Bolton (40)
33	6 66 87 289	2	0	Bolton (40)
34	6 66 87 631	1	1	Bolton (40)
35	66	2	0	Marlborough (42)
36	66 85 87 207	3	0	Marlborough (42)
37	2	3	0	Marlborough (42)
38		1	0	Marlborough (42)
39	16 66 151 196 439	1	1	Marlborough (42)
40	149 151 196 609	1	1	Marlborough (42)
41	82 148 151 431 434	3	1	Colchester (43)
42	82 85	1	1	Colchester (43)
43	85 161	1	1	Colchester (43)
44	2 11	3	0	Colchester (43)
45	2 11	1	0	Colchester (43)
46	16 149 429	1	1	Colchester (43)
47	354 615 616 637	1	0	Colchester (43)

Sector No.	ConnDOT Route No.	No. of ConnDOT Trucks	No. of Rentals	Current Garage
48	32 642	2	0	Franklin (48)
49	97 207 660	1	0	Franklin (48)
50	87 207 610	1	1	Franklin (48)
51	2 32	3	0	Franklin (48)
52	2	2	0	Franklin (48)
53	354 608 616	1	1	Franklin (48)
54	82 163 612	1	1	Franklin (48)
55	I-95	3	0	Waterford (46)
56	I-95	1	0	Waterford (46)
57	1 213	2	0	Waterford (46)
58	1 161 432	1	1	Waterford (46)
59	1 85 641 643	2	0	Waterford (46)
60	156 161	1	1	Waterford (46)
61	I-95 623 624 638	4	0	Waterford (46)
62	I-395 693	3	0	Waterford (46)
63	32 437 635	2	0	Waterford (46)
64	77 80	1	1	Guilford (45)
65	17 79 80	2	0	Guilford (45)
66	1 77 146	1	1	Guilford (45)

Sector No.	ConnDOT Route No.	No. of ConnDOT Trucks	No. of Rentals	Current Garage
67	1 22 79 450 718	2	0	Guilford (45)
68	I-95 450	3	0	Guilford (45)
69	I-95 718	1	0	Guilford (45)
70	17 68 147 157	1	0	Guilford (45)
71	156	1	1	Old Saybrook (47)
72	1 154 628	1	1	Old Saybrook (47)
73	I-95	3	0	Old Saybrook (47)
74	I-95 449	3	0	Old Saybrook (47)
75	I-95 154 156	1	0	Old Saybrook (47)
76		1	0	Old Saybrook (47)
77	1 81 145	2	0	Old Saybrook (47)
78	1 153 166 625	2	0	Old Saybrook (47)
79	117 184 349	2	0	Groton (50)
80	I-95	3	0	Groton (50)
81	1 117 349 614 649	2	0	Groton (50)
82	2 78 184 201	1	1	Groton (50)
83	1 27 184 234 SR627	1	1	Groton (50)

Sector No.	ConnDOT Route No.	No. of ConnDOT Trucks	No. of Rentals	Current Garage
84	1 1A 215	1	1	Groton (50)
85	I-95	3	0	Groton (50)
86	I-95	2	0	Groton (50)
87	I-95 SR614	1	0	Groton (50)
88	80 148 154 602 604 21	1	1	Tylerville (44)
89	80 145 148	2	0	Tylerville (44)
90	9	3	0	Tylerville (44)
91		1	0	Tylerville (44)
92	9	3	0	Tylerville (44)
93	9	1	0	Tylerville (44)
94	82 148 154	2	0	Tylerville (44)
95	81 148	2	0	Tylerville (44)
96	I-395	3	1	Norwich (51)
97		1	0	Norwich (51)
98		2	1	Norwich (51)
99	117 214	1	1	Norwich (51)
100	12	2	0	Norwich (51)
101	2A 12	1	1	Norwich (51)
102	I-395	1	0	Norwich (51)
103	2 82 SR642	1	1	Norwich (51)
104	164 165 605	1	1	Occum (49)
105	49 184 216 617 626	1	1	Occum (49)

Sector No.	ConnDOT Route No.	No. of ConnDOT Trucks	No. of Rentals	Current Garage
106	138 165	1	1	Occum (49)
107	138 164 169	4	0	Occum (49)
108	201	2	0	Occum (49)
109	12 97 169	4	0	Occum (49)
110	2 2A	2	0	Occum (49)

The removal of repair facility and roadway garage decision variables from the model has significantly reduced the model's data requirements.

Equipment quantity, transportation cost and roadway sector demand data all reside in the input file that is used with the linear programming software that is incorporated into the DSS. This software is called GAMS (Brooke, Kendrick and Meeraus 1988), which is an acronym for General Algebraic Modeling System. Appendix A shows an example of a GAMS input file, including all of the data required to run the prototype system. In Section III, assumptions that have been used for estimating various input parameters related to the roadway sectors are discussed. Campbell and Davis (1991) discuss the estimation of parameters related to repair facilities and roadway garages.

Because all data is included in the GAMS input file, the link between the first two DSS components shown in Figure 6 is seamless. The second component will now be discussed.

The DSS Engine

Campbell and Davis (1994) identify five categories for the engine component of a DSS. For the current project, the engine falls into the category of a management science / operations research model. More specifically, the model is of the form of a linear programming (LP) problem. This type of problem is simpler than a mixed integer programming (MIP) problem, which is the type of problem that applies for the model presented by Campbell and Davis (1993). The key difference between the two model types is that all decision variables in an LP are continuous, while some of those in an MIP must take on integer values. The integer variables complicate the problem significantly. Winston (1991) describes both types of problems and solution methods that apply for each type. He also discusses network programming problems, which are a sub-category of general linear programming problems. A network programming formulation of the two-stage problem is presented in Section III.

Prior literature on facility location and maintenance system design has already been reviewed in Campbell and Davis (1991) and Campbell and Davis (1993). One addition to those reviews is a paper by Robinson, Gao and Muggenborg (1993), which presents a formulation of a distribution problem that is similar to the two-stage model used in the current project. This model was used to investigate alternative facility configurations for Dowbrands, Inc. For other relevant facility location literature, see Campbell and Davis (1991) and Campbell and Davis (1993).

Output from the facility location model included as the engine component of the DSS is communicated to the user through the DSS's human interface. This is also where the model's inputs that are not already in the data base must come from.

The DSS Human Interface

As mentioned above, the prototype DSS has been built using the GAMS software. At its present stage of development, the human interface component of the DSS is simply the input / output features of the software, which are described in the GAMS User's Guide (Brooke, Kendrick and Meeraus 1988). However, because this interface is not very user-friendly, a better interface has been designed based on the use of a geographic information system (GIS). Kolli, Damodaran and Evans (1993) discuss methods for using a GIS as part of a DSS for solving facility location and logistics problems. The article includes discussion of a method for integrating mapping and optimization software packages.

