AN OPTIMUM ALLOCATION APPROACH TO CLOSING OR RELOCATING HIGHWAY MAINTENANCE GARAGES IN IOWA

FINAL REPORT

DEPARTMENT OF TRANSPORTATION
IOWA

PREPARED BY

OFFICE OF TRANSPORTATION RESEARCH
PLANNING AND RESEARCH DIVISION
IOWA DEPARTMENT OF TRANSPORTATION

IN COOPERATION WITH
FEDERAL HIGHWAY ADMINISTRATION
U.S. DEPARTMENT OF TRANSPORTATION

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RESEARCH PARTICIPANTS

Principal Investigator:

Paul T. Nkansah
Graduate Student Research Assitant
Departments of Industrial Engineering/
Statistics
Iowa State University
Ames, Iowa

Project Director:

Saleem Baig, P.E.
Transportation Research Engineer
Office of Transportation Research
Iowa Department of Transportation

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I. EXECUTIVE SUMMARY

Highway maintenance engineers and administrators are often confronted with a number of problems related to highway maintenance work programs. One of these problems is concerned with determining the optimum number and locations of highway maintenance garages in a given area. Serious decline in highway revenues and a high inflation rate have made it necessary to examine existing maintenance practices and to allocate reduced financial resources more effectively and efficiently. Searching for and providing of reasonable solutions to these problems is the focus of this research project.

The methodology used is to identify and modify for use (if necessary) those models which have already been developed. Models which could give optimum number and locations of highway maintenance garages were found to be too theoretical and/or practically infeasible. Consequently, research focus was shifted from these models to other models that could compare alternatives and select the best among these alternatives. Three such models -- the Alabama model, California model, and Louisiana model, were identified and studied.

The three models identified differed in their capabilities. The Louisiana model is the most comprehensive. It is then followed by the California model. The Alabama model has the fewest capabilities. The following table shows the three models and a summary of their capabilities.

Capabilities	MODEL		
	Alabama (Optimum Allocation)	California	Louisiana
1. Best Alternative Garage Location	Yes	Yes	Yes
2. Relocation of a Garage	Yes	Yes	Yes
3. Closing of a Garage	Yes	Yes	Yes
4. Operating Costs	Yes	Yes	Yes
5. Capital Costs	No	Yes	No
6. Staffing Needs	No	Yes	Yes
7. Comparison of Different Work Crew Sizes	No	No	Yes
8. Comparison of Different Maintenance Strategies	No	No	Yes
9. Comparison of Different Work Scheduling Policies	No	No	Yes
10. Comparison of Different Types and Numbers of Equipments	No	No	Yes

The input data requirements for the three models are also different. The Louisiana model has the largest number of input data requirements. The California model and the Alabama model follow each other in decreasing order in numbers of input data requirements.

The following table shows the three models and their input data requirements. The input data not currently available in Iowa DOT are also shown in the Table.

Input Data Requirements	MODEL		
	Alabama (Optimum Allocation)	California	Louisiana
1. Dollars of Maintenance Effort on Route Basis	Yes	Yes	Yes
2. Man-hours of Maintenance Effort on Route Basis*	No	Yes	No
3. Crew Travel Times*	Yes	Yes	Yes
4. Crew Travel Distances*	No	Yes	No
5. Frequency of Occurrence of Each Work Activity*	No	No	Yes
6. Times of Occurrence and Durations of Emergency Activities*	No	No	Yes
7. Rate of Personnel Absenteeism*	No	No	Yes
8. Rate of Equipment Breakdown*	No	No	Yes

* Data not currently collected by the Office of Maintenance, Highway Division, Iowa DOT.

Of the three models considered, the Alabama model has the fewest capabilities. Yet, because it requires only two types of input data and one of them was already available in Iowa DOT, it was selected for use in this study. The Alabama model is referred to as the Optimum Allocation model.

The Optimum Allocation model was successfully applied to 15 maintenance garages in a study area selected by the Office of Maintenance. First, the existing allocation system in the study area (highway segments assigned to garages) was examined, using the model. Results recommended only four highway segments be reallocated to a different maintenance area of the existing system. This indicates the existing allocation system used by the Office of Maintenance is good for all practical purposes. However, if the route allocation determined by the Optimum Allocation model is used, there could be an annual cost savings of approximately $2,800 (using maintenance vehicle average speed of 35 mph) and approximately $2,500 (using maintenance vehicle average speed of 40 mph).

Secondly, the Optimum Allocation model was used to 'close' the garages at Humboldt and Forest City. When the garage at Humboldt was closed, annual cost savings of approximately $7,500 (using average speed of 35 mph) and approximately $10,200 (using average speed of 40 mph) were projected. The projected annual cost savings, when the garage at Forest City was closed, were approximately $11,700 (using average speed of 35 mph) and approximately $13,000 (using average speed of 40 mph).

Finally, the Optimum Allocation model was used to demonstrate its garage relocation capability as follows:

1. With the garage at Forest City assumed to be closed, the garages at Estherville and Gerled were moved to Armstrong and Buffalo Center, respectively. This move resulted in projected annual cost savings of approximately $600 (using average speed of 35 mph and without considering capital costs). Clearly, this is not a significant amount of cost savings.
2. With the garage at Forest City assumed to be closed, the garage at Estherville was again relocated at Armstrong but the garage at Gerled was moved to Thompson. This new arrangement yielded a projected annual cost savings of approximately $3,700 (using average speed of 35 mph and without considering capital costs).

The cost savings reported above are subject to the limitations of this study. The limitations pertain to the applicability of the cost multiplier concept to the Iowa highway maintenance work program; the sensitivity of the travel time adjusted costs to speed and the percentage of maintenance cost associated with snow and ice control activities; and the reliability of the maintenance cost data used.

A number of recommendations have been given to alleviate the effects of the limitations of this study. It is recommended that additional data be collected by the Iowa DOT for use in any future comprehensive highway maintenance study.

The computer program utilized in the Optimum Allocation model was developed by the IBM and is available for lease at a cost of about $500 per month. This computer program is also available at the Iowa State University and it is this program which was used for this study. The total computer cost for this study was $150 and the average cost per run was approximately $10.

In summary, this study has successfully identified a model (Optimum Allocation Model) that can utilize the data currently available in the Iowa DOT. Also, it can optimally assign highway segments to maintenance garages and evaluate the cost impact of closing or relocating a specified maintenance garage in a given study area.

II. INTRODUCTION

Highway maintenance activity is an integral part of any state's highway transportation work program. In Iowa, highway maintenance activities are carried out by six Highway Division District Offices, located in different parts of the state. The Office of Maintenance, Highway Division, located at the central headquarters of the Iowa Department of Transportation (Iowa DOT) in Ames, acts in an advisory capacity to the districts on matters concerning policies and administration of the statewide Highway Maintenance Work Program (See Appendix 1).

Each Highway Division District is currently divided into four maintenance residencies and each residency is further sub-divided into highway maintenance areas. A maintenance area contains one or more highway maintenance garages (See Appendix 2).

The fiscal year 1980 Maintenance Work Program of the Iowa DOT consisted of about 120 functions involving about 1,790 employees. The total cost for the program was 50.9 million dollars. This total cost consisted of labor costs (30.8 million dollars), equipment costs (8.5 million dollars), and material costs (11.6 million dollars).

Serious decline in highway revenues and a high inflation rate caused the Iowa DOT to review its existing highway maintenance practices. The aim of this review was to provide the same level of highway maintenance services with reduced financial resources. 'System Preservation' is now the top priority of the Iowa DOT.

One way to achieve this goal is to re-examine the existing locations of highway maintenance garages to determine whether or not some of these could be closed or relocated, resulting in more efficient use of available resources.

Closing a highway maintenance garage increases travel cost. On the other hand, maintaining a garage involves overhead costs. Closing a garage, therefore, is cost beneficial only when the resulting increase in travel cost is less than the overhead costs of that garage.

A highway maintenance garage must be optimally located within its maintenance area to minimize the loss in productivity associated with time spent traveling to the maintenance work sites. Where existing garages may not be optimally located, it is advantageous (in terms of cost savings) to examine several relocation possibilities.

III. OBJECTIVES

Initially, the objective of this study was to identify and modify for use (if necessary) models already developed that could determine the optimum number, size, and location of highway maintenance garages in Iowa. The approach in searching for models already developed was necessary because of time constraints on this study.

During the early stages of the study, it became apparent that models which could give optimum solutions were either too theoretical and/or practically infeasible. In other cases, the required input data for the model use was not available from the Iowa DOT highway maintenance records. Consequently, research focus was shifted from optimum models to other models that could compare alternatives and select the best among those alternatives.

The objective of this report, therefore, is to identify and modify for use (if necessary) models that can:

1. Evaluate alternative highway maintenance garage locations in a given study area based on cost considerations; and
2. Evaluate the cost impact of closing and/or relocating a highway maintenance garage in a given study area.

IV. MODEL SELECTION PROCESS

Extensive literature review of highway maintenance garage related studies was made (1, 2, 3, 4, 5, 6, 7, 11, 12, 13, 14, 15, 16, 18, 19, 21). The rationale was to identify models already developed. Any suitable model identified would then be modified, if necessary, to utilize the type of data currently available in Iowa DOT maintenance records.

Three different models were identified as being capable of addressing the objectives of this study. For brevity, the models will be referred to as the California Model, Louisiana Model, and Alabama Model. A brief description of the three models is given below.

A. California Model

1. Type of Model

The California model (19) is a deterministic simulation model. A deterministic simulation model is a "Laboratory" in which various alternatives are tested. The values of the input variables are assumed to be known with certainty and are constant over time. For example, under the deterministic assumption, the same amount of shoulder maintenance work is performed on a given route in each year of the simulation period (say 30 years). A simulation model is not expected to find the optimum solution for any particular problem; rather it helps identify the best solution among alternatives.

2. Capability of Model

The California model is capable of addressing the following types of problems:

a. Evaluate alternative garage locations...for example, is garage location 'x' better than garage location 'y'?

b. Evaluate the cost impact of closing a garage...for example, if garage 'x' is closed, will there be an increase or decrease in the total maintenance cost? and

c. Estimate the staffing needs of a garage...for example, how many man-hours per year are associated with garage 'x' maintenance activities?

The model uses both operating and capital costs in solving the above problems.

3. Key Input Data

The following data are necessary for developing the input data for the model:

a. Maintenance effort (in dollars and man-hours) for all the routes in the study area;

b. Crew travel times from garages to work sites;

c. Crew travel distances from garages to work sites;

d. Travel frequencies for all routes in the study area. A travel frequency for a route is an estimate of the number of times the work crew visits that route in order to satisfy its maintenance demand. It is estimated from the time consumed by the crew's travel, the speed of their travel, and the travel distances;

e. Weighting factors. A weighting factor is a subjective measure of the maintenance effort expended within each predetermined segment of a route. The factors are determined by experienced local supervisors and managers; and

f. Capital costs. These include land costs, the value of the existing garages utilized in the proposed solution, investment in new garages, the value of any garages which are replaced, and the remaining value of all land and improvements at the end of the study period.

Note: Records on man-hours of maintenance effort (on route basis), crew travel times, and crew travel distances are not currently available in Iowa DOT.

4. Output Data

For each alternative set of garage locations, the following output data is obtained:

a. Annualized cost (operating and capital costs) for the entire study area;

b. Maintenance effort (in man-hours/year) for each garage; and

c. Graphical plots which suggest the maintenance area for each garage.

5. Computer Program

The computer program for the California model is very complicated and not well documented. Close consultations with the California DOT (CALTRANS) officials would be required to adapt the program to successfully run on the computer facilities in the Iowa DOT.

B. Louisiana Model

1. Type of Model

The Louisiana model (14, 15, 16) is a probabilistic simulation model. Unlike the California model, the values of the input variables are assumed to change with time and hence are not known with certainty. The values are determined by probability distributions. For example, under the probabilistic assumption, the amount of shoulder maintenance work performed on a given route in each year of the simulation period is determined from a given probability distribution. The probability distribution shows the relative frequency of occurrence for each type of maintenance activity on the given route. The distribution is determined from historical data and/or pilot study.

2. Capability of Model

The Louisiana model is designed to address the following types of problems (15):

a. Evaluate changes in work crew sizes...for example, what effect would the addition of two equipment operators have?

b. Evaluate quantities and types of equipment...for example, which could be better, adding two trucks of size A or three trucks of size B?

c. Evaluate work scheduling policies...for example, should long or short duration activities be chosen first when setting schedules with scarce resources?

d. Evaluate different maintenance strategies...for example, there is more than one way to repair a road defect. Which policy is better in the long run?

e. Evaluate alternative garage locations (including material base locations)... for example, how much of material x should be kept on hand and where should it be located? and

f. Evaluate the cost impact of closing a garage.

The model uses operating costs in solving the above problems.

3. Input Data

The following is an abbreviated list of the model's input data (16):

a. Single-value constants that provide limiting values for the simulation (e.g., number of work-activity types, number of years to be simulated);

b. Descriptions of activity types, equipment types, staff types, and range of weather conditions;

c. Distribution parameters for absenteeism and breakdowns of equipment;

d. Staff, equipment, and material costs;

e. Resource availability files (staff, equipment, and material);

f. Equipment characteristics file;

g. Point-to-point travel times;

h. Work-activity characteristics file (specification by activity type for each crew option, equipment, and staff needs; material needed; performance rate; indicators of effect of various weather types on work activity; etc.);

i. Probabilistic description of weather by season;

j. Alternative garage (and material) locations;

k. Work-activity parameter sets for use in work-activity occurrence distributions;

l. Parameter sets for weather-dependent activities;

m. Parameter set for emergency-activity duration and time between occurrence specification; and

n. Simulation specifications (length of simulation, number of files, etc.).

Concerning the above input data, items 'c, g, k', and 'm' are currently not available in Iowa DOT; item 'i' may be obtained from climatological data; the material aspect of item 'e' may be difficult to obtain.

4. Output Data

A fairly detailed description of the model's output data is given below (16):

a. Input listing--a complete listing of all model input;

b. Quarterly performance report--report by activity type, which includes planned and actual quantities for material and labor hours used, total cost, cost per unit, and hours per unit, as well as labor cost, material cost, overtime labor cost, travel cost, fringe benefits, and operational service (contract) costs;

c. Activity frequency table--the number of occurrences of each type of work activity in each maintenance area;

d. Manpower characteristics table--a summary for each garage location that lists by staff type the number of periods worked, the number of absentee hours, the number of overtime hours worked, the average number of staff units not assigned each period, the absenteeism cost, and the standby cost;

e. Equipment characteristics table--a summary for each garage location that lists by equipment type the number of periods the equipment was in use, the number of hours the equipment spent in transit, the capacity of the equipment, the number of times breakdowns of the equipment occurred, and the average number of each equipment unit not assigned (leftover) to an activity each period;

f. Material characteristics table--a summary for each material base location that lists by material type the average number of each material type remaining in inventory, the number of times each material was required, the average demand for each material type per period, the number of times an activity could not be worked because of lack of material, and total material demand per year;

g. Time-loss table--a summary by activity number of the frequency and percentage of the reasons (such as insufficient staff, unavailable equipment, insufficient material, and bad weather) for time loss;

h. Time-loss breakdown by resource type--a more detailed version of the time-loss table that summarizes, for each activity, the number of times that each equipment and staff type caused a delay;

i. Personnel substitutions--a summary of the personnel substitutions performed during the period simulated, e.g., the number of times (work periods) that equipment operators of type i were used when less-qualified operators (type j) would have been adequate; and

j. Overall work-activity statistics--summary statistical values for each activity regarding its overall time in the system, including the number of occurrences, the average length of occurrence, longest and shortest activity time span, and others.

5. Computer Program

The computer program for the Louisiana model is complex but well documented by the Louisiana DOT and Development. An interactive input module has been developed and appended to the front of the simulation model. The purpose of the module is to make it easier to enter the model's input. In fact, the module is streamlined enough for the frequent user and descriptive enough for the novice user.

The compatibility of the computer facilities in the Iowa DOT and Louisiana DOT was not investigated.

C. Alabama Model

1. Type of Model

The Alabama model (1, 2, 4) is a (deterministic) linear programming model. A linear programming model is a mathematical tool for optimally allocating limited resources to achieve desired goals under specified conditions. The limited resources, in this case, are the garages, the desired goal is to maintain an acceptable level of highway maintenance service, and the specified conditions are the assumptions made in the study.

The model focuses on the relationship between garage-to-route travel time and the corresponding cost of route maintenance.

2. Capability of Model

The Alabama model is capable of addressing the following types of problems:

a. Determine the optimum maintenance areas for all garages in a given study area...for example, a given study area has 15 garages; which routes should each garage serve so as to minimize the total maintenance cost?

b. Evaluate alternative garage locations.

c. Evaluate the cost impact of closing and/or relocating a garage.

The model uses operating costs in solving the above problems.

3. Key Input Data

The following data are necessary for developing the input data for the model:

a. Maintenance effort (in dollars) for all the routes in the study area; and

b. Crew travel times from garages to work sites.

Crew travel times are not currently available in Iowa DOT. Estimation of these crew travel times and the development of the input data are fully described in Section V.

4. Output Data

For a given set of garage locations, the model's output will consist of the following:

a. Annualized cost (operating costs only) for the entire study area; and

b. The optimum allocation of highway segments (see Section V.C.) to all mainteannce garages in a given study area.

5. Computer Program

The Alabama model uses a computer program developed by IBM. The program is available for lease from IBM at a cost of about $500 per month (according to the Alabama DOT). The computer program is also available at the Iowa State University which has been used in this study.

D. Model Selected

The three models discussed above (Subsections A, B, and C) differ in their capabilities and in their respective input data requirements. Of the three models, the Louisiana model is the most comprehensive (in terms of capabilities) and the most realistic (in terms of modeling assumptions). However, its input data requirements are too many and some of the required data (see Section IV.B.3.) are not currently available at Iowa DOT. The Louisiana model was not, therefore, selected because the data currently available at Iowa DOT is not sufficient enough to develop a meaningful input data for this model.

The California model is capable of addressing almost all garage related problems. However, this model was not selected because the necessary data for accurately estimating the travel frequencies (see Section IV.A.3.) were not currently available at Iowa DOT. Crude estimates of travel frequencies could not be used because travel frequencies play a very significant role in the model (travel frequencies are estimates of the number of times routes are visited in order to satisfy their maintenance demands). Errors in these travel frequencies are cumulative during the simulation period. For example, in a 30-year simulation period, an error in a travel frequency estimate is repeated 30 times. Clearly, this is not acceptable.

Of the three models considered, the Alabama model has the fewest capabilities. Thiw model was selected because data was either available or could be estimated. The only required data for use in this model not currently available (at Iowa DOT) was crew travel times. Travel time could, however, be reasonably estimated from maintenance vehicle average speeds and actual garage-to-worksite distances.

The Alabama model (the model selected) will, henceforth, be referred to as an Optimum Allocation model.

V. OPTIMUM ALLOCATION MODEL (ALABAMA MODEL) APPLIED TO A STUDY AREA

A. Study Area

The study area for this project was provided by the Office of Maintenance and is shown in Appendix 3. It consists of 15 garages, 12 maintenance areas, and 1,061.93 miles of highways.

B. Assumptions

The following assumptions are made in this study:

1. With the concurrence of the Office of Maintenance, maintenance vehicles are assumed to travel at average speeds of 35 or 40 mph for all maintenance activities. These average speeds will be used to calculate travel times.
2. The maintenance cost associated with a route in a given maintenance area is assumed to be uniformly distributed along the route.
3. Any highway formed is represented by its midpoint. Thus the maintenance cost of a segment is assumed to be concentrated at its midpoint. Also, travel times are calculated from garages to midpoints of segments.
4. The travel times from garage 'x' to segment 'y' and from segment 'y' to garage 'x' are assumed to be the same.
5. The cost of servicing a segment from a garage is assumed to vary as a function of travel time between the garage and segment. This relationship is illustrated in Table 1 (page 25).
6. The garages in the study area are assumed to have unlimited capacities. This means the garages can be expanded, if necessary, to service all the segments optimally assigned to them.
7. Whenever a garage relocation possibility is studied, the garage overhead costs before and after its relocation is assumed to be the same.
8. Capital costs and staffing needs are not considered in this study.

C. <u>Highway Segments</u>

All the routes in the study area were broken up into suitable segments based on the following criteria:

1. Segments should not be more than 25 miles long (criteria set by the Office of Maintenance);

2. Segments should be reasonably short (so as to increase the accuracy of the model);

3. Segments should be reasonably long (so as to minimize the computation time involved and hence reduce the costs associated with the study); and

4. The end points of a segment should be suitable for turning maintenance vehicles around (junction, intersection, or a town).

A total of 96 segments ranging from 2.9 miles to 21.2 miles were formed in the study area. Appendix 3 shows the study area and 10 of the 96 segments formed. The lengths (in miles) of 10 of the segments are shown in Appendix 4.

D. <u>Travel Time Estimation</u>

Two sets of travel times corresponding to average speeds of 35 mph and 40 mph were estimated. The basic formula used is:

$$\text{Travel Time (in minutes)} = \frac{\text{Distance (in Miles)}}{\text{Speed (Miles Per Hour)}} \times 60$$

The shortest and most logical travel distances from garage locations to midpoint of segments were calculated using the Statewide Mileage Table (<u>10</u>), the Primary Road Inventory and Mileage Summary (<u>9</u>), and the Maintenance Area Responsibility Maps (<u>8</u>). As an example, let us calculate the travel time from segment no. 4 to the garage at Algona.

Length of segment no. 4 = 8.78 miles

(The shortest distance from the center of Algona to the center of Armstrong) = 35 miles

Therefore,

$$\begin{pmatrix}\text{the shortest distance from} \\ \text{the center of Algona to the} \\ \text{midpoint of segment no. 4}\end{pmatrix} = 35 + \frac{8.78}{2} \text{ miles}$$

$$= 39.39 \text{ miles}$$

Let

Vehicle average speed = 35 mph

Then

$$\text{Travel Time} = \frac{39.39}{35} \times 60 \text{ minutes}$$

$$= \underline{68 \text{ minutes}}$$

The travel times from 10 of the 96 segments to six of the 15 garages in the study area are shown in Appendix 5.

E. Travel Time Estimation Technique

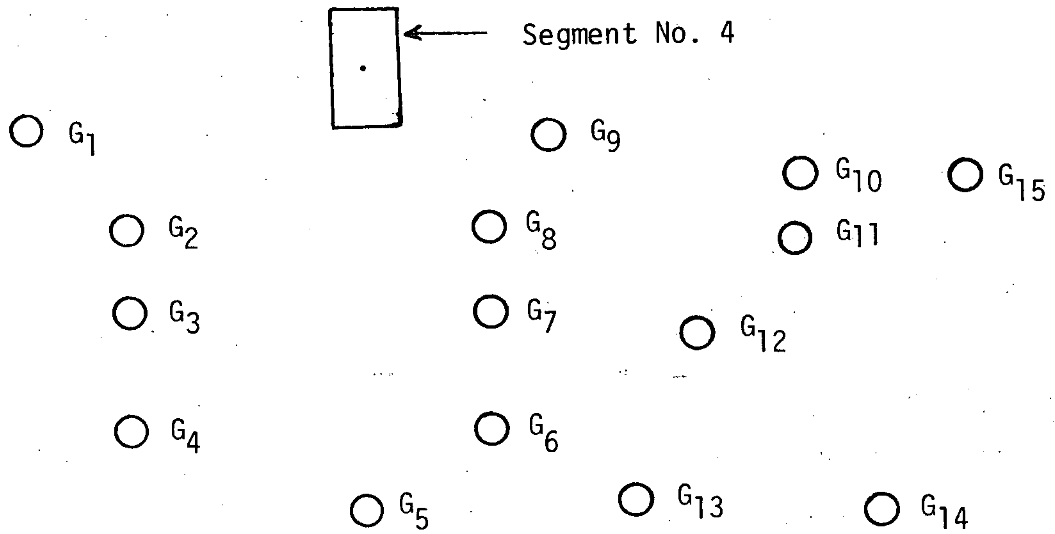
The Optimum Allocation model used in this study requires that the travel times from all segments to all garages be known. In this study, the 1,440 (96 segments x 15 garages) travel times were estimated. We will, henceforth, call this data set as Complete Data set.

Estimating 1,440 travel times manually takes a lot of time. A technique is described below that permits one to estimate only those travel times that have a reasonable chance of being utilized by the model.

A schematic drawing of segment no. 4 and the 15 garages in the study area is shown below.

Illustration 1

A Schematic Drawing of Highway Segment No. 4 and 15 Garages



LEGEND: ○ -- Highway Maintenance Garage Location

In the above schematic drawing, if there are no capacity restrictions on the garages, the model will definitely allocate segment no. 4 to one of the garages G_1, G_2, G_8, and G_9 due to their closer locations to segment no. 4. Hence the travel times from these garages to segment no. 4 are the only ones which are very important. The other travel times (the unimportant travel times) will not affect the optimum solution even though their presence in the model is necessary.

Instead of estimating the 'unimportant travel times' a large fictitious travel time (greater than any of the 'important travel times' in the study area) can be chosen to represent them. For the given study area, the 'important travel times' were found to be less than or equal to 60 minutes. Thus, any travel time greater than 60 minutes was unimportant for the purpose of this study.

From Table 1 (page 25), it can be observed that any travel time greater than 165 minutes has a cost multiplier of 8.0. Thus, any number greater than 165 can be easily used as a fictitious number. Arbitrarily, the fictitious number was chosen to be 200. This means any 'unimportant travel time' is replaced by 200 minutes.

The type of data as described above will be called a Partial Data set. Thus the Partial Data set consists of travel times less than or equal to 60 minutes and fictitious travel times of 200 minutes. The Partial Data set will be compared with the Complete Data set in Section VI.

F. Basic Maintenance and Overhead Costs

The fiscal year 1980 labor and equipment costs for all the routes in the study area were provided by the Office of Maintenance. The overhead costs for the 15 garages in the study area were also supplied by the same office. These costs are shown in Appendix 6.

The fiscal year 1980 labor, equipment, and garage-related overhead costs were adjusted for inflation to reflect what these costs would be if the same maintenance activities were done in fiscal year 1981. The adjustment rates used were provided by the Office of Maintenance and are shown below:

Labor......... 5.4% (cost of living raise granted to employees in 1980-81)

Equipment..... 13.0%

Overhead...... 15.0%

The 1981 adjusted costs are referred to as the basic labor cost, basic equipment cost, and basic overhead cost. Then a basic maintenance cost is defined as:

$$\begin{pmatrix}\text{Basic Maintenance}\\ \text{Cost}\end{pmatrix} = \begin{pmatrix}\text{Basic Labor}\\ \text{Cost}\end{pmatrix} + \begin{pmatrix}\text{Basic Equipment}\\ \text{Cost}\end{pmatrix}$$

The 1981 basic costs for 10 of the 96 segments are given in Appendix 4.

Sample Calculation:

Consider Estherville maintenance area (Appendix 6).

(Fiscal Year 1980 Labor Cost)
(for State Route No. 15) = \$12,236

Therefore

Basic Labor Cost = (12,236)(1.054) dollars

= \$12,897

(Fiscal Year 1980 Equipment)
(Cost for State Route No. 15) = \$13,680

Therefore

Basic Equipment Cost = (13,680) (1.13) dollars

= \$15,458

Hence

(Basic Maintenance Cost)
(for State Route No. 15) = (12,897 + 15,458) dollars

= \$28,355

(Fiscal Year 1980 Overhead)
(Cost for Estherville Garage) = \$20,843

Therefore

Basic Overhead Cost = (20,843)(1.15) dollars

= \$23,969

The basic maintenance cost associated with each route was proportionally allocated (with respect to length) to the segments forming that route. For example, state route no. 15 in Estherville maintenance area is 15.3 miles long. Two segments (segment no. 4 and segment no. 5) were formed from this route. Segment no. 4 is 8.78 miles long and segment no. 5 is 6.52 miles long. The basic maintenance cost for State route no. 15 is \$28,355 (calculated above).