For the unfamiliar reader, it is helpful to define the term GIS. While numerous definitions of GIS have been suggested, the following is sufficient for present purposes:

> According to Dueker and Kjerne (1979), a GIS is "a system of hardware, software, data, people, organizations, and institutional arrangements for collecting, analyzing, and disseminating information about areas of the earth."

All definitions of GIS include:

- An element of information that contains a geographic reference, allowing the information to be mapped, and

- Attribute information, either statistical or textural in nature, which can be tied to a geographic reference.

In short, GIS deals with the management of geographically based information.

The numerous applications of GIS technology to transportation include work by Osman and Hayashi (1994) on pavement management, by Lewis (1990) on demand modeling, and by Davis et al. (1995) on integration of land-use and transportation. A recent report by Vonderohe et al. (1993) specifically examines the status of GIS in transportation agencies.

In the present case, the GIS usage falls in the category of automated mapping/facilities management (AM/FM). This category of use is popular with utility companies and government agencies in locating underground pipes and cables, tracking energy use, providing digital inventories of physical facilities and aiding in planning their maintenance.

Examples of input and output formats that have been designed for the GIS interface were presented in Section I of this report. These examples were generated using a GIS called ARC/INFO, which is a software package produced by Evironmental Systems Research Institute, Inc.

The link between the engine component of the DSS and the GIS human interface remains to be completed. The work required to complete this link is discussed further in Sections IV and V. Before that, the model that constitutes the engine component of the DSS is further discussed.

III. THE MATHEMATICAL MODEL

The mathematical model of ConnDOT's maintenance system has been evolving since the original study was begun in 1990. Initially, the single-stage model described in Campbell and Davis (1991) was developed to represent the situation where only the repair facilities could be reconfigured. The objective function of that model reflected a trade-off between costs of keeping repair facilities open and costs of transporting equipment from garages to repair facilities. The key decision variables represented which facilities to keep open, which to expand, and what the assignments of garages to repair facilities should be. Garage locations were assumed to be fixed in the single-stage model.

The extension from a single-stage to a two-stage model added a great deal of complexity to the problem. The two-stage model described in Campbell and Davis (1993) includes decision variables that represent which roadway garages should be kept open. Other decision variables represent assignments of roadway sectors to garages. Data-gathering requirements increased substantially when the second stage was added to the model. Costs associated with each of the 55 roadway garages were needed to build the model, as were the maintenance requirements of each of the state's 300 roadway sectors. Distances between roadway sectors and garages were also required so that costs of transporting equipment from garages to roadways could be represented. Once the model was built and the problem was solved, the solution would include the following:

- -- which repair facilities to keep open and which to expand;
- -- which garages to keep open and which to expand;
- -- assignments of garages to repair facilities;
- -- amounts of equipment required at each garage; and
- -- costs associated with the reconfigured system.

Increased model size and complexity went along with the increased scope. But, as described in Section I of this report, it turned out that the scope of the model described in Campbell and Davis (1993) went beyond what would be most useful for ConnDOT Maintenance.

To better meet ConnDOT's requirements, the model has been simplified by eliminating decision variables related to the repair facilities and garages. It remains a two-stage model, but it answers fewer questions, and the data-gathering requirements are less arduous. Also, the elimination of integer variables associated with the repair facilities and garages makes it a much easier problem to solve, which means that computation times are greatly reduced.

Since decisions regarding which repair facilities and garages to keep open are no longer made by the model, these decisions must be made by the user of the DSS. Prior to using the model to establish assignments of garages and roadway sectors, the user must specify the following:

$\{F\}$ = the set of open repair facilities; and

$\{I\}$ = the set of open roadway garages.

Also, for all $f \epsilon \{F\}$, the following must be known:

P_f = the capacity of repair facility f, in terms of equipment serviceable.

And for each $i \epsilon \{I\}$, the following must be given:

Q_i = the capacity of garage i, in terms of equipment that could be housed there.

The user can choose to use existing capacity levels for the garages and repair facilities, or they could change any of them to represent expansions under consideration. The existing capacity levels of the facilities are the default values built into the model.

Also built into the model are the following cost parameters:

U_{fi} = the total annual cost of transporting a unit of equipment from garage i to facility f for repair; and
T_{ij} = the total annual cost of serving a unit of sector j demand from garage i.

In building the model, these cost parameters are estimated based on distances between facilities and garages (for U_{fi}) and between garages and roadway sectors (for T_{ij}).

Besides the roadway garages, there are other facilities in the system that are sources of equipment that must be repaired. These other facilities, such as airports and electrical repair facilities, are those represented by triangles in Figure 1. Let the set $\{K\}$ represent these facilities, and the set $\{I \cup K\}$ represents all sources of equipment sent to repair facilities. In the model, the facilities in $\{K\}$ are treated like those in $\{I\}$, except that roadway sectors cannot be served be equipment located at facilities in $\{K\}$.

The final set of information that is built into the model is the maintenance requirements of the roadway sectors. For each element j in the set of roadway sectors, $\{J\}$, the following is defined:

DS_j = the demand in sector j, in terms of equipment required to serve that sector.

To build the prototype model, DS_j values were estimated as follows:

SR_j = snow removal equipment required for sector j.
$\{J_i\}$ = the set of sectors served by garage i in the existing system.
$\sum_{j \in \{J_i\}} SR_j$ = total amount of snow removal equipment for all sectors assigned to garage i in the existing system.

$$DS_j = D_i SR_j \Big/ \sum_{j \in \{J_i\}} SR_j .$$

The values for SR_j and the definitions of $\{J_i\}$ were available from snow plow route records provided by ConnDOT maintenance, as shown earlier in Table 1. D_i values have been known since the time of the single-stage study, as reported in Campbell and Davis (1991).

In addition to the capacity, cost and demand parameters defined above, let us also define the following decision variables:

X_{fi} = the amount of garage i equipment served by repair facility f; and

XS_{ij} = the amount of sector j demand served by garage i.

Linear Programming Formulation

The linear programming model shown below represents the problem of assigning a given set of garages to a given set of repair facilities while simultaneously assigning a fixed set of roadway sectors to the given set of garages so as to minimize total transportation costs:

$$\text{minimize} \quad \sum_{f\epsilon\{F\}} \sum_{i\epsilon\{I\cup K\}} U_{fi}X_{fi} + \sum_{i\epsilon\{I\}} \sum_{j\epsilon\{J\}} T_{ij}XS_{ij} \qquad (1)$$

subject to:

$$\sum_{i\epsilon\{I\cup K\}} X_{fi} \leq P_f \qquad f\ \epsilon\ \{F\} \qquad (2)$$

$$\sum_{f\epsilon\{F\}} X_{fi} \leq Q_i \qquad i\ \epsilon\ \{I\} \qquad (3)$$

$$\sum_{i\epsilon\{I\}} XS_{ij} = DS_j \qquad j\ \epsilon\ \{J\} \qquad (4)$$

$$\sum_{j\epsilon\{J\}} XS_{ij} = \sum_{f\epsilon\{F\}} X_{fi} \qquad i\ \epsilon\ \{I\} \qquad (5)$$

$$\sum_{f\epsilon\{F\}} X_{fk} = D_k \qquad k\ \epsilon\ \{K\} \qquad (6)$$

$$X_{fi},\ XS_{ij} \geq 0 \qquad (7)$$

The objective function, (1), includes the transportation costs associated with serving garages from repair facilities and roadway sectors from garages. Constraint set (2) enforces repair facility capacity restrictions, and (3) does the same for the roadway garages. Constraint set (4) ensures that all roadway sector maintenance requirements are satisfied, and (5) establishes garage equipment levels based on the roadway sectors that the garages serve. Constraint set (6) makes sure that the equipment repair requirements of the other facilities in the system are taken care of. (7) completes the formulation by restricting all decision variables to be non-negative.

The model formulated above has been built and solved using the GAMS software package (Brooke, Kendrick and Meeraus 1988). Appendix A shows the GAMS input for a two-stage model based on ConnDOT's District 2. The equations shown on page A.16 of the appendix corresponds closely to those given by (1) - (6). Most of the rest of the input shown in the appendix consists of definitions of the sets, parameters and decision variables associated with the model.

Because all of the decision variables in the model are continuous, the formulation given by (1) - (7) is that of a standard linear programming (LP) problem. Because it has a special structure, the two-stage problem can also be formulated as a minimum cost network flow (or transhipment) problem, which is a class of LP problems that can be solved much more efficiently than standard LPs (Winston 1991). Another advantage of network formulations is that they can be depicted using convenient graphical representations.

Network Programming Formulation

To illustrate the network formulation of the two-stage problem, consider a simple example composed of two repair facilities (R1 and R2), four roadway garages (G1, G2, G3 and G4) one other facility (O1), and four roadway sectors (S1, S2, S3, and S4). The network corresponding to this problem is shown in Figure 7.

The capacities of the repair facilities, in terms of equipment serviceable (i.e. P_1 and P_2) are shown as flows into the network. This capacity is distributed to roadway garages and other facilities, with any extra capacity going to a dummy node. The total flow going to the dummy (D_d) is calculated as follows:

$$D_d = \sum_{f \in \{F\}} P_f - \sum_{k \in \{K\}} D_k - \sum_{j \in \{J\}} DS_j$$

Flows along arcs that connect repair facility nodes to garage nodes incur costs of U_{ij}, as indicated on the arc connecting R1 and G1. Also indicated is the fact that the flows along these arcs are unconstrained (i.e., no upper bounds).

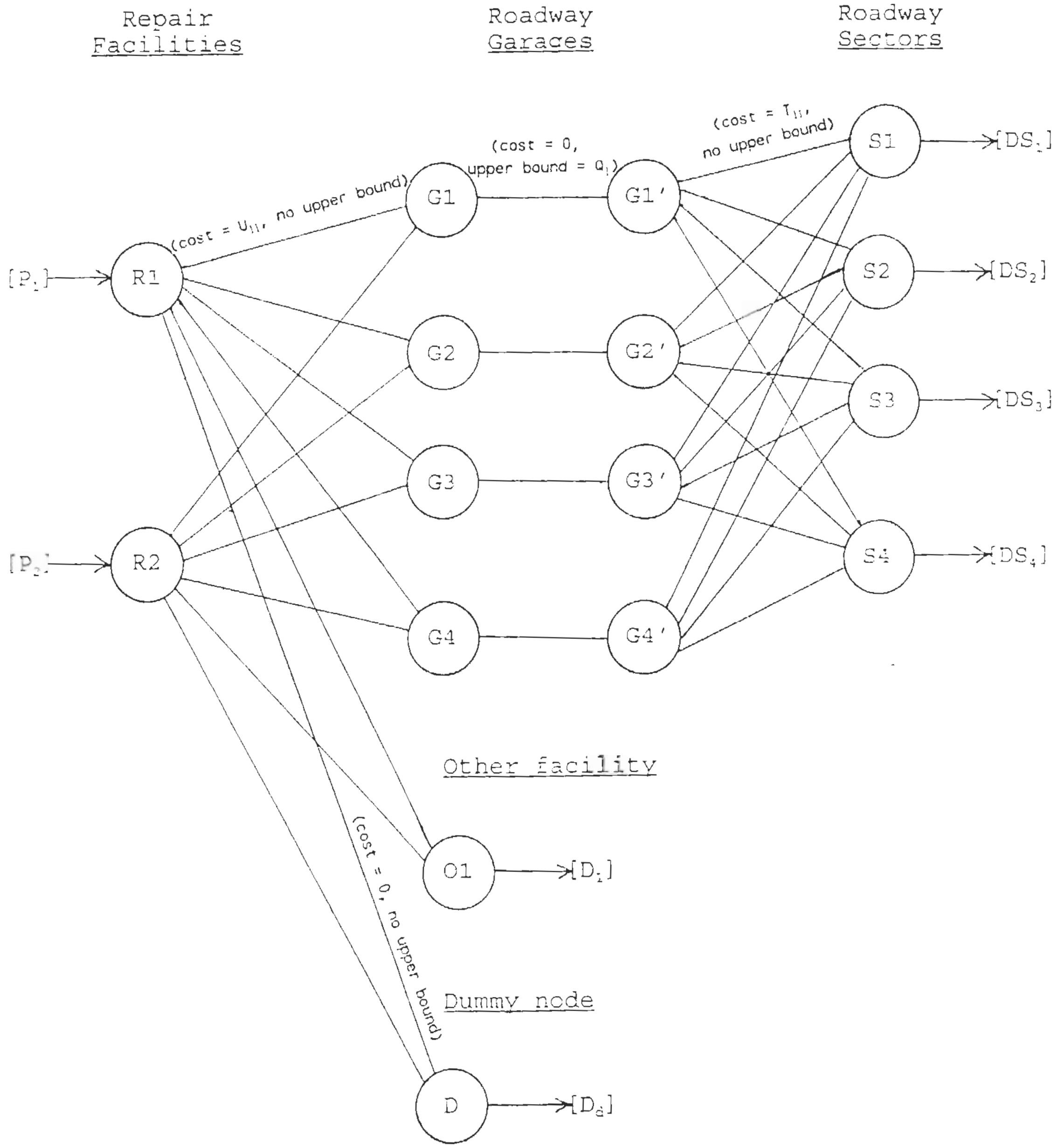

Figure 7. Network representation of an example two-stage problem.