Therefore

$$\left(\begin{array}{l}\text{Basic Maintenance Cost}\\ \text{for Segment No. 4}\end{array}\right) = \frac{(8.78)}{(15.3)} (28{,}355) \text{ dollars}$$

$$= \underline{\$16{,}272}$$

and

$$\left(\begin{array}{l}\text{Basic Maintenance Cost}\\ \text{for Segment No. 5}\end{array}\right) = (\$28{,}355 - \$16{,}272)$$

$$= \underline{\$12{,}083}$$

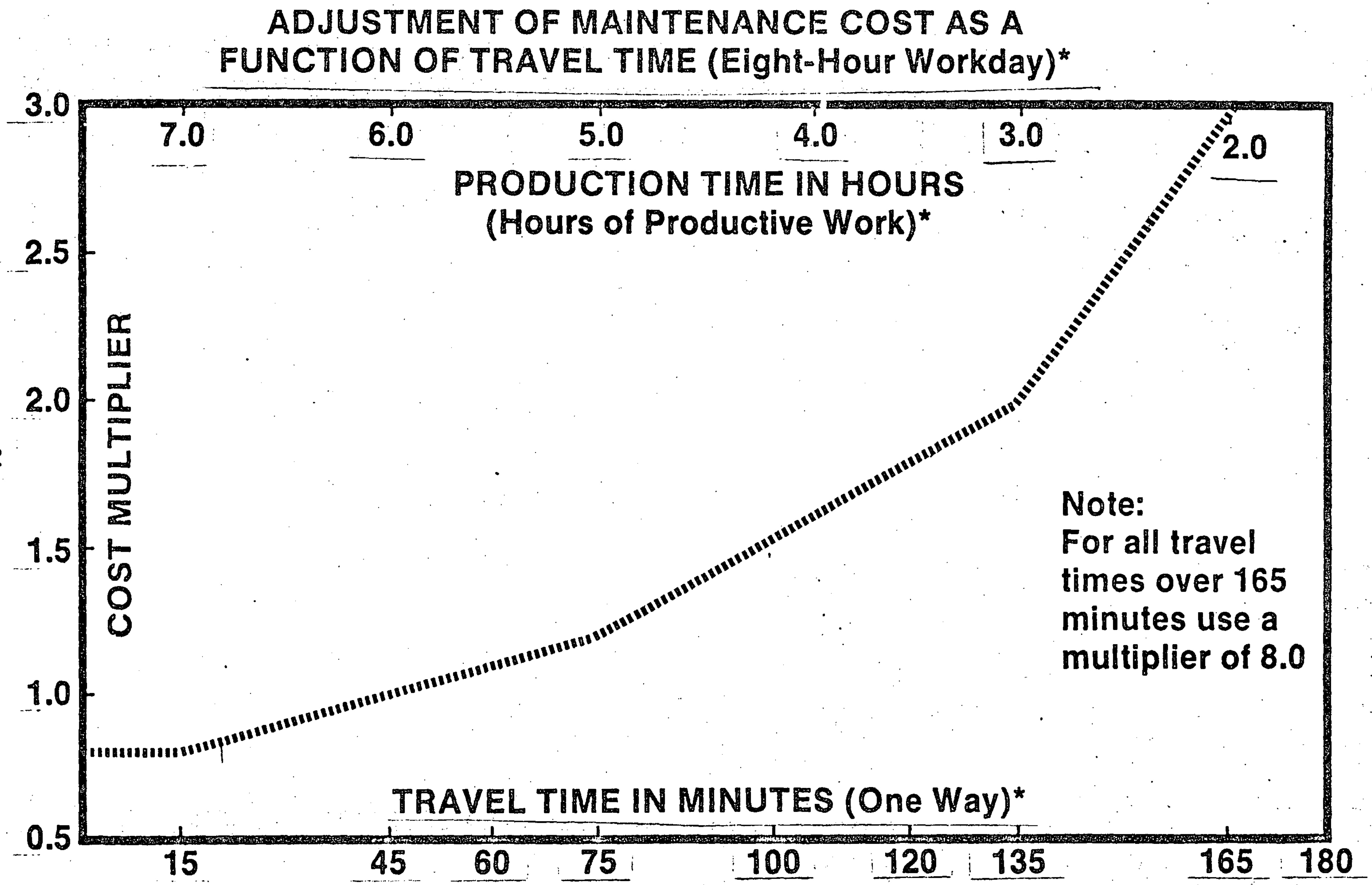
G. Travel Time Adjusted Costs

The basic maintenance cost for each segment was adjusted for travel time based on the following criteria: (1, 2)

1. One-way travel time less than 45 minutes would result in more than six hours of productive work (for an eight-hour work day) at the work site. This would result in less cost associated with nonproductive travel. On the other hand, travel time greater than 45 minutes would result in less productive work and consequently in greater maintenance cost.

2. The relationships stated above have been studied by Bell (1, 2) in a project prepared for the Alabama DOT. He quantified the above relationships by the use of a cost multiplier which is derived from the travel time. A graphical illustration of the relationships is shown in Illustration 2. Also, a tabular version of this relationship is shown in Table 1. Both the logic used and the cost multipliers developed were found to be acceptable by the Office of Maintenance.

Illustration 2



*Not part of the original graph.

Source: Alabama Department of Transportation (See References 1, 2, 4)

Table 1
Basic Maintenance Cost Multiplier as a Function of Travel Time (Eight-Hour Work Day)

One-Way Travel Time from Garage to Segment (Minutes)	Productive Work (Hours)	Basic Maintenance Cost Multiplier
00- 15	7.5 - 7.0	0.8
15 - 75	7.0 - 5.0	0.8 - 1.2
75 - 135	5.0 - 3.0	1.2 - 2.0
135 - 165	3.0 - 2.0	2.0 - 3.0
≥ 165	≤ 2.0	8.0

a. Sample Calculation of Cost Multiplier

Basic Logic:

(45 minutes one-way Travel Time) is equivalent to (≡) 6 hours of productive work.

and

(6 hours of Productive Work) ≡ a Cost Multiplier of 1.0

thus

(i) (7 hours of Productive Work) ≡ to a Cost Multiplier of 0.8 (i.e. $\frac{6}{7}$)

(ii) (5 hours of Productive Work) ≡ to a Cost Multiplier of 1.2 (i.e. $\frac{6}{5}$)

The basic maintenance cost for any highway segment in the study area is multiplied by the appropriate cost multiplier to obtain the travel time adjusted cost for that particular segment as serviced from a particular garage under consideration.

b. Sample Calculations of Travel Time Adjusted Cost

Consider highway segment no. 4 in Estherville Maintenance area.

Basic Maintenance Cost = \$16,272 (Section V.F.)

(Travel Time from Algona Garage) = 68 minutes (Section V.D.)
(to Midpoint of Segment 4)

Cost Multiplier (Using Table 1) = 1.153

Therefore

$$\begin{pmatrix}\text{Travel Time Adjusted}\\ \text{Cost}\end{pmatrix} = \begin{pmatrix}\text{Cost}\\ \text{Multiplier}\end{pmatrix} \times \begin{pmatrix}\text{Basic Maintenance}\\ \text{Cost}\end{pmatrix}$$

$$= (1.153)\ (\$16{,}272)$$

$$= \underline{\underline{\$18{,}762}}$$

The travel time adjusted costs for the 96 segments as serviced from each of the 15 garages were calculated using computer. The computer program used and a sample output are respectively shown in Appendices 7 and 8.

VI. OPTIMUM ALLOCATION MODEL RESULTS

Two speeds, 35 and 40 mph, were provided by the Office of Maintenance as two possible maintenance vehicle average speeds for all maintenance activities. Using these two speeds, one at a time, the Optimum Allocation model was applied to the study area. The results obtained are described in this section. The computer program used is described in Appendix 9.

A. Maintenance Vehicle Average Speed = 35 mph

1. Complete Data and Partial Data Sets

Complete Data and Partial Data sets have been defined and described in Section V.E. Using a speed of 35 mph, the Optimum Allocation model was applied to the study area using the two data sets, one at a time. The operating costs based on the two data sets are shown in Table 2 below. Also shown in Table 2 are the operating costs for the two data sets when the existing allocation is used. The existing allocation refers to the 1981 maintenance areas in the study area without utilizing optimum allocation procedures.

Table 2
Comparison of Operating Costs for Two Types of Data and Two Different Allocations.
Vehicle Average Speed = 35 mph

(1) Item	Operating Costs*		(4) Cost Savings By Using Optimum Allocation (1981) (Dollars) (2)-(3)
	(2) Existing Allocation (Dollars)	(3) Optimum Allocation (Dollars)	
Complete Data	1,972,278	1,969,392	2,886
Partial Data	1,972,278	1,969,392	2,886

* Operating costs are based on travel time adjusted costs.

It is seen from the above table that the operating costs determined by optimum allocation is the same for both the Complete Data and Partial Data sets. The same is true for the operating costs determined by the existing allocation. It was also found that the allocation of the 96 segments to the 15 garages was the same irrespective of the data set used. It is, therefore, concluded that the Complete Data and Partial Data sets are equivalent.

The computer cost was the same for both types of data sets. There was, however, a big difference in the number of travel times estimated. Only 353 travel times were estimated in the Partial Data set as compared to the 1,440 estimates in the Complete Data set. This shows a 75 percent reduction in the number of travel times estimated. It is concluded, therefore, that the Partial Data set technique can be utilized with significant savings in computation time. The only caution in using this technique is to identify, in the beginning of the study, all garages that are candidates for closure. Then, aided by this knowledge, the important travel times are identified and estimated.

2. Existing and Optimum Allocations

The existing allocation refers to the current maintenance areas in the study area. These maintenance areas were determined by the Office of Maintenance without the use of Optimum Allocation procedures. The two allocations will now be compared on the basis of operating costs.

The Optimum Allocation model was applied to the study area. Four segments were reallocated resulting in cost savings of $2,886. The segments reallocated and the corresponding cost savings are shown below in Table 3. The new maintenance areas after the four segments had been reallocated are shown in Appendix 10.

Table 3
Segments Reallocated Under Optimum Allocation.
Vehicle Average Speed = 35 mph

(1) Segment No.	Existing Allocation (2) Assigned To Garaged At:	(3) Operating Costs* (Dollars)	Optimum Allocation (4) Assigned To Garaged At:	(5) Operating Costs* (Dollars)	Cost Savings By Using Optimum Allocation (1981) (Dollars) (3) (5)
10	Emmetsburg	7,772	Algona	7,484	288
12	Emmetsburg	9,478	Pocahontas	8,831	647
13	Pocahontas	6,216	Algona	5,924	292
57	Forest City	19,085	Gerled	17,426	1,659
		42,551		39,665	2,886

* Operating costs are based on travel time adjusted costs.

Since only four segments were reallocated, it shows the current allocation of highway segments to existing garages is good within the study area. Nevertheless, the modifications suggested by the Optimum Allocation model could be made with resulting 'annual' cost savings of $2,886.

3. Closing of Garages

The Optimum Allocation model was used to evaluate the cost impact of closing a garage. The necessary modifications to the model in order to close a garage is described in Appendix 9.

The garages at Humboldt and Forest City were closed, one at a time. Later, both were closed at the same time. The results are shown in Table 4.

Table 4
Cost Analysis of Closing Humboldt and Forest City Garages Using Optimum Allocation
Average Speed = 35 mph

(1) Item	Operating Costs* (2) Garage(s) NOT Closed (Dollars)	(3) Garage(s) Closed (Dollars)	(4) Increased Travel Cost (Dollars) (3) - (2)	(5) Overhead Cost of Garage(s) Closed (Dollars)	(6) Cost Savings (1981) (Dollars) (5) - (4)
Humboldt Garage	1,969,392	1,980,675	11,283	18,785	7,502
Forest City Garage	1,969,392	1,976,981	7,589	19,374	11,785
Humboldt and Forest City Garages	1,969,392	1,988,264	18,872	38,159	19,287

*Operating costs are based on travel time adjusted costs.

It is seen from the above table that 'annual' cost savings of $7,502 and $11,785 will be realized if Humboldt and Forest City garages respectively are closed. If both garages are closed at the same time, the 'annual' cost savings will be $19,287. The new maintenance boundaries after the garages are closed are shown in Appendix 11.

4. Relocation of Garages

The ability of the Optimum Allocation model to evaluate alternative garage locations is illustrated in this section. The garages selected to be relocated in this study were not provided by the Office of Maintenance. The Office of Maintenance staff was, however, advised of the garages selected.

When a garage is relocated, new travel times from all segments to that particular garage will have to be estimated. The Partial Data technique described in Section V.E. was used to reduce the computation time involved. The necessary modifications in the input data are described in Appendix 9.

Two relocation possibilities were examined. The first one dealt with relocating the garages at Estherville and Gerled to Armstrong and Buffalo Center, respectively. In the second investigation, the garage at Estherville was relocated to Armstrong but the garage at Gerled was relocated to Thompson. In both cases, the garage at Forest City was considered closed. The results obtained are shown in Table 5 below.

Table 5
Cost Analysis of Relocating Garages at
Estherville and Gerled Using Optimum Allocation
Average Speed = 35 mph

(1) Activity	Operating Costs* (2) Garages NOT Relocated (Dollars)	Operating Costs* (3) Garages Relocated (Dollars)	(4) (2) - (3) Cost Savings due to Relocation (Dollars) (1981)
Relocating Estherville at Armstrong and Gerled at Buffalo Center (Forest City Closed)	1,976,981	1,976,373	608 **
Relocating Estherville at Armstrong and Gerled at Thompson (Forest City Closed)	1,976,981	1,973,262	3,719 **

* Operating costs are based on travel time adjusted costs.
** Capital costs are not considered. Overhead costs (before relocation) are assumed to be the same (after relocation).

It is observed from the above table that almost negligible 'annual' cost savings ($608) are realized if the garages at Estherville and Gerled are relocated respectively to Armstrong and Buffalo Center. On the other hand, significant 'annual' cost savings ($3,719) can be achieved if the garage at Estherville is relocated at Armstrong but the garage at Gerled is relocated at Thompson.

B. Maintenance Vehicle Average Speed = 40 mph

Using a maintenance vehicle average speed of 40 mph, new Complete Data and Partial Data sets were formed as described in Section V.E. The two data sets were again compared in this case and found to be equivalent as before (see Section VI.A.1). Thus, the Partial Data set technique can be used for any speed.

With the new data set, the existing and optimum allocations of highway segments in the study area were again examined. The results are shown below in Table 6.

Table 6
Segments Reallocated Under Optimum Allocation
Average Speed = 40 mph

(1) Segment No.	Existing Allocation		Optimum Allocation		(6) Cost Savings By Using Optimum Allocation (1981) (Dollars) (3) - (4)
	(2) Assigned To Garage At:	(3) Operating Costs* (Dollars)	(4) Assigned To Garage At:	(5) Operating Costs* (Dollars)	
10	Emmetsburg	7,556	Algona	7,304	252
12	Emmetsburg	9,235	Pocahontas	8,670	565
13	Pocahontas	5,987	Algona	5,732	255
57	Forest City	18,515	Gerled	17,063	1,452
		41,293		38,769	2,524

* Operating costs are based on travel time adjusted costs.

It is observed from the above table that four segments were reallocated. These segments are the same as those reallocated when a speed of 35 mph was used (see Section VI.A.2). However, this time, 'annual' cost savings of $2,554 (instead of $2,886) was realized. The reduced cost savings resulting from the new higher speed (40 mph) is discussed and explained in Section VI.C.

Again, based on the new data set, the garages at Humboldt and Forest City were closed and the cost impact evaluated. The results are shown in Table 7 below.

Table 7
Cost Analysis of Closing Humboldt and
Forest City Garages Using Optimum Allocation
Average Speed = 40 mph

(1) Activity	Operating Costs		(4) Increased Travel Cost (Dollars) (3) - (2)	(5) Overhead Cost of Garage Closed (Dollars)	(6) Cost Savings (1981) (Dollars) (5) - (4)
	(2) Garage NOT Closed (Dollars)	(3) Garage Closed (Dollars)			
Humboldt Garage	1,947,401	1,955,949	8,548	18,785	10,237
Forest City Garage	1,947,401	1,953,758	6,357	19,374	13,017

* Operating costs are based on travel time adjusted costs.

From the above table, it is seen that cost savings of $10,237 and $13,017 would respectively be achieved if the garages at Humboldt and Forest City were closed. These cost savings are substantially greater than those obtained when a lower speed (35 mph) was used (see Section VI.A.3). The increased cost savings associated with the higher speed is discussed and explained in Section VI.C.

C. Sensitivity Analysis

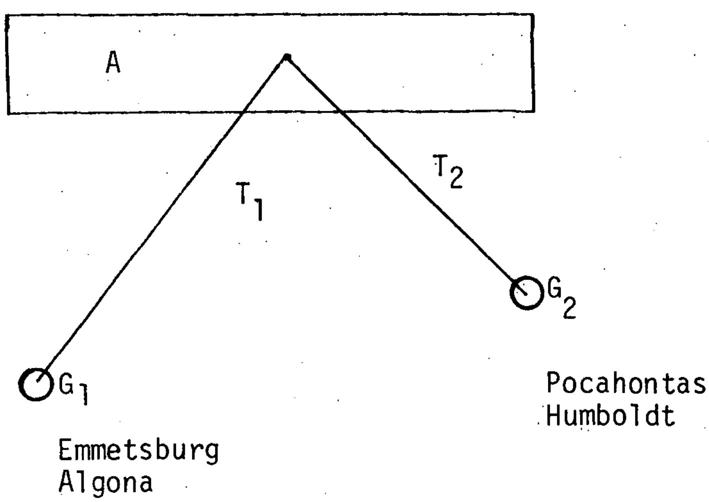
The sensitity of speed to cost savings was investigated in this study by using two different speeds--35 and 40 mph. The results were shown in Subsections A and B above. They are shown again, in compact form, in Table 8.

Table 8
Comparison of Cost Savings Using
Two Different Average Speeds

(1) Activity	Cost Savings (1981 Dollars)		(4) Difference in Cost Savings (3) - (2)
	(2) 35 mph	(3) 40 mph	
Optimum Allocation (All Garages)	2,886	2,524	- 362
Humboldt Garage Closed	7,502	10,237	+2,735
Forest City Garage Closed	11,785	13,017	+1,232

From the above table, it is observed that cost savings associated with optimum allocation decreases as speed increases. On the other hand, cost savings associated with closing a garage increases as speed increases. These variations in cost savings with different speeds are explained below.

Illustration 3
A Schematic Drawing of a Highway Segment
and Two Maintenance Garages



Legend: A - Highway Segment
T_1, T_2 - Travel Times
G_1, G_2 - Maintenance Garages

1. Consider the above schematic drawing. Let A represent highway Segment No. 12 (in the study area). Also let G_1 and G_2 be the garages at Emmetsburg and Pocahontas respectively. T_1 and T_2 are then the respective one-way travel times from Garages G_1 and G_2 to the midpoint of highway Segment A. T_1 is greater than T_2.

Under existing allocation system, segmnet A was serviced by Garage G_1 but under optimum allocation it was serviced by Garage G_2. The reduction in travel time was $T_1 - T_2$, and this determined the cost savings. It was found that the difference ($T_1 - T_2$) was smaller at a higher speed (40 mph) than it was at a lower speed (35 mph). For example, at 35 mph, T_1 was 27 minutes and T_2 was 18 minutes. Thus, ($T_1 - T_2$) was nine minutes. At 40 mph, T_1 was 24 minutes and T_2 was 16 minutes. Hence, ($T_1 - T_2$) was eight minutes. This shows a decrease of one minute (9-8). Since ($T_1 - T_2$) decreased with increasing speed, the associated cost savings correspondingly decreased.

2. Consider again the same schematic drawing shown in Illustration 3. This time, let A represent highway segment No. 43 (in the study area). Also let G_1 and G_2 be the garages at Algona and Humboldt respectively. T_1 and T_2 are then the respective one-way travel times from garages G_1 and G_2 to the midpoint of highway segment A.

When Garage G_2 (Humboldt) was closed, segment A was serviced by Garage G_1 (Algona). At 35 mph, the one-way travel times were T_1 = 35 minutes and T_2 = 10 minutes; hence ($T_1 - T_2$) = 25 minutes, and this determined the increase in travel cost. At 40 mph, the one-way travel times were T_1 = 31 minutes and T_2 = 9 minutes. Thus the difference was, ($T_1 - T_2$) = 22 minutes. This shows a decrease of three minutes (25-22). Since ($T_1 - T_2$) decreased with increasing speed, the associated travel cost correspondingly decreased.

The cost savings (determined by: overhead cost - increased travel cost) consequently increased since a smaller cost (increased travel cost) was being subtracted from the same overhead cost.

The 'differences' in cost savings resulting from a 5 mph increase in speed from 35 to 40 mph are shown in column (4) of Table 8. These 'differences' are substantial and they do indicate the sensitivity of cost savings to speed. An obvious implication of this is the need for accurate estimation of maintenance vehicle average speed.

D. Snow and Ice Control Activities and Travel Time Adjusted Costs

The maintenance vehicle average speed for snow and ice control activities is generally lower than that for other maintenance activities. Using a single average speed for all maintenance activities may inflate or deflate the travel time adjusted costs. The extent of inflation or deflation depends on the percentage of maintenance cost attributable to snow and ice control activities.

In this section, three strategies for estimating travel time adjusted costs are investigated. The change in travel time adjusted costs with the percentage of maintenance cost attributable to snow and ice control activities is examined. The three strategies to be investigated are:

1. Use one maintenance vehicle average speed for <u>all</u> maintenance activities;
2. Use one maintenance vehicle <u>weighted</u> average speed for <u>all</u> maintenance activities; and
3. Use two maintenance vehicle average speeds--one for snow and ice control activities and the other for the remaining maintenance activities.

Before investigating the above strategies, the percentage of the fiscal year 1980 maintenance cost attributable to snow and ice control activities must be known.

These percentages were provided by the Office of Maintenance and are shown in Table 9 below.

Table 9
The Percentage of Fiscal Year 1980 Labor and Equipment Costs Attributable to Snow and Ice Control Activities in the Study Area

Maintenance Area	% of 1980 Labor Cost for Snow and Ice Control Activities	% of 1980 Equipment Cost for Snow and Ice Control Activities
Estherville	20.4	35.1
Emmetsburg	18.3	23.2
Pocahontas	27.6	43.3
Rockwell	26.6	39.6
Ft. Dodge & Gowrie	25.3	39.2
Humboldt	19.4	36.7
Algona & Gerled	23.8	38.2
Forest City	28.2	41.2
Garner	22.5	34.9
Clarion	23.6	39.8
Webster City & Williams	22.6	38.1
Hanlontown	25.2	42.4
Average for Study Area	23.6	37.6

Source: Office of Maintenance, Iowa Department of Transportation

In addition to the percentages given above (Table 9), the maintenance vehicle average speed for snow and ice control activities and the corresponding average speed for other maintenance activities should be known. According to the Office of Maintenance, the average speed for snow and ice control activities is about 35 mph and the average speed for the other maintenance activities is about 40 mph. These average speeds are used to investigate the three strategies outlined earlier.

It is important to note that the two speeds given above are <u>not</u> maintenance vehicle average speeds for all maintenance activities. Rather, the 35 mph is assumed to be the average speed for only snow and ice control activities while the 40 mph is assumed to be the average speed for the other maintenance activities. Prior to this section, these two speeds have been assumed to be average speeds for all maintenance activities.

Consider segment no. 43 to be serviced from the garage at Algona (see Appendix 3). The basic maintenance cost is $42,359 (see Appendix 4).

Strategy No. 1: Assume One Maintenance Vehicle Average Speed

$$\text{Maintenance Vehicle Average Speed} = \frac{35+40}{2}\text{ mph}$$

$$= \underline{37.5}\text{ mph}$$

Travel Time from Segment No. 43 to Algona Garage = 33 minutes

Cost Multiplier (From Table 1) = 0.920

∴ Travel Time Adjusted Cost = (0.920) (42,359) dollars

= $38,970

Strategy No. 2: Assume One Maintenance Vehicle Weighted Average Speed

From Table 9, the percentage of labor and equipment cost for snow and ice control activities is 31 percent. The other maintenance activities constitute the remaining 69 percent. These percentages are used as weights to calculate the weighted average speed for all maintenance activities as shown below.

$$\text{Maintenance Vehicle Weighted Average Speed} = (0.31)(35\text{ mph}) + (0.69)(40\text{ mph})$$

$$= \underline{38.5}\text{ mph}$$

Travel Time from Segment No. 43 to Algona Garage = 32 minutes

Cost Multiplier (From Table 1) = 0.913

∴ Travel Time Adjusted Cost = (0.913)(42,359)dollars

= $38,674

Strategy No. 3: Assume Two Maintenance Vehicle Average Speeds

The percentage of labor and equipment cost for snow and ice control activities is 31%. This percentage was used under strategy 2. Since the strategies will be compared with each other, the same percentage is used in this case.

The basic maintenance cost for Segment No. 43 is $42,359. Out of this amount, $13,131 (i.e. 31% of $42,359) is attributable to snow and ice control activities, and the remaining $29,228 to other maintenance activities.

a. Snow and Ice Control Activities

Assume Maintenance Vehicle Average Speed	= 35 mph
Travel Time from Segment No. 43 to Algona Garage	= 35 minutes
Cost Multiplier (Table 1)	= 0.933
∴ Travel Time Adjusted Cost	= (.933)(13.131) dollars
	= $12,251

b. Other Maintenance Activities

Assume Maintenance Vehicle Average Speed	= 40 mph
Travel Time from Segment No. 43 to Algona Garage	= 31 minutes
Cost Multiplier (Table 1)	= 0.907
∴ Travel Time Adjusted Cost	= (0.907)(29,228) dollars
	= $26,510

Combining the two travel time adjusted costs (a+b), we have:

Travel Time Adjusted Cost (for Strategy 3)	= $12,251 + $26,510
	= $38,761

The above calculations were made for five different percentages of maintenance cost attributable to snow and ice control activities. The results are given in Table 10 below.

Table 10
Comparison of Three Methods of Estimating Travel Time Adjusted Costs for Different Percentages of Snow and Ice Control Activities

(1) % of Maintenance Cost Attributable to Snow and Ice Control Activities	Travel Time Adjusted Cost (Dollars)*			(5)	(6)
	(2) Strategy 1 One Average Speed	(3) Strategy 2 One Weighted Average Speed	(4) Strategy 3 Two Average Speeds	(4)-(2)	(4)-(3)
70%	38,970	39,129	39,191	+159	+ 62
50%	38,970	38,970	38,970	0	0
40%	38,970	38,758	38,860	-212	+102
31%	38,970	38,674	38,761	-296	+ 87
15%	38,970	38,462	38,585	-508	+123

* Travel time adjusted cost for Segment no. 43

Of the three strategies examined, strategy no. 3 is the most realistic, in that for each highway segment, it considers snow and ice control activities separately from the other maintenance activities. Strategies no. 1 and no. 2 are therefore compared with strategy no. 3 as a means of measuring their accuracy. The deviations found are shown in columns (5) and (6) of Table 10.

It is seen from columns (5) and (6), Table 10, that:

1. The deviations of strategy no. 1 from strategy no. 3 range from +$159 to -$508 and the deviations of strategy no. 2 from strategy no. 3 range from 0 to +$123. This shows that strategy no. 1 is more sensitive to percentage of maintenance cost attributable to snow and ice control activities than strategy no. 2.
2. For each percentage of maintenance cost shown in column (1), the absolute deviation (in dollars) of strategy no. 2 from strategy

no. 3 is smaller than the corresponding absolute deviation of strategy no. 1 from strategy no. 3. Therefore strategy no. 2 is more accurate than strategy no. 1 in terms of its closeness to strategy no. 3.