In the network there are two sets of nodes representing roadway garages (e.g. G1 and G1'). The arcs that connect these have flow limitations placed on them to represent garage capacity constraints. In terms of the mathematical formulation presented earlier, the upper bounds on these arcs enforce constraint set (3).

Each of the roadway sector nodes shown in Figure 7 has an outward flow associated with it. These outward flows represent the maintenance requirements of the sector, in terms of equipment required to maintain it. The arcs that connect garage nodes to roadway sector nodes enable flows that represent assignments of sectors to garages. Note that the costs of transporting equipment to sectors from garages are included along these arcs.

The other facility, which is represented by node O1 in Figure 7, has an outward flow equivalent to its equipment repair requirements. The arcs connecting O1 to the repair facility nodes are similar to the ones that connect garages to repair facilities.

The graphical depiction of the network enables simple explanations of how the model can be modified to reflect DSS user inputs. The closing of a repair facility corresponds to the removal of the associated node and all connecting arcs, and the addition of a new facility corresponds to adding a node. Changes in the configuration of garages and other facilities would have similar effects on those sets of nodes. Capacity, cost and demand changes are also easily represented.

Although the network diagram is a more convenient communication tool than the mathematical formulation, it still represents a level of abstraction beyond a simple map such as that shown in Figures 3, 4 and 5. To make the DSS as user-friendly as possible, it is preferable to work with input and output screens in the form of maps. This is where the geographic information system (GIS) interface comes in.

IV. INCORPORATING A GEOGRAPHIC INFORMATION SYSTEM

The prototype DSS that is based on ConnDOT's District 2 does not at this time include a GIS link to the linear programming software. The GIS component has been designed, but it has not been implemented. Implementation requires creating an interface between the GIS software and the GAMS linear programming software. The programming of that interface is beyond the scope of the current project. The purpose of this section is to describe and illustrate a design for the GIS component.

The GIS component is designed to be used for input to and output from the DSS. In terms of input, the following must be specified by the user:

- -- which repair facilities are open;
- -- which roadway garages are open;
- -- capacities of all facilities;
- -- any fixed assignments of garages to repair facilities or roadway sectors to garages.

Specification of open repair facilities and roadway garages can be done using a display like that shown in Figure 3. Using the personal computer's mouse, the user would click on any facility whose status they would like to change. Changes in status would include changing the capacity of the facility or closing it entirely (which corresponds to setting its capacity to zero). As the DSS is currently designed, the user would not be able to add a facility whose data is not already programmed into the model. As it stands, this type of change would require reprogramming of the DSS.

The user may wish to fix certain assignments that should not be changeable by the DSS. The GIS could be used for that by selecting an appropriate menu item (i.e., garage assignments or sector assignments), and clicking on the pair of items involved in the assignment. Alteration of the linear programming model, along the lines discussed in Appendix B, would then be performed automatically by the DSS.

After the user has specified all inputs, a "solve" menu item would be selected on the GIS and the linear programming software would be executed. The user would wait a short amount of time until the DSS returned a message indicating that the problem had been solved. They would then choose amongst the various solution display options available.

One option for displaying solution output would be a map showing assignments of garages to repair facilities. An example of such a map is shown in Figure 4. The assignments on this map correspond to the District 2 assignments that are given in the GAMS output shown in Appendix D.

Another option for viewing output is to see the amount of equipment that is assigned to each garage. This output would be accessible through a table that would be displayed by the GIS when that particular menu item was selected.

Another menu item would initiate display of roadway sector assignments to garages. For example, Figure 5 shows the sectors that are assigned to the Mansfield garage (garage 39) in the optimal solution given in Appendix D. Because partial assignments are possible, a way of indicating these in the GIS display is necessary. For the purposes of Figure 5, sector 33's assignment is shown like that of the other sectors, even though the solution in Appendix D indicates that the sector is only partially assigned to the garage. Several methods for representing partial assignments are possible (e.g., percentages could be shown on the map for all partial assignments).

Display of transportation cost information is also possible, as are summaries of capacity utilizations. It is also possible to develop a program that could highlight differences between solutions. This would be particularly useful for comparing a DSS-generated solution against the assignments that exist in the current maintenance system.

The possibilities for displaying output are so numerous that they all cannot be described here. The primary purpose of this section has been to illustrate the types of options that are available and to communicate some likely methods for facilitating user input and displaying model output. If the programming of the GIS/LP interface is undertaken as part of a follow-on project, then the format of the input and output screens would need to be further detailed. The requirements of end-users within ConnDOT should be further solicited and considered at that stage of system development.

V. CONCLUSION

This report has described a prototype DSS designed to enable ConnDOT to evaluate alternative user-specified maintenance system configurations. Given the sets of open and closed repair facilities and garages, the DSS makes assignments of garages to repair facilities and roadway sectors to garages so as to minimize total transportation costs. At the current stage of development, the DSS is set up to handle only one of ConnDOT's four maintenance districts. This limits the usefulness of the system because it cannot completely consider interactions across districts, such as when a garage in District 2 (e.g., Mansfield) is served by a repair facility in District 1 (e.g., West Willington).

Another limitation of the prototype DSS is the fact that a GIS has not been incorporated into it. Section IV describes how the GIS component would work, but the actual programming of the LP/GIS interface has not been undertaken.

As it stands, the prototype DSS is not very user-friendly. Appendix A presents an example of the input format required by the GAMS software, and Appendix B discusses how the input could be changed to reflect different facility configurations. Appendix C describes how to execute the software, and Appendix D discusses the interpretation of GAMS output. From these appendices, it is obvious that the user interface component of the DSS requires further development to make the system easy to use. Ease-of-use is a desirable DSS feature that has not been built into the prototype system.

The main contribution of the prototype system is that it demonstrates the feasibility of building the engine and database components of the DSS. Expanding the scope of these components to include the entire state would be a straightforward undertaking. Another contribution of the research is the design of how these components can be integrated with a GIS component. Combined with the prototype system, the GIS description completes the specification of the DSS.