It is also seen from column (1), Table 10, that when the percentage of maintenance cost for snow and ice control activities is 50 percent, all the three strategies are equivalent.

Although strategy no. 3 is the most realistic of the three strategies considered, it is computationally prohibitive if the study area contains a large number of highway segments.

Strategy no. 2 is acceptable because it is practical, reasonably accurate, requires far less computations than strategy no. 3, and it has about the same level of computations as strategy no. 1.

VII. CONCLUSION

Three models--Alabama model (Optimum Allocation model), California model, and Louisiana model--have been studied in this project. These models differed in their capabilities and in their data requirements. The Optimum Allocation model (Alabama model), though it had the fewest capabilities, was the one selected because the input data required by this model was currently available in the Iowa DOT.

The Optimum Allocation model (Alabama model) was successfully applied to a study area selected by the Office of Maintenance. First, the existing allocation system in the study area (highway segments assigned to garages) was examined using the model. Only four highway segments resulted in a different allocation than the existing allocation system which is being used by the Office of Maintenance. This shows the existing allocation system is good for all practical purposes. However, if the allocation system determined by the Optimum Allocation model is used, there will be 'annual' cost savings of approximately $2,800 (using maintenance vehicle average speed of 35 mph) and approximately $2,500 (using maintenance vehicle average speed of 40 mph) respectively.

Secondly, the Optimum Allocation model was used to close the garages at Humboldt and Forest City. When the garage at Humboldt was closed, 'annual' cost savings of approximately $7,500 (using average speed of 35 mph) and approximately $10,200 (using average speed of 40 mph) were realized. The 'annual' cost savings, when the garage at Forest City was closed, were approximately $11,700 (using average speed of 35 mph) and approximately $13,000 (using average speed of 40 mph) respectively.

Finally, the Optimum Allocation model was used to demonstrate its garage relocation capability as follows:

1. With the garage at Forest City assumed to be closed, the garages at Estherville and Gerled were moved to Armstrong and Buffalo Center respectively. This move resulted in 'annual' cost savings of approximately $600 (using average speed of

35 mph and without considering capital costs). Clearly, this is not a significant amount of cost savings.

2. With the garage at Forest City assumed to be closed, the garage at Estherville was again relocated at Armstrong but the garage at Gerled was moved to Thompson. This new arrangement yielded in 'annual' cost savings of approximately $3,700 (using average speed of 35 mph and without considering capital costs).

The cost savings reported above are subject to the limitations of this study. The limitations pertaining to the reliability of cost multipliers, maintenance vehicle average speed, and maintenance cost data used in this study are discussed in Section VIII.

The computer program utilized in the model was developed by the IBM and is available for lease at a cost of about $500 per month. This computer program is also available at the Iowa State University and it is this program which was used for this study. The total computer cost for this study was $150 and the average cost per run was approximately $10.

In conclusion, this study has successfully identified a model (Optimum Allocation Model) that can utilize the data currently available in the Iowa DOT. Also, it can optimally assign highway segments to maintenance garages and evaluate the cost impact of closing or relocating a specified maintenance garage in a given study area.

VIII. LIMITATIONS OF STUDY

The following limitations have been identified with this study:

A. Cost Multipliers:

The cost multiplier concept utilized in this study was used to adjust the basic maintenance cost to reflect the 'actual cost' due to loss of productive time. Though the logic of the cost multiplier concept is sound, its effectiveness is difficult to evaluate. In view of this, the accuracy of the results obtained in this study may have been affected.

B. Maintenance Vehicle Average Speed:

It was observed in this study that the travel time adjusted costs were sensitive to both speed and the percentage of maintenance cost associated with snow and ice control activities. Since a 'simple' average speed was used for all maintenance activities, the travel time adjusted costs calculated might have been inflated (see Section VI.D.). Furthermore, the average speeds used in this study may not be the 'actual' average speed of maintenance vehicles in the study area.

C. Maintenance Cost Data

The study was based on the fiscal year 1980 maintenance cost data only. These costs were adjusted for inflation but they were not adjusted for conditions such as weather, severity and frequency of maintenance work, etc. The results obtained are, therefore, sensitive to future highway maintenance-related conditions.

Also, the maintenance cost data used in this study included travel costs. These travel costs could not be extracated from the other maintenance costs due to the record keeping procedures of the Iowa DOT. The general effect of these 'built-in travel costs' is to increase the maintenance operating costs determined by the model. As a result, cost savings associated with relocating maintenance garages may be inflated while cost savings associated with closing maintenance garages may be deflated. The degree of inflation or deflation depends on the magnitude of the travel costs.

IX. RECOMMENDATIONS

A. The relationship between travel time, hours of productive work, and the cost multipliers should be investigated further with the help of Iowa DOT highway maintenance supervisors. The graph shown in Illustration 1 should be redrawn if it is found to be necessary. Table 1 should then be changed to match the new graph.

B. Garage-to-work site travel times should be collected independently for snow and ice control activities as well as for other maintenance activities. If this is not feasible, a reasonable approximation is to accurately determine separate maintenance vehicle average speeds for snow and ice control activities and the other maintenance activities. A weighted average speed for all maintenance activities can then be determined and utilized (see Section VI.D.).

C. Efforts should be made to include historical and future maintenance cost data in future studies. Historical cost data could be utilized in the form of an annualized average cost based on a given number of years. Future cost data is difficult to estimate. However, one must reasonably predict what the future highway maintenance activities will be and then quantify them in monetary terms. This is not easy but efforts should be made in that direction.

D. The Louisiana model is recommended for use in any future comprehensive maintenance study. To be able to use this model, however, the following additional data should be collected:

1. Garage-to-work site travel times for snow and ice control activities as well as for other maintenance activities;
2. Frequency of occurrence of each work activity;
3. The times of occurrence of emergency activities and their durations when they do occur;
4. Rate of (personnel) absenteeism; and
5. Rate of equipment breakdown.

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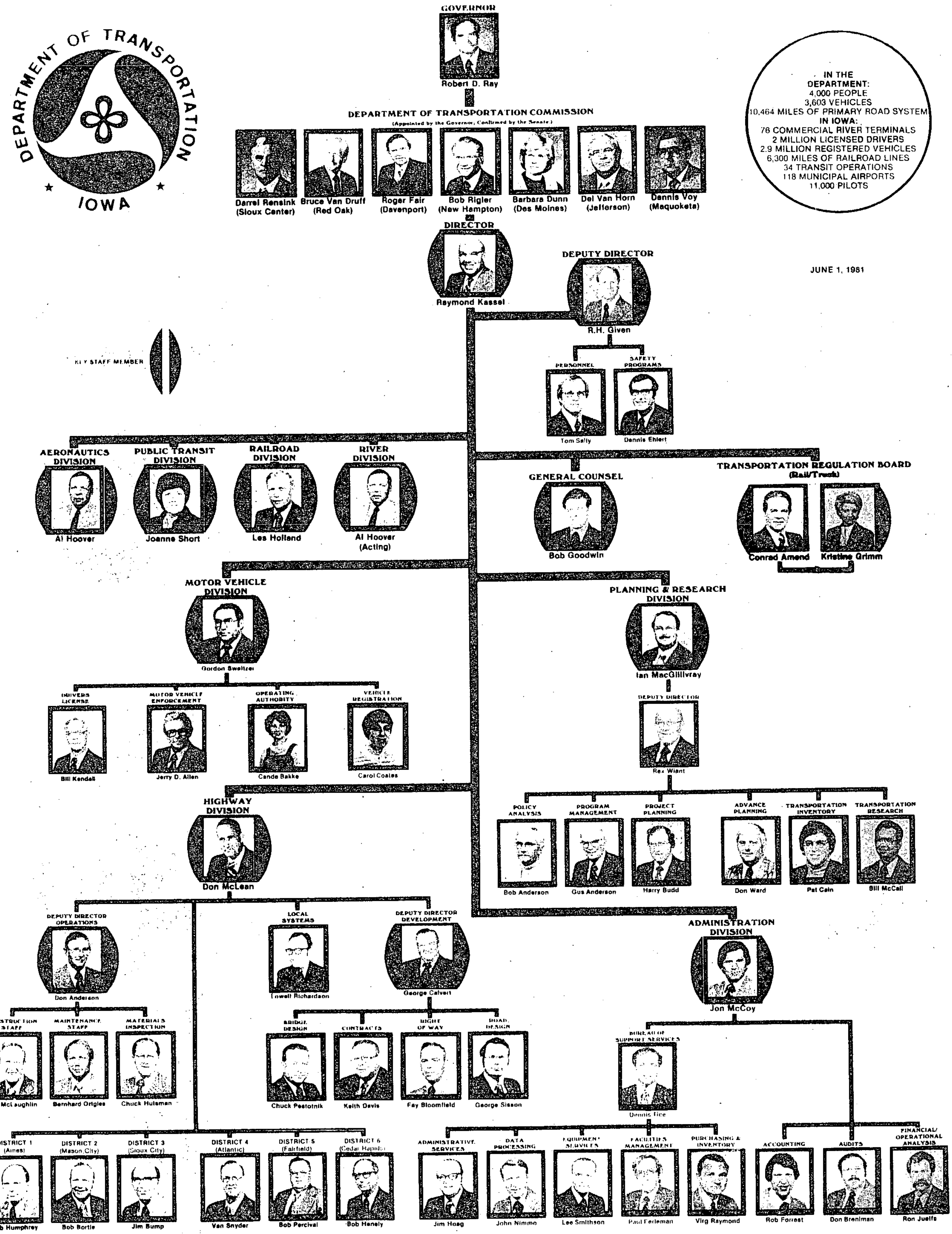
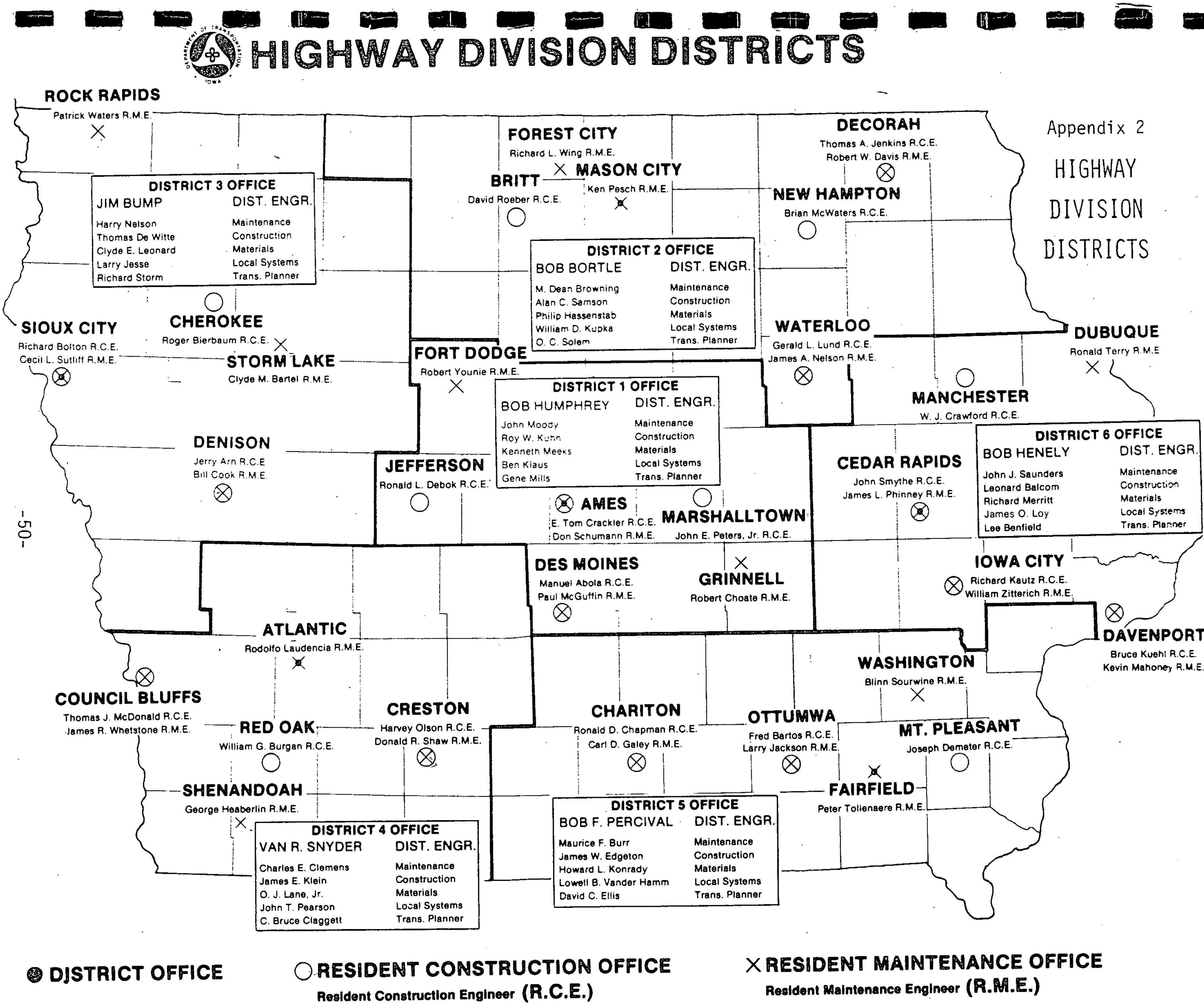
APPENDICES