The description of the prototype model and the GIS component could serve as a basis for discussing how best to design the more comprehensive DSS that would model the entire state. The development and implementation of such a system would not be inhibited by any major technical barriers -- open questions are primarily related to what input/output features would best suit ConnDOT's needs.

In the introduction section, the evolution of the model from a single-stage to a two-stage system was described. Also described was the change in direction from a system where the model determined which facilities to open and close to a system where the user specifies these as inputs. This simplified the model and resulted in a system more in line with ConnDOT's needs.

The data-gathering requirements of the simplified two-stage model are less than those of the original two-stage model, but they are still non-trivial. The expansion of the DSS to include the entire state and the programming of the LP/GIS interface should only be undertaken if there is a high probability that the resulting system would be useful to ConnDOT Maintenance. This report provides information that should be sufficient for estimating the benefits that the fully developed system would offer. The determination of whether or not these benefits are likely to be worth the costs that further system development would entail is now in the hands of ConnDOT.

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APPENDIX A. Example of Input for the GAMS Software

```
*    Two-Stage Model of ConnDOT's District 2 Maintenance System
*    Principal Investigators:  Gerard Campbell and Christian Davis

SET I   set of maintenance garages and other sources of equipment
  /GAR39, GAR40, GAR42 * GAR54, OTH10, OTH11, OTH12, OTH13, OTH18,
  OTH20, OTH21/;

SET F   set of repair facilities
  /WWL,HIG,OSA,PUTN,LIS/;

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

SET J  roadway sectors
 /SEC1 * SEC110/;

PARAMETER P(F)   present capacity based on equipment servicable
 / WWL 99.6, HIG 110.04, OSA 130.92, PUTN 110.04, LIS 120.48/;

SCALARS    TMULT      travel cost multiplier           /1.00/;

TABLE G(I,E)  quantity of type e equipment at garage i
        TYPE1A  TYPE1B  TYPE2  TYPE3  TYPE4  TYPE5
GAR39      3       0       1      5      3      4
GAR40      9       3       1      9      8     27
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
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
OTH18      6       2       6     11      8     12
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
GAR39      0       0       0      0      0     1
GAR40      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
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
```

```
OTH18      0       0       0      0      0     2
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
        WWL    HIG    OSA    PUTN    LIS
GAR39  12.94  30.76  35.39  24.44  16.21
GAR40  15.03  31.74  9999   34.49  28.96
GAR42  24.64  19.51  26.84  38.73  25.21
GAR43  26.62  18.66  23.58  9999   18.93
GAR44  38.21  5.49   11.96  9999   29.79
GAR45  9999   23.26  17.27  9999   9999
GAR46  36.71  28.91  13.75  9999   14.2
GAR47  9999   16.7   0.66   9999   27.61
GAR48  25.39  28.28  27.25  30.41  7.0
GAR49  26.78  34.36  28.77  25.65  0.92
GAR50  9999   39.26  24.1   36.14  16.43
GAR51  27.98  33.05  22.48  31.31  7.21
GAR52  25.3   9999   39.81  16.34  11.91
GAR53  16.05  9999   9999   8.35   23.18
GAR54  23.17  9999   9999   0      25.44
OTH10  9999   35.52  20.36  9999   15.51
OTH11  9999   17.63  4.01   9999   31.68
OTH12  9999   35.29  22.35  31.26  5.82
OTH13  26.79  9999   9999   14.85  12.67
OTH18  12.5   27.96  31.99  28.02  20.0
OTH20  9999   26.05  10.89  9999   17.19
OTH21  27.25  33.00  22.6   31.53  7.13     ;

TABLE TIME(I,F)   travel time between facility f and garage i
        WWL    HIG    OSA    PUTN    LIS
GAR39  0.28   0.67   0.74   0.50   0.36
GAR40  0.30   0.57   9999   0.75   0.66
GAR42  0.54   0.42   0.53   0.85   0.47
GAR43  0.59   0.41   0.46   9999   0.35
GAR44  0.76   0.12   0.26   9999   0.60
GAR45  9999   0.48   0.32   9999   9999
GAR46  0.76   0.52   0.25   9999   0.30
GAR47  9999   0.31   0.02   9999   0.54
GAR48  0.54   0.58   0.51   0.54   0.14
GAR49  0.58   0.70   0.53   0.45   0.02
GAR50  9999   0.73   0.46   0.72   0.37
GAR51  0.59   0.67   0.42   0.56   0.15
GAR52  0.55   9999   0.77   0.30   0.26
GAR53  0.35   9999   9999   0.17   0.50
GAR54  0.50   9999   9999   0.00   0.46
OTH10  9999   0.64   0.37   9999   0.35
OTH11  9999   0.35   0.09   9999   0.61
OTH12  9999   0.69   0.42   0.59   0.13
OTH13  0.59   9999   9999   0.26   0.24
OTH18  0.26   0.62   0.62   0.61   0.46
OTH20  9999   0.47   0.20   9999   0.36
OTH21  0.57   0.66   0.42   0.54   0.14    ;

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

/GAR39.SEC1     22.042
GAR39.SEC2     21.077
GAR39.SEC3     14.888
GAR39.SEC4     17.787
GAR39.SEC5     17.904
GAR39.SEC6     23.154
GAR39.SEC7     20.620
GAR39.SEC8     21.468
GAR39.SEC11    21.912
GAR39.SEC12    21.943
GAR39.SEC13    23.300
GAR39.SEC14    23.637
GAR39.SEC17    20.464
```

GAR39.SEC49	15.540
GAR39.SEC50	12.326
GAR39.SEC51	19.477
GAR39.SEC52	18.147
GAR39.SEC53	21.498
GAR39.SEC54	21.164
GAR39.SEC96	18.454
GAR39.SEC97	19.733
GAR39.SEC98	22.707
GAR39.SEC101	22.506
GAR39.SEC102	19.459
GAR39.SEC103	18.984
GAR39.SEC107	22.088
GAR39.SEC109	22.343
GAR39.SEC110	23.831
GAR40.SEC19	24.833
GAR40.SEC20	24.536
GAR40.SEC23	12.611
GAR40.SEC24	20.533
GAR40.SEC25	20.548
GAR40.SEC26	21.882
GAR40.SEC27	17.060
GAR40.SEC28	14.034
GAR40.SEC29	11.103
GAR40.SEC30	7.212
GAR40.SEC31	10.121
GAR40.SEC32	9.328
GAR40.SEC33	13.622
GAR40.SEC34	7.618
GAR40.SEC35	19.110
GAR40.SEC36	15.533
GAR40.SEC37	20.584
GAR40.SEC38	19.876
GAR40.SEC39	22.837
GAR40.SEC42	20.605
GAR40.SEC44	22.173
GAR40.SEC45	20.499
GAR40.SEC46	22.364
GAR40.SEC47	19.764
GAR40.SEC48	21.161