KEY STAFF AND OFFICE DIRECTORS



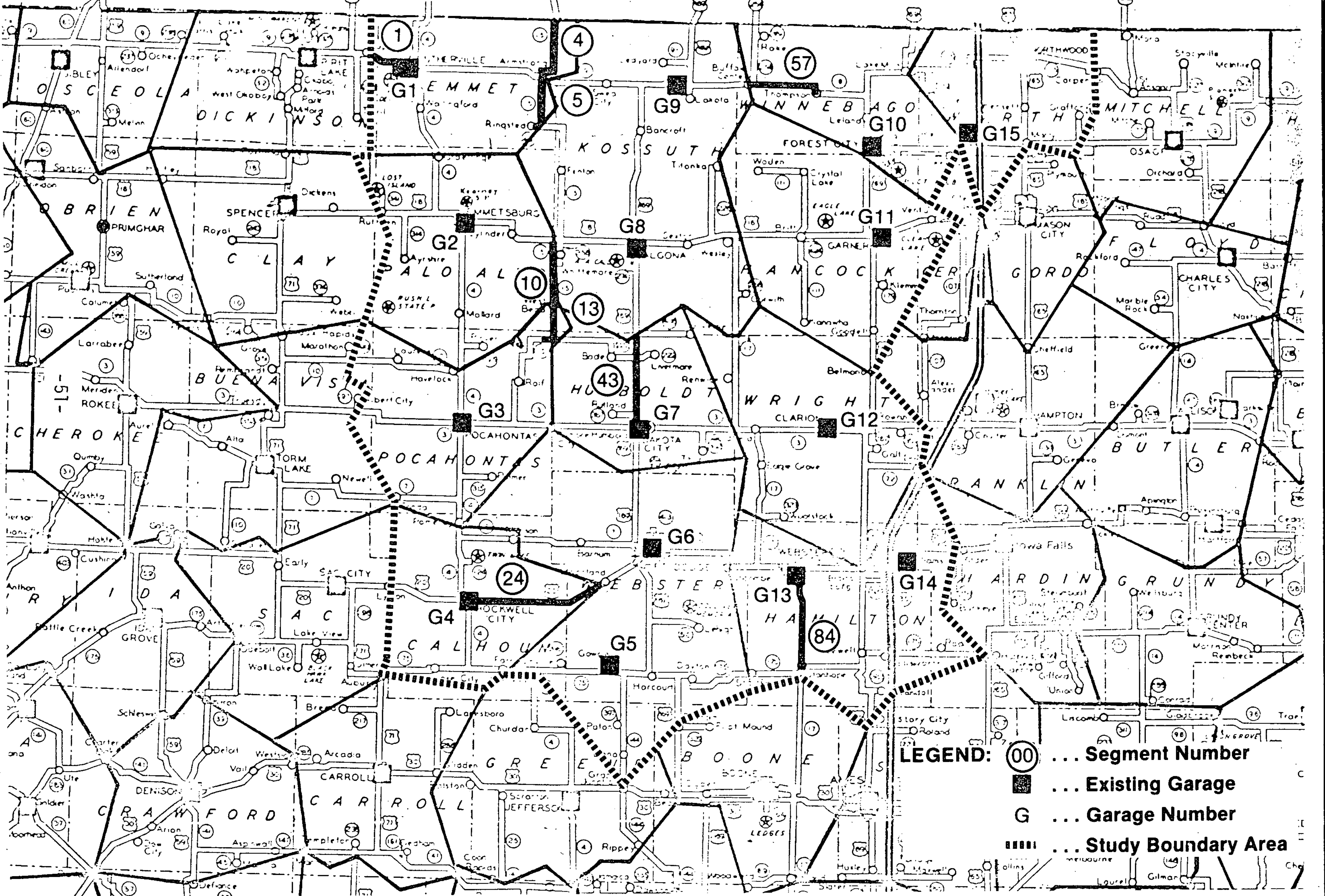
Appendix 2

HIGHWAY DIVISION DISTRICTS



APPENDIX 3

Study Area Showing 15 Garages and 10 Highway Segments



Appendix 4

A Sample of 10 Highway Segments Formed, their Lengths, and Basic Maintenance Costs

Highway Segment No.	Length of Segment (Miles)	Route No.	Maintenance Area	*Basic Maintenance Costs (1981 Dollars)
1	5.90	9	Estherville	13,814
4	8.78	15	Estherville	16,272
5	6.52	15	Estherville	12,083
10	8.23	15	Emmetsburg	8,635
12	7.76	4	Emmetsburg	10,770
13	5.68	15	Pocahontas	6,258
24	18.33	20	Rockwell City	32,155
43	12.17	169	Humboldt	42,359
57	8.50	69,105	Forest City	20,745
84	12.78	17	Williams	32,708

* 1981 labor and equipment costs based on the 1980 cost (see Appendix 6), adjusted for inflation.

Appendix 5

Sample of Estimated One-Way
Travel Times--From 10 Segments to 6 Garages
Average Speed = 35 mph

Highway Segment No.	One-Way Travel Time (in minutes) From Segment to Garage (G)					
	Emmetsburg (G_2)	Pocahontas (G_3)	Humboldt (G_7)	Algona (G_8)	Gerled (G_9)	Forest City (G_{10})
1	48	92	132	91	70	123
4	74	114	109	68	42	95
5	60	100	95	54	39	93
10	30	56	70	25	73	97
12	27	18	59	70	115	139
13	42	44	58	37	85	109
24	105	59	56	97	143	162
43	78	52	10	35	83	107
57	108	146	110	69	21	33
84	160	117	76	117	157	122

Appendix 6

Fiscal Year 1980 Labor, Equipment, and Overhead Costs for the Routes and Garages in the Study Area

Location and Number of Garage	1980 Garage Related Overhead Costs (Dollars)	Routes Served by Garage	1980 Labor Cost (Dollars)	1980 Equipment Cost (Dollars)
Estherville (2202)	20,843	4	24,969	21,117
		9	28,659	22,562
		15	12,236	13,680
		615	295	275
Emmetsburg (3305)	21,266	4	20,884	15,683
		15	4,797	3,167
		18	27,132	19,177
Pocahontas (3306)	21,193	3	22,505	13,564
		4	14,748	9,744
		7	9,265	7,961
		10	12,401	8,886
		15	12,159	9,495
		607	66	14
Rockwell City (3302)	14,240	4	22,788	14,837
		7	7,075	7,414
		20	27,675	19,920
		124	709	427
		175	23,299	14,282
Ft. Dodge & Gowrie (1208)	54,728	7	14,856	12,532
		20	25,839	21,675
		50	6,257	4,883
		169	48,565	33,165
		175	69,225	20,304
Humboldt (2204)	16,335	3	22,693	16,495
		169	35,788	22,678

Appendix 6 (Cont'd.)

Location and Number of Garage	1980 Garage Related Overhead Costs (Dollars)	Routes Served by Garage	1980 Labor Cost (Dollars)	1980 Equipment Cost (Dollars)
Alonga & Gerled (2205)	29,671	9	26,406	15,759
		15	21,892	15,947
		17	5,835	5,558
		18	27,693	24,462
		169	51,922	43,658
		226	4,792	4,821
		274	3,304	2,886
		602	1,037	1,471
Forest City (2209)	16,847	9	32,865	31,247
		69	31,559	27,959
		105	63	34
		640	79	15
		646	72	15
Garner (2203)	28,504	18	26,081	19,434
		69	22,865	19,668
		111	15,741	10,802
Clarion (2210)	28,193	3	23,345	15,072
		17	21,688	15,560
		69	24,234	18,029
		72	12,018	7,950
Webster City (1206)	26,094	17	28,223	17,999
		20	18,846	13,219
		175	19,533	14,249
		520	35,048	21,233
Williams (1207)	31,771	20	27,881	16,815
		35	77,197	57,273
		69	21,803	14,551
		175	19,427	12,068
		383	428	167
		520	8,397	6,337
Hanlontown (2108)	45,759	9	33,972	26,288
		35	61,019	50,095
		65	19,907	16,572
		105	28,723	24,967

Source: Office of Maintenance, Highway Division, Iowa DOT.

Appendix 7

Computer Program for Computing Travel Time Adjusted Costs

NOTES: * - The number '60' used here is such that any travel time greater than 60 minutes is an 'unimportant travel time' (see Section V.E.).

** - The number '200' used here is a fictitious travel time as described in Section V.E.

```
DATA A;INFILE A;INPUT NODE $1-6          (T1-T15) (4.0) COST 67-72;  00010014
IF  T1>60*THEN  T1=200;**                                            00020020
IF  T2>60*THEN  T2=200;**                                            00030020
IF  T3>60*THEN  T3=200;**                                            00040020
IF  T4>60*THEN  T4=200;**                                            00050020
IF  T5>60*THEN  T5=200;**                                            00060020
IF  T6>60*THEN  T6=200;**                                            00070020
IF  T7>60*THEN  T7=200;**                                            00080020
IF  T8>60*THEN  T8=200;**                                            00090020
IF  T9>60*THEN  T9=200;**                                            00100020
IF T10>60*THEN T10=200;**                                            00110020
IF T11>60*THEN T11=200;**                                            00120020
IF T12>60*THEN T12=200;**                                            00130020
IF T13>60*THEN T13=200;**                                            00140020
IF T14>60*THEN T14=200;**                                            00150020
IF T15>60*THEN T15=200;**                                            00160020
IF T1 >165 THEN COST1 =8*COST;                                       00170000
IF T2 >165 THEN COST2 =8*COST;                                       00180000
IF T3 >165 THEN COST3 =8*COST;                                       00190000
IF T4 >165 THEN COST4 =8*COST;                                       00200000
IF T5 >165 THEN COST5 =8*COST;                                       00210000
IF T6 >165 THEN COST6 =8*COST;                                       00220000
IF T7 >165 THEN COST7 =8*COST;                                       00230000
IF T8 >165 THEN COST8 =8*COST;                                       00240000
IF T9 >165 THEN COST9 =8*COST;                                       00250000
IF T10>165 THEN COST10=8*COST;                                       00260000
IF T11>165 THEN COST11=8*COST;                                       00270000
IF T12>165 THEN COST12=8*COST;                                       00280000
IF T13>165 THEN COST13=8*COST;                                       00290000
IF T14>165 THEN COST14=8*COST;                                       00300000
IF T15>165 THEN COST15=8*COST;                                       00310014
```

Computer Program for Computing Travel Time Adjusted Costs

```
IF 165>=T1 >=135 THEN COST1 =((  T1 -75)/30)*COST;
IF 165>=T2 >=135 THEN COST2 =((  T2 -75)/30)*COST;
IF 165>=T3 >=135 THEN COST3 =((  T3 -75)/30)*COST;
IF 165>=T4 >=135 THEN COST4 =((  T4 -75)/30)*COST;
IF 165>=T5 >=135 THEN COST5 =((  T5 -75)/30)*COST;
IF 165>=T6 >=135 THEN COST6 =((  T6 -75)/30)*COST;
IF 165>=T7 >=135 THEN COST7 =((  T7 -75)/30)*COST;
IF 165>=T8 >=135 THEN COST8 =((  T8 -75)/30)*COST;
IF 165>=T9 >=135 THEN COST9 =((  T9 -75)/30)*COST;
IF 165>=T10>=135 THEN COST10=((  T10-75)/30)*COST;
IF 165>=T11>=135 THEN COST11=((  T11-75)/30)*COST;
IF 165>=T12>=135 THEN COST12=((  T12-75)/30)*COST;
IF 165>=T13>=135 THEN COST13=((  T13-75)/30)*COST;
IF 165>=T14>=135 THEN COST14=((  T14-75)/30)*COST;
IF 165>=T15>=135 THEN COST15=((  T15-75)/30)*COST;
IF 135> T1 >=75 THEN COST1 =(((.8*T1 )+12)/60)*COST;
IF 135> T2 >=75 THEN COST2 =(((.8*T2 )+12)/60)*COST;
IF 135> T3 >=75 THEN COST3 =(((.8*T3 )+12)/60)*COST;
IF 135> T4 >=75 THEN COST4 =(((.8*T4 )+12)/60)*COST;
IF 135> T5 >=75 THEN COST5 =(((.8*T5 )+12)/60)*COST;
IF 135> T6 >=75 THEN COST6 =(((.8*T6 )+12)/60)*COST;
IF 135> T7 >=75 THEN COST7 =(((.8*T7 )+12)/60)*COST;
IF 135> T8 >=75 THEN COST8 =(((.8*T8 )+12)/60)*COST;
IF 135> T9 >=75 THEN COST9 =(((.8*T9 )+12)/60)*COST;
IF 135> T10>=75 THEN COST10=(((.8*T10)+12)/60)*COST;
IF 135> T11>=75 THEN COST11=(((.8*T11)+12)/60)*COST;
IF 135> T12>=75 THEN COST12=(((.8*T12)+12)/60)*COST;
IF 135> T13>=75 THEN COST13=(((.8*T13)+12)/60)*COST;
IF 135> T14>=75 THEN COST14=(((.8*T14)+12)/60)*COST;
IF 135> T15>=75 THEN COST15=(((.8*T15)+12)/60)*COST;
IF  75> T1 >=15 THEN COST1 =(((.4*T1 )+42)/60)*COST;
IF  75> T2 >=15 THEN COST2 =(((.4*T2 )+42)/60)*COST;
IF  75> T3 >=15 THEN COST3 =(((.4*T3 )+42)/60)*COST;
IF  75> T4 >=15 THEN COST4 =(((.4*T4 )+42)/60)*COST;
IF  75> T5 >=15 THEN COST5 =(((.4*T5 )+42)/60)*COST;
IF  75> T6 >=15 THEN COST6 =(((.4*T6 )+42)/60)*COST;
IF  75> T7 >=15 THEN COST7 =(((.4*T7 )+42)/60)*COST;
IF  75> T8 >=15 THEN COST8 =(((.4*T8 )+42)/60)*COST;
IF  75> T9 >=15 THEN COST9 =(((.4*T9 )+42)/60)*COST;
IF  75> T10>=15 THEN COST10=(((.4*T10)+42)/60)*COST;
IF  75> T11>=15 THEN COST11=(((.4*T11)+42)/60)*COST;
IF  75> T12>=15 THEN COST12=(((.4*T12)+42)/60)*COST;
IF  75> T13>=15 THEN COST13=(((.4*T13)+42)/60)*COST;
IF  75> T14>=15 THEN COST14=(((.4*T14)+42)/60)*COST;
IF  75> T15>=15 THEN COST15=(((.4*T15)+42)/60)*COST;
IF  T1 <15 THEN COST1 =.8*COST;
IF  T2 <15 THEN COST2 =.8*COST;
IF  T3 <15 THEN COST3 =.8*COST;
IF  T4 <15 THEN COST4 =.8*COST;
IF  T5 <15 THEN COST5 =.8*COST;
IF  T6 <15 THEN COST6 =.8*COST;
IF  T7 <15 THEN COST7 =.8*COST;
```