GAR40.SEC49	24.928
GAR40.SEC50	20.864
GAR40.SEC53	23.242
GAR40.SEC97	24.766
GAR42.SEC23	21.069
GAR42.SEC24	22.692
GAR42.SEC25	21.310
GAR42.SEC26	20.329
GAR42.SEC28	14.853
GAR42.SEC29	10.297
GAR42.SEC30	18.222
GAR42.SEC31	18.388
GAR42.SEC32	22.732
GAR42.SEC33	13.670
GAR42.SEC34	12.353
GAR42.SEC35	1.391
GAR42.SEC36	10.315
GAR42.SEC37	2.782
GAR42.SEC38	4.705
GAR42.SEC39	7.855
GAR42.SEC40	10.455
GAR42.SEC41	17.317
GAR42.SEC42	13.349
GAR42.SEC43	21.620
GAR42.SEC44	10.818
GAR42.SEC45	9.376
GAR42.SEC46	7.433
GAR42.SEC47	8.572
GAR42.SEC48	19.641
GAR42.SEC49	23.052
GAR42.SEC50	19.957
GAR42.SEC51	16.671
GAR42.SEC52	18.538
GAR42.SEC53	13.301
GAR42.SEC54	18.690
GAR42.SEC62	24.558
GAR42.SEC88	22.279
GAR42.SEC89	23.422
GAR42.SEC90	23.935
GAR42.SEC91	21.455
GAR42.SEC92	23.212
GAR42.SEC93	22.227
GAR42.SEC94	17.529
GAR42.SEC96	22.598
GAR42.SEC97	22.646
GAR42.SEC102	22.880
GAR42.SEC103	22.709
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GAR54.SEC7     17.513
GAR54.SEC8     9.262
GAR54.SEC9     4.463
GAR54.SEC10    3.237
GAR54.SEC11    5.126
GAR54.SEC12    5.781
GAR54.SEC13    11.306
GAR54.SEC14    4.681
GAR54.SEC15    4.817
GAR54.SEC16    8.937
GAR54.SEC17    12.700
GAR54.SEC18    10.221
GAR54.SEC19    6.926
GAR54.SEC20    12.485
GAR54.SEC21    9.646
GAR54.SEC22    6.852
GAR54.SEC23    24.836
GAR54.SEC24    16.175
GAR54.SEC25    23.889
GAR54.SEC26    19.181
GAR54.SEC27    21.074
GAR54.SEC28    24.777
GAR54.SEC32    24.007
GAR54.SEC102   23.762
GAR54.SEC107   24.475 /;

PARAMETER DISTANCE(I,J) corrected distance between gar i and sect j;

DISTANCE(I,J)$(DT(I,J) EQ 0) = 9999;
DISTANCE(I,J)$(DT(I,J) NE 0) = DT(I,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 15) =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) * (25.0 - 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) = C(F,I)/DEM(I);

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

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

PARAMETER DS(J)  / sec1 1.28,
  SEC2 1.28, SEC3 1.28, SEC4 1.28, SEC5 1.28, SEC6 2.14,
  SEC7 0.86, SEC8 1.71, SEC9 3.31, SEC10 1.32, SEC11 3.31,
  SEC12 1.32, SEC13 3.31, SEC14 1.99, SEC15 2.65, SEC16 2.65,
  SEC17 1.64, SEC18 1.23, SEC19 1.64, SEC20 1.23, SEC21 1.23,
  SEC22 1.64, SEC23 0.65, SEC24 0.65, SEC25 0.65, SEC26 0.87,
  SEC27 0.87, SEC28 1.52, SEC29 0.87, SEC30 3.23, SEC31 3.23,
  SEC32 2.42, SEC33 3.23, SEC34 2.42, SEC35 2.39, SEC36 2.39,
  SEC37 3.58, SEC38 1.19, SEC39 1.79, SEC40 1.79, SEC41 6.00,
  SEC42 2.57, SEC43 2.57, SEC44 5.15, SEC45 2.57, SEC46 2.57,
  SEC47 1.72, SEC48 2.13, SEC49 1.06, SEC50 1.61, SEC51 3.2,
  SEC52 2.13, SEC53 1.60, SEC54 1.60, SEC55 1.88, SEC56 0.63,
  SEC57 1.26, SEC58 0.94, SEC59 1.26, SEC60 0.94, SEC61 2.51,
  SEC62 1.88, SEC63 1.26, SEC64 1.50, SEC65 2.00, SEC66 1.50,
  SEC67 2.00, SEC68 2.99, SEC69 1.00, SEC70 1.00, SEC71 2.51,
  SEC72 2.51, SEC73 5.03, SEC74 5.03, SEC75 1.68, SEC76 1.68,
  SEC77 3.65, SEC78 3.35, SEC79 1.76, SEC80 2.65, SEC81 1.76,
  SEC82 1.32, SEC83 1.32, SEC84 1.32, SEC85 2.65, SEC86 1.76,
```

```
  SEC87 0.88, SEC88 1.85, SEC89 2.47, SEC90 3.70, SEC91 1.23,
  SEC92 3.70, SEC93 1.23, SEC94 2.47, SEC95 2.47, SEC96 3.00,
  SEC97 0.86, SEC98 2.14, SEC99 1.28, SEC100 1.71, SEC101 1.28,
  SEC102 0.86, SEC103 2.14, SEC104 1.76, SEC105 1.76, SEC106 1.76,
  SEC107 3.51, SEC108 2.34, SEC109 3.51, SEC110 2.34/;

PARAMETER T(I,J)  total annual cost to service a unit of sector j
   demand from garage i;

T(I,J)=DISTANCE(I,J)* TMULT;

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

   Q(I) = 1.1*dem(i);

VARIABLES

   X(F,I)     amount of garage i equipment served by repair facility f
   XS(I,J)    amount of sector j demand served by garage i
   Z          total cost;

POSITIVE VARIABLES X, XS ;


EQUATIONS
   COST            objective function
   OTHER(I)        all of other facility i demand must be met
   SUPPLY(F)       capacity of facility f cannot be exceeded
   JDEM(J)         all of sector j demand must be met
   ISUPPLY(I)      equipment availability at garage i
   SPACE(I)        limits equipment housed at garage i ;