Computer Program for Computing Travel Time Adjusted Costs

```
IF  T8 <15 THEN COST8 =.8*COST;
IF  T9 <15 THEN COST9 =.8*COST;
IF  T10<15 THEN COST10=.8*COST;
IF  T11<15 THEN COST11=.8*COST;
IF  T12<15 THEN COST12=.8*COST;
IF  T13<15 THEN COST13=.8*COST;
IF  T14<15 THEN COST14=.8*COST;
IF  T15<15 THEN COST15=.8*COST;
DATA B;SET A;
FILE PRINT;
X='X';
M+1;
L+1;
P='1.0';
J='COST';
O='NOD';
PUT @5 X @6 M @15 J @25 (COST1) (8.1) @40 O @43 L @53 P;
M+1;
PUT @5 X @6 M @15 J @25 (COST2) (8.1) @40 O @43 L @53 P;
M+1;
PUT @5 X @6 M @15 J @25 (COST3) (8.1) @40 O @43 L @53 P;
M+1;
PUT @5 X @6 M @15 J @25 (COST4) (8.1) @40 O @43 L @53 P;
M+1;
PUT @5 X @6 M @15 J @25 (COST5) (8.1) @40 O @43 L @53 P;
M+1;
PUT @5 X @6 M @15 J @25 (COST6) (8.1) @40 O @43 L @53 P;
M+1;
PUT @5 X @6 M @15 J @25 (COST7) (8.1) @40 O @43 L @53 P;
M+1;
PUT @5 X @6 M @15 J @25 (COST8) (8.1) @40 O @43 L @53 P;
M+1;
PUT @5 X @6 M @15 J @25 (COST9) (8.1) @40 O @43 L @53 P;
M+1;
PUT @5 X @6 M @15 J @25 (COST10) (8.1) @40 O @43 L @53 P;
M+1;
PUT @5 X @6 M @15 J @25 (COST11) (8.1) @40 O @43 L @53 P;
M+1;
PUT @5 X @6 M @15 J @25 (COST12) (8.1) @40 O @43 L @53 P;
M+1;
PUT @5 X @6 M @15 J @25 (COST13) (8.1) @40 O @43 L @53 P;
M+1;
PUT @5 X @6 M @15 J @25 (COST14) (8.1) @40 O @43 L @53 P;
M+1;
PUT @5 X @6 M @15 J @25 (COST15) (8.1) @40 O @43 L @53 P;
```

Appendix 8

Sample Computer Output of Travel Time Adjusted Costs. Average Speed = 35 mph

a. Complete Data Set

*		*		
X1	COST	11051.20000	NOD1	1.00000
X2	COST	14090.30000	NOD1	1.00000
X3	COST	19708.00000	NOD1	1.00000
X4	COST	27628.00000	NOD1	1.00000
X5	COST	33679.20000	NOD1	1.00000
X6	COST	110512.0000	NOD1	1.00000
X7	COST	27075.40000	NOD1	1.00000
X8	COST	19523.80000	NOD1	1.00000
X9	COST	16116.30000	NOD1	1.00000
X10	COST	25417.60000	NOD1	1.00000
X11	COST	31772.20000	NOD1	1.00000
X12	COST	110512.0000	NOD1	1.00000
X13	COST	110512.0000	NOD1	1.00000
X14	COST	110512.0000	NOD1	1.00000
X15	COST	32693.10000	NOD1	1.00000
X16	COST	15986.40000	NOD2	1.00000
X17	COST	20649.10000	NOD2	1.00000
X18	COST	29042.00000	NOD2	1.00000
X19	COST	41298.20000	NOD2	1.00000
X20	COST	57284.60000	NOD2	1.00000
X21	COST	159864.0000	NOD2	1.00000
X22	COST	39699.60000	NOD2	1.00000
X23	COST	28775.50000	NOD2	1.00000
X24	COST	23579.90000	NOD2	1.00000
X25	COST	37301.60000	NOD2	1.00000
X26	COST	47293.10000	NOD2	1.00000
X27	COST	159864.0000	NOD2	1.00000
X28	COST	159864.0000	NOD2	1.00000
X29	COST	159864.0000	NOD2	1.00000
X30	COST	47959.20000	NOD2	1.00000
X31	COST	33510.40000	NOD3	1.00000
X32	COST	45518.30000	NOD3	1.00000
X33	COST	65903.60000	NOD3	1.00000
X34	COST	99134.90000	NOD3	1.00000
X35	COST	99134.90000	NOD3	1.00000
X36	COST	335104.0000	NOD3	1.00000
X37	COST	73164.40000	NOD3	1.00000
X38	COST	50265.60000	NOD3	1.00000
X39	COST	43284.30000	NOD3	1.00000
X40	COST	65903.80000	NOD3	1.00000
X41	COST	77073.90000	NOD3	1.00000
X42	COST	115890.1000	NOD3	1.00000
X43	COST	335104.0000	NOD3	1.00000
X44	COST	335104.0000	NOD3	1.00000
X45	COST	78749.40000	NOD3	1.00000
X46	COST	15512.60000	NOD4	1.00000
X47	COST	19417.90000	NOD4	1.00000
X48	COST	27987.80000	NOD4	1.00000
X49	COST	39595.20000	NOD4	1.00000
X50	COST	34171.20000	NOD4	1.00000
X51	COST	130176.0000	NOD4	1.00000
X52	COST	26903.00000	NOD4	1.00000
X53	COST	13767.00000	NOD4	1.00000
X54	COST	15946.60000	NOD4	1.00000
X55	COST	23865.60000	NOD4	1.00000
X56	COST	28421.80000	NOD4	1.00000
X57	COST	40680.00000	NOD4	1.00000
X58	COST	130176.0000	NOD4	1.00000

Notes:

The relevant columns are marked with asterisk (*).

X1 is theoretically defined as the fraction of segment No. 1 allocated to garage No. 1 (see Appendix 9, Section b(1)).

'11051.2' is the travel time adjusted cost from garage No. 1 to segment No. 1.

b. Partial Data Set

X1	COST	11051.2	NOD1	1.0
X2	COST	14090.3	NOD1	1.0
X3	COST	110512.0	NOD1	1.0
X4	COST	110512.0	NOD1	1.0
X5	COST	110512.0	NOD1	1.0
X6	COST	110512.0	NOD1	1.0
X7	COST	110512.0	NOD1	1.0
X8	COST	110512.0	NOD1	1.0
X9	COST	110512.0	NOD1	1.0
X10	COST	110512.0	NOD1	1.0
X11	COST	110512.0	NOD1	1.0
X12	COST	110512.0	NOD1	1.0
X13	COST	110512.0	NOD1	1.0
X14	COST	110512.0	NOD1	1.0
X15	COST	110512.0	NOD1	1.0
X16	COST	15986.4	NOD2	1.0
X17	COST	20645.1	NOD2	1.0
X18	COST	159864.0	NOD2	1.0
X19	COST	159864.0	NOD2	1.0
X20	COST	159864.0	NOD2	1.0
X21	COST	159864.0	NOD2	1.0
X22	COST	159864.0	NOD2	1.0
X23	COST	159864.0	NOD2	1.0
X24	COST	159864.0	NOD2	1.0
X25	COST	159864.0	NOD2	1.0
X26	COST	159864.0	NOD2	1.0
X27	COST	159864.0	NOD2	1.0
X28	COST	159864.0	NOD2	1.0
X29	COST	159864.0	NOD2	1.0
X30	COST	159864.0	NOD2	1.0
X31	COST	33510.4	NOD3	1.0
X32	COST	335104.0	NOD3	1.0
X33	COST	335104.0	NOD3	1.0
X34	COST	335104.0	NOD3	1.0
X35	COST	335104.0	NOD3	1.0
X36	COST	335104.0	NOD3	1.0
X37	COST	335104.0	NOD3	1.0
X38	COST	335104.0	NOD3	1.0
X39	COST	43284.3	NOD3	1.0
X40	COST	335104.0	NOD3	1.0
X41	COST	335104.0	NOD3	1.0
X42	COST	335104.0	NOD3	1.0
X43	COST	335104.0	NOD3	1.0
X44	COST	335104.0	NOD3	1.0
X45	COST	335104.0	NOD3	1.0
X46	COST	15512.6	NOD4	1.0
X47	COST	130176.0	NOD4	1.0
X48	COST	130176.0	NOD4	1.0
X49	COST	130176.0	NOD4	1.0
X50	COST	130176.0	NOD4	1.0
X51	COST	130176.0	NOD4	1.0

Appendix 9

The Optimum Allocation Model and the MPSX Computer Program

a. The Optimum Allocation Model

Let

Xij = fraction of highway segment 'i' allocated to maintenance garage 'j';

Cij = cost of servicing highway segment 'i' from maintenance garage 'j'; and

Z = total maintenance cost for study area.

Suppose there are 'n' highway segments and'm' maintenance garages in the study area. Then the classical linear programming (17) formulation is

$$\text{Minimize } Z = \sum_{i=1}^{n} \sum_{j=1}^{m} Cij\ Xij$$

$$\text{Subject to } \sum_{j=1}^{m} Xij = 1,\ i = 1, 2, ---, n$$

$$Xij \geq 0$$

In this study, the above formulation has been called the Optimum Allocation model.

In the Optimum Allocation model (as formulated above), it is possible to obtain fractional values of the Xij's. To avoid this problem one could reformulate it as an integer programming model (20) by changing the constraints $Xij \geq 0$ to

$$Xij = \begin{cases} 1, & \text{if highway segment 'i' is allocated to maintenance garage 'j'} \\ 0, & \text{otherwise} \end{cases}$$

In the integer programming formulation, the Xij's are either zero or one. There is, however, a disadvantage in that efficient computerized algorithms for solving large-scale integer programming problems (like the MPSX computer program for linear programming problems) are not readily available. In view of this, the Optimum Allocation model was not formulated as an integer programming model.

Even though it is possible to obtain fractional values for the Xij's in the Optimum Allocation model, they rarely occur. In fact, both in this study and the project prepared for the Alabama DOT by Bell (1), fractional values never occurred.

If one of the maintenance garages in the Optimum Allocation model is to be closed, then an additional constraint is needed. Suppose garage j* is to be closed. Then the new Optimum Allocation model is

$$\text{Minimize} \quad Z = \sum_{i=1}^{n} \sum_{j=1}^{m} Cij \quad Xij$$

$$\text{Subject to} \quad \sum_{j=1}^{m} Xij = 1, \; i=1, 2, ---, n$$

$$\sum_{i=1}^{n} Xij = 0, \; j=j^*$$

$$Xij \geq 0$$

b. The MPSX Computer Code

The MPSX computer code of IBM (17) is a highly efficient computer program capable of solving large-scale linear programming problems. This computer program was used in this study to solve the optimum allocation problem.

The input format, control program, and data format have been combined in a logical sequence to form one continuous program.

The computer program as used to evaluate the cost impact of closing the garages at Humboldt and Forest City is shown in Section b(7), Page 69.

(1) The Xij Variables

The Xij's defined in Section 'a' were defined differently in the MPSX computer program used. The relationships between the two definitions are given on the following page.

Allocation Model	MPSX Computer Program	Variable Description
$X_{1,1}$	X_1	Fraction of segment 1 allocated to garage 1
$X_{1,2}$	X_2	" " " 1 " " " 2
----	----	
$X_{1,15}$	X_{15}	" " " 1 " " " 15
$X_{2,1}$	X_{16}	" " " 2 " " " 1
----	----	
$X_{2,15}$	X_{30}	" " " 2 " " " 15
$X_{3,1}$	X_{31}	" " " 3 " " " 1
----	----	
$X_{95,15}$	X_{1425}	" " " 95 " " " 15
$X_{96,1}$	X_{1426}	" " " 96 " " " 1
----	----	
$X_{96,15}$	X_{1440}	" " " 96 " " " 15

(2) Comments on the MPSX Computer Program

The following explanation pertains to the MPSX computer program given in Section b(7).

(i) The program steps have been numbered for reference purposes only.

(ii) Each program step indicates the required information to be punched on a card.

(iii) Only those variables supplied by the user are explained below:

Step No. 1: - "xxxx' is a 'box number' to be provided by Iowa State University (ISU)

- 'yyyyy' is an account number to be given by ISU

- 'NKANSA' is a user supplied name* for the job

Step No. 2: - 'yy' is an account protection number to be given by ISU

Step No. 7: - 'PAUL' is a user supplied name* for the data

Step No. 8: - 'GARSTUDY' is a user supplied name* for the program

Step No. 12: - 'COST' is a user supplied name* for the Cij's (defined in Section 'a' above).

Step No. 13: - 'MCOST' is a user supplied name* for the total maintenance cost 'Z' (defined in Section 'a' above).

Step No. 20: - 'PAUL' is as explained in Step No. 7.

Step No. 22: - 'COST' is as explained in Step No. 12.

Step No. 23: - 'NOD1' is a user supplied name* for highway segment no. 1.

Step No. 118: - 'NOD96' is a user supplied name* for highway segment no. 96. It is the last segment formed in the study area.

Step No. 119: - 'CLOS7' is a user supplied name* for the first garage to be closed. In this case it is Humboldt garage (garage no. 7).

Step No. 120: - 'CLOS10' is a user supplied name* for the second garage to be closed. In this case it is Forest City garage (garage no. 10).

Step No. 122: - 'X1' is as defined in Section b(1).

- 'COST' is as explained in Step No. 12.

- '11051.2' is the travel time adjusted cost associated with X1, using average speed of 35 mph and the partial data set technique (see Section V.E.).

Step No. 129: - 'X7' is theoretically defined as the fraction of segment no. 1 allocated to garage no. 7 (Humboldt garage). Since garage no. 7 is to be closed, this step ensures that no part of segment no. 1 is allocated to garage no. 7. That is, X7=0. Similarly, X22, X37, X52, ---- (occurring at intervals of 15 because there are 15 garages) must be zero. To ensure this, steps similar to Step No. 129 are 'repeated' whenever a step containing any of the 'X' variables X22, X37, X52, ----, X1432 is encountered.