COST ..   Z =E= SUM((F,I)$(DIST(I,F) LE 40),(U(F,I)*X(F,I)))
     +SUM((I,J)$(DISTANCE(I,J) LT 25),T(I,J)*XS(I,J)) ;

OTHER(I)$(GF(I) NE 1)..   SUM(F$(DIST(I,F) LE 40),(X(F,I))) =E= DEM(I);

SUPPLY(F)..  SUM(I$(DIST(I,F) LE 40),X(F,I)) =L= P(F);

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

ISUPPLY(I)$(GF(I) EQ 1)..  SUM(J$(MAP1(I,J) GT 0), (XS(I,J))) =E=
                           SUM(F$(DIST(I,F) LE 40),(X(F,I))) ;

SPACE(I)$(GF(I) EQ 1)..  SUM(F$(DIST(I,F) LE 40),(X(F,I))) =L= Q(I);


MODEL CONNDOT /ALL/;

SOLVE CONNDOT USING LP MINIMIZING Z;

DISPLAY X.L, XS.L ;
```

APPENDIX B. Changing Inputs to the GAMS Software

The input shown in Appendix A is stored as a DOS text file on a diskette that has been provided to ConnDOT along with a copy of the GAMS software. The file is labeled DIST2.GMS on the diskette. GAMS does not include an editor that can be used to modify the input file. However, since GAMS accepts DOS text files, any editor that saves files in that format can be used. Many word processors have the capability of saving files as DOS text. For example, this can be done in WordPerfect 5.1 by hitting <CTRL><F5>, then selecting option 1 (DOS Text), and then selecting option 1 again (SAVE). To retrieve the GAMS input file using WordPerfect 5.1, simply treat it as any other word processing file (i.e., use <F5>, specify the appropriate disk drive, and then select option 1 after the cursor is positioned next to the file name). The file can then be modified as if it were any other document in the word processor.

The following four types of changes to the model are described in this appendix:
1) closing a repair facility or changing its capacity;
2) closing a garage or changing its capacity;
3) fixing the assignment of a garage to a repair facility;
4) fixing the assignment of a roadway sector to a garage.
Each of these changes is described individually below.

1) Closing a repair facility or changing its capacity.

Repair facility capacities are specified using the parameter P(F) in the GAMS model (see page A.1). Closing a facility is simply a matter of setting its capacity to zero. For example, the following modification to the GAMS input shown on page A.1 will effectively close the Higganum repair facility:

```
PARAMETER P(F)   present capacity based on equipment servicable
/ WWL 99.6, HIG 0.0, OSA 130.92, PUTN 110.04, LIS 120.48/;
```

Note that all other facility capacities are unchanged.

Now say that we wanted to increase the capacity of the Lisbon facility by 20% while simultaneously closing Higganum. The following modification to the input accomplishes this:

```
PARAMETER P(F)   present capacity based on equipment servicable
/ WWL 99.6, HIG 0.0, OSA 130.92, PUTN 110.04, LIS 144.58/;
```

Other changes to repair facility capacities could be implemented in a similar way.

2) Closing a roadway garage or changing its capacity.

The capacity of a garage is specified using the parameter Q(I) in the GAMS model. This is shown on page A.16 of Appendix A. In the prototype model, the capacity of a garage is assumed to be 110% of the equipment that is assigned to it in the current system. For any garage, this capacity level can be changed by adding a line to the input, inserted directly above the line that says "VARIABLES" on page A.16. As an example, say we wanted to set the capacity of garage 39 equal to 15.5 standard units of equipment. The following, inserted as indicated above, would accomplish that:

```
Q('GAR39') = 15.5;
```

To close a garage, for example garage 43, we would set its capacity to zero, as shown below:

```
Q('GAR43') = 0.0;
```

Any number of lines of this type could be added to close garages or change their capacities. If multiple specifications are made for the same garage, the one that appears latest in the file would be used.

3) Fixing a garage to repair facility assignment.

A garage is assigned to a repair facility by modifying the model so that transportation costs from that garage to any other facility are extremely high. As an example, say we wanted to assign garage 42 to the Lisbon repair facility. This can be done by inserting the following set of lines just above the VARIABLES line of the input file shown on page A.16:

```
PARAMETER UT42(F,I);
UT42(F,'GAR42') = U(F,'GAR42') * 9999.;
UT42('LIS','GAR42') = U('LIS','GAR42');
U(F,'GAR42') = UT42(F,'GAR42');
```

Assignment of any garage to any repair facility can be made in a similar way.

4) Fixing a roadway sector to garage assignment.

The procedure for this is essentially the same as that for fixing a garage to repair facility assignment -- i.e., transportation costs are modified. The following sequence of lines inserted above the VARIABLES line of the input file shown on page A.16 would ensure that sector 29 is assigned to garage 39:

```
PARAMETER T29(I,J);
T29(I,'SEC29') = T(I,'SEC29') * 9999.;
T29('GAR39','SEC29') = T('GAR39','SEC29');
T(I,'SEC29') = T29(I,'SEC29');
```

Assignments of any roadway sector to any garage can be made in a similar manner.

APPENDIX C. Executing the GAMS Software

The GAMS software should be installed on the hard drive of a personal computer according to the instructions given in the GAMS User's Guide. With the software installed and the computer's directory set to that of GAMS, insert the diskette containing the model DIST2.GMS in the computer's A drive and type the following command to initiate execution:

```
GAMS A:DIST2
```

Various messages will appear as the problem is being solved, and finally one of the messages will indicate that execution has been completed. A large file named DIST2.LST will be saved on the hard drive. This file includes the solution to the problem that was inputted through the DIST2.GMS file. To view the .LST file or to print it, simply retrieve is as a document using a word processor such as WordPerfect 5.1. Appendix D describes how to interpret the solution, which appears on the last few pages of the DIST2.LST file.

APPENDIX D. Interpreting Output from the GAMS Software

Much of the output contained in the DIST2.LST file is only of interest to a technical specialist. The key portions of the output for most users are included on the last few pages of the file. There, the total cost of the solution and the values of decision variables are reported. For the problem given in Appendix A, these portions of the DIST2.LST file are shown below.

```
                       LOWER     LEVEL     UPPER    MARGINAL

---- VAR Z              -INF   1734.175     +INF       .

  Z           TOTAL COST


**** REPORT SUMMARY :        0     NONOPT
                             0 INFEASIBLE
                             0  UNBOUNDED


^HGAMS 2.23 DOS-386                                95/07/23 13:10:11  PAGE     70
DIST2
E X E C U T I N G


----    1090 VARIABLE  X.L           AMOUNT OF GARAGE I EQUIPMENT SERVED BY
                                    REPAIR FACILITY F

           GAR39       GAR40       GAR42       GAR43       GAR44       GAR45

WWL        5.753      11.300
HIG                                9.247                  21.054
OSA                                                                   13.167
LIS                                           19.760

   +       GAR46       GAR47       GAR48       GAR49       GAR50       GAR51

OSA       14.498      29.502
LIS                               11.673      18.220      16.984      15.092

   +       GAR52       GAR53       GAR54       OTH10       OTH11       OTH12

OSA                                                        9.780
PUTN                   9.854      21.846
LIS        6.630                               4.910                   5.310

   +       OTH13       OTH18       OTH20       OTH21

WWL                   13.340
OSA                                7.540
LIS       10.110                               5.610
```

```
----   1090 VARIABLE  XS.L          AMOUNT OF SECTOR J DEMAND SERVED BY GARAGE  I

                SEC1        SEC2        SEC3        SEC4        SEC5        SEC6

GAR49                                                          1.280       2.140
GAR52          1.280       1.280       1.280       1.280

      +         SEC7        SEC8        SEC9       SEC10       SEC11       SEC12

GAR52          0.860
GAR54                      1.710       3.310       1.320       3.310       1.320

      +        SEC13       SEC14       SEC15       SEC16       SEC17       SEC18

GAR53          0.954                                           1.640
GAR54          2.356       1.990       2.650       2.650                   1.230

      +        SEC19       SEC20       SEC21       SEC22       SEC23       SEC24

GAR39                                                          0.650
GAR53          1.640       1.230       1.230       1.640                   0.650

      +        SEC25       SEC26       SEC27       SEC28       SEC29       SEC30

GAR39                      0.870                   1.520
GAR40                                                                      3.230
GAR42                                                          0.870
GAR52          0.650
GAR53                                  0.870

      +        SEC31       SEC32       SEC33       SEC34       SEC35       SEC36

GAR39                                  2.713
GAR40          3.230       2.420                   2.420
GAR42                                                          2.390
GAR43                                                                      2.390
GAR48                                  0.517

      +        SEC37       SEC38       SEC39       SEC40       SEC41       SEC42

GAR42          3.580                   1.790       0.617
GAR43                      1.190                                           2.570
GAR44                                              1.173       6.000

      +        SEC43       SEC44       SEC45       SEC46       SEC47       SEC48

GAR43                      5.150       2.570       2.570       1.720
GAR46          2.570
GAR48                                                                      2.130

      +        SEC49       SEC50       SEC51       SEC52       SEC53       SEC54

GAR43                                                          1.600
GAR48                      1.610       3.200       2.130
GAR49          1.060
GAR51                                                                      1.600

      +        SEC55       SEC56       SEC57       SEC58       SEC59       SEC60

GAR46          1.880       0.630       1.260       0.940       1.260       0.940
```

```
       1090 VARIABLE  XS.L          AMOUNT OF SECTOR J DEMAND SERVED BY GARAGE I

    +       SEC61       SEC62       SEC63       SEC64       SEC65       SEC66

GAR45                                           1.500       2.000       1.500
GAR46       2.510       1.052       1.260
GAR51                   0.828

    +       SEC67       SEC68       SEC69       SEC70       SEC71       SEC72

GAR45       2.000       2.990       1.000       1.000
GAR47                                                       2.510       2.510

    +       SEC73       SEC74       SEC75       SEC76       SEC77       SEC78

GAR45                                                       1.177
GAR47       5.030       5.030       1.680       1.680       2.473       3.350

    +       SEC79       SEC80       SEC81       SEC82       SEC83       SEC84

GAR46                               0.196
GAR50       1.760       2.650       1.564       1.320       1.320       1.320

    +       SEC85       SEC86       SEC87       SEC88       SEC89       SEC90

GAR44                                           0.311       2.470       3.700
GAR47                                           1.539
GAR50       2.650       1.760       0.880

    +       SEC91       SEC92       SEC93       SEC94       SEC95       SEC96

GAR44       1.230                   1.230       2.470       2.470
GAR47                   3.700
GAR51                                                                   3.000

    +       SEC97       SEC98       SEC99      SEC100      SEC101      SEC102

GAR49                                                                   0.860
GAR51       0.860       2.140       1.280       1.710       1.280

    +      SEC103      SEC104      SEC105      SEC106      SEC107      SEC108

GAR48       2.086
GAR49                   1.760                   1.760       3.510       2.340
GAR50                               1.760
GAR51       0.054

    +      SEC109      SEC110

GAR49       3.510
GAR51                   2.340


**** FILE SUMMARY

INPUT   C:\GAMS386\DIST2.GMS
OUTPUT  C:\GAMS386\DIST2.LST


EXECUTION TIME       =        2.300 SECONDS       VER: 386-EK-009
```

The interpretation of this output is fairly straightforward. The total cost of the solution is given by the value shown under the "LEVEL" column for VAR Z on page D.1. In this case, the value is $ 1734.175.

Values for the X decision variables, which indicate garage to repair facility assignments, are given in tabular form on page D.1. The values in the table indicate the amount of equipment sent from garage i to repair facility f. Thus, the values indicate not only the assignment, but also how much equipment is to be housed at garage i in the optimal solution. For example, the output on page D.1 indicates that garage 48 houses 11.673 standard units of equipment, and all of this equipment goes to Lisbon for repair. It is possible for a garage's equipment to go to more than one repair facility. This situation, which did not occur in the solution to the example problem, would be indicated by having multiple entries in the column associated with a particular garage. The amount of equipment housed at the garage would then be calculated by summing all the entries in the garage's column. Each of the entries would be associated with a different repair facility to which that amount of equipment would be assigned.

The assignments of roadway sectors to garages are handled in a similar manner via the XS variables. The table showing XS values, which starts on page D.2, is larger than the table of X values because there are many more roadway sectors than garages. The total amount of equipment going to a sector from a garage is equal to the demand of that sector. Sector demand values are shown in the input file given in Appendix A beginning on page A.15 under the parameter DS(J). In the XS table that begins on page D.2, note that in certain cases the demand of a sector is served by more than one garage. For example, the output on page D.2 indicates that .954 of sector 13's demand (which totals 3.31) is served by garage 53, and 2.356 of it is served by garage 54. Splits such as this occur because of capacity limitations at the garages that are closest to the sectors. Note that the number of split sectors that appear in the solution are relatively few (i.e. only 8 out of the 110 sectors are split).

Graphical representation of the solution shown above is given in Section I. Possibilities for improving the presentation of the model's output are discussed in Section IV, where the GIS interface is described.