Step No. 133: - Explanation of this step is the same as that of Step No. 129 except that X7 should be replaced with X10 and the set {X22, X37, ----, X1432} should be replaced with the set {X25, X40, ----, X1435} .

Step No. 1567: - 'X1440' is the last 'X' variable.

Step No. 1569: - 'MCOST' is as defined in Step No. 13.

* Any name used should not be more than eight letters or characters.

(3) Optimum Allocation

To optimally allocate highway segments to a given number of maintenance garages in a study area, the steps in the computer program associated with closing a garage should be deleted. Thus steps similar to Step No. 119 and Steps 129, 146, 163, ----, 1558 associated with garage no. 7 (or Step No. 120 and Steps No. 133, 150, 167, ----, 1562 associated with garage no. 10) should not be included.

The number of highway segments and maintenance garages in the study area will determine the number of steps. It should be noted that the computer program given is for 96 highway segments and 15 maintenance garages.

(4) Closing of Maintenance Garages

To close a maintenance garage, steps similar to Step No. 119 and Steps No. 129, 146, 163, ----, 1558 associated with garage no. 7 (or Step No. 119 and Steps No. 133, 150, 167, ----, 1562 associated with garage no. 10) should be included in the computer program. The actual step numbers will depend on the size of the problem. If two or more maintenance garages are to be closed, appropriate changes in the computer program will have to be made.

(5) Relocation of Maintenance Garages

Relocation of maintenance garages can be handled in two ways. These are described on the following page.

Approach 1

In the MPSX computer program, simply regard the 'old' maintenance garage (maintenance garage at old location) as the 'new' maintenance garage (maintenance garage at new location). But the 'old' travel time adjusted costs in the computer program should be replaced by the 'new' travel time adjusted costs (as determined from the new location). In this approach, the computer program should not contain any of those steps associated with closing a maintenance garage (i.e., steps such as 119 or 120, 129 or 133, 146 or 150, etc. should not be included). This approach was used in the study.

Approach 2

In this alternative approach, the maintenance garage to be relocated is first closed as described in section b(4) above. At the same time, a new maintenance garage is created at the new location. The travel time adjusted costs associated with this new location are calculated. An implication of this approach is that the number of maintenance garages in the computer program is increased by one for any maintenance garage relocated. This will increase the size of the problem and may lead to an increase in computer time.

b(6) Sample Output of the MPSX Computer Program

<u>Notes:</u> (i) The relevant columns are those marked with asterisk (*)

(ii) The optimum solution is:

$X_1 = X_{1,1} = 1.0$ with service cost of \$11,051.2

$X_2 = 0 = X_3 = X_4 = \ldots\ldots = X_{15}$

This means segment No. 1 is allocated to garage No. 1.

$X_{16} = X_{2,1} = 1.0$ with service cost of \$15,986.4

$X_{17} = 0 = X_{18} = X_{19} = \ldots\ldots = X_{30}$

This means segment No. 2 is allocated to garage No. 1

Total maintenance cost = \$1,969,392.4 (see next page)

0 *1 2 *3 4 *5 6 7 8 9 10 11

.MPSX-PTF19.. EXECUTOR. MPSX RELEASE 1 MOD LEVEL 6 PAGE 44 - 81/070

SECTION 2 - COLUMNS

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
98	X1 $X_{1,1}$	BS	1.00000	11051.20000	.	NONE	.
99	X2	LL	.	14090.30000	.	NONE	3039.10000
100	X3	LL	.	110512.00000	.	NONE	99460.80000
101	X4	LL	.	110512.00000	.	NONE	99460.80000
102	X5	LL	.	110512.00000	.	NONE	99460.80000
103	X6	LL	.	110512.00000	.	NONE	99460.80000
104	X7	LL	.	110512.00000	.	NONE	99460.80000
105	X8	LL	.	110512.00000	.	NONE	99460.80000
106	X9	LL	.	110512.00000	.	NONE	99460.80000
107	X10	LL	.	110512.00000	.	NONE	99460.80000
108	X11	LL	.	110512.00000	.	NONE	99460.80000
109	X12	LL	.	110512.00000	.	NONE	99460.80000
110	X13	LL	.	110512.00000	.	NONE	99460.80000
111	X14	LL	.	110512.00000	.	NONE	99460.80000
112	X15 $X_{1,15}$	LL	.	110512.00000	.	NONE	99460.80000
113	X16 $X_{2,1}$	BS	1.00000	15986.40000	.	NONE	.
114	X17	LL	.	20649.10000	.	NONE	4662.70000
115	X18	LL	.	159864.00000	.	NONE	143877.60000
116	X19	LL	.	159864.00000	.	NONE	143877.60000
117	X20	LL	.	159864.00000	.	NONE	143877.60000
118	X21	LL	.	159864.00000	.	NONE	143877.60000
119	X22	LL	.	159864.00000	.	NONE	143877.60000
120	X23	LL	.	159864.00000	.	NONE	143877.60000
121	X24	LL	.	159864.00000	.	NONE	143877.60000
122	X25	LL	.	159864.00000	.	NONE	143877.60000
123	X26	LL	.	159864.00000	.	NONE	143877.60000
124	X27	LL	.	159864.00000	.	NONE	143877.60000
125	X28	LL	.	159864.00000	.	NONE	143877.60000
126	X29	LL	.	159864.00000	.	NONE	143877.60000
127	X30 $X_{2,15}$	LL	.	159864.00000	.	NONE	143877.60000
128	X31 $X_{3,1}$	BS	1.00000	33510.40000	.	NONE	.
129	X32	LL	.	45518.30000	.	NONE	12007.90000
130	X33	LL	.	[illegible]	.	[illegible]	[illegible]

b(6) Sample Output of the MPSX Computer Program

```
.MPSX-PTF19..  EXECUTOR.  MPSX  RELEASE 1  MOD LEVEL 6                          PAGE    41  -   81/070
SOLUTION    (OPTIMAL)
TIME =      0.05 MINS.  ITERATION NUMBER =      96

            ...NAME...      ...ACTIVITY...       DEFINED AS
            FUNCTIONAL      1969392.39999        COST
            RESTRAINTS                           MCOST
```

Appenix 9 contd.

b(7) MPSX Computer Program
for Closing Humboldt and Forest City Garages

```
Steps
 1.  //xxxx      JØB yyyyy 'NKANSA'
 2.  /*KEY  yy   TIME=20,LINES=16K
 3.  //S1    EXEC  MPSX
 4.  //MPSCOMP.SYSIN DD  *
 5.            PROGRAM
 6.            INITIALZ
 7.            MØVE(XDATA,'PAUL')
 8.            MØVE(XPBNAME,'GARSTUDY')
 9.            CØNVERT('SUMMARY')
10.            BCDØUT
11.            SETUP('MIN')
12.            MØVE(XØBJ,'CØST')
13.            MØVE(XRHS,'MCØST')
14.            PRIMAL
15.            SØLUTIØN
16.            EXIT
17.            PEND
18.  /*
19.  //MPSEXEC.SYSIN DD  *
20.  NAME          PAUL
```

b(7) MPSX Computer Program
for Closing Humboldt and Forest City Garages

Steps	01	02 03	04	05 06 07 08 09 10 11 12	13 14	15 16 17 18 19 20 21 22	23 24	25 26 27 28 29 30 31 32 33 34 35 36	37 38 39	40 41 42 43 44 45 46 47	48 49	50 51 52 53 54 55
21	R	ΦW	S									
22		N		CΦST								
23		E		NΦD1								
24		E		NΦD2								
		...		----								
118		E		NΦD96								
119		E		CLΦS7								
120		E		CLΦS10								
121	C	ΦL	U	MNS								
122				X1		CΦST		11051.2		NΦD1		1.0
				...		....		....		-----		----
128				X7		CΦST		110512.0		NΦD1		1.0
129				X7		CLΦS7		1.0				
130				X8		CΦST		110512.0		NΦD1		1.0
				....		....		....		....		...
132				X10		CΦST		110512.0		NΦD1		1.0
133				X10		CLΦS10		1.0				
134				X11		CΦST		110512.0		NΦD1		1.0
				....		....		.....		----		--.
138				X15		CΦST		110512.0		NΦD1		1.0

Appendix 9 contd.

b(7) MPSX Computer Program
for Closing Humboldt and Forest City Garages

Steps	05–12	15–22	25–36	40–47	50–55
139	X16	CΦST	15986.4	NΦD2	1.0
	....	....	.....	....	....
145	X22	CΦST	159864.0	NΦD2	1.0
146	X22	CLΦS7	1.0		
147	X23	CΦST	159864.0	NΦD2	1.0
	....	....	......	......	.....
149	X25	CΦST	159864.0	NΦD2	1.0
150	X25	CLΦS10	1.0		
151	X26	CΦST	159864.0	NΦD2	1.0
	.....	....	....	....	.....
1557	X1432	CΦST	568992.0	NΦD96	1.0
1558	X1432	CLΦS7	1.0		
1559	X1433	CΦST	568992.0	NΦD96	1.0
	....	....	....	....	.....
1561	X1435	CΦST	69227.0	NΦD96	1.0
1562	X1435	CLΦS10	1.0		
1563	X1436	CΦST	59744.2	NΦD96	1.0
	....	....	....	....	.....
1566	X1439	CΦST	568992.0	NΦD96	1.0
1567	X1440	CΦST	59270.0	NΦD96	1.0

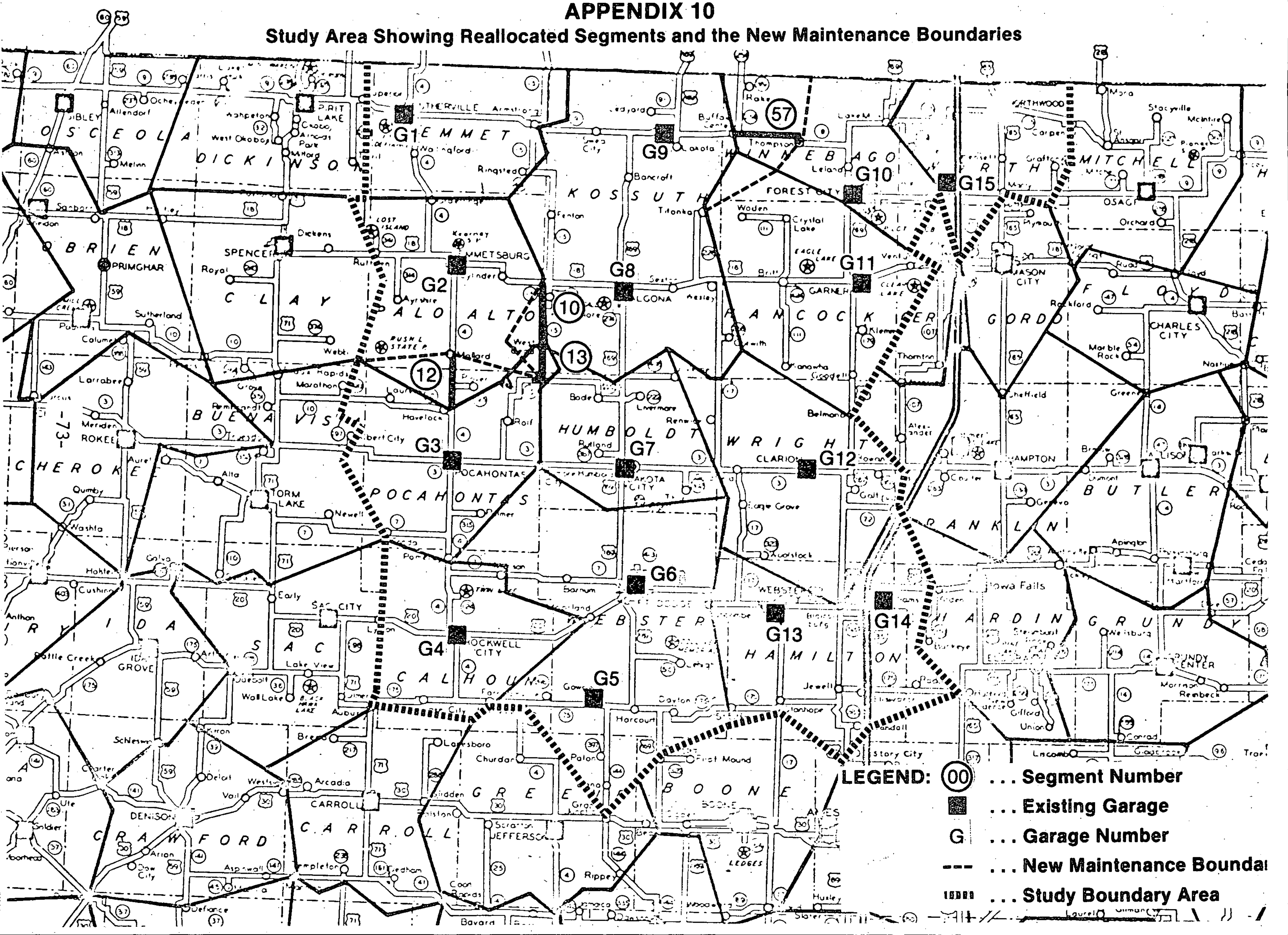
Appendix 9 contd.

b(7) MPSX Computer Program
for Closing Humboldt and Forest City Garages

Steps	01	02 03	04	05–12	13 14	15–22	23 24	25–36	37–39	40–47	48 49	50–54
1568	R	HS										
1569				MCØST		NØD1		1.0		NØD2		1.0
1570				MCØST		NØD3		1.0		NØD4		1.0
.				. . . .		. . . . . .		. . . . .		. . . . .		. . . . .
1616				MCØST		NØD95		1.0		NØD96		1.0
1617	E	ND	A	TA								
1618	/	*										
1619	/	/										

APPENDIX 10

Study Area Showing Reallocated Segments and the New Maintenance Boundaries



APPENDIX 11

Study Area Showing New Maintenance Boundaries After Humboldt and Forest City Garages are Closed