Assessing Highway Field Maintenance Office Locations by the *p*-Median Model

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Deciding when to establish a new highway maintenance office and where to put this new office is often a difficult process. A modeling technique may assist in making such difficult decisions. The *p*-median model is widely used in the business field to study the attractiveness between potential service facilities and the audience receiving these services. The model has proved successful in selecting optimum locations for business and government facilities, and it may be readily adapted to the highway field office problem. The theoretical basis, characteristics, and constraints associated with the *p*-median model are discussed. For any fixed number of service facilities, the model finds their optimum locations, such that total system travel is minimized between the facilities and the maintenance sites (adjacent nodes in the road network). The model can also be adapted to optimize two levels of maintenance offices, in which groups of offices at the lower level report to offices at an upper level. Several examples are used to show modeling methods for selecting the best number of field offices and their optimum locations. Weighting factors (lane-miles of pavement, population, maintenance budgets, etc.) are applied to travel distances to modify the attractiveness between nodes and facilities and thus improve the model. An example is given to illustrate calibrating the model in this manner.

State highway departments have widely differing philosophies about the number and locations of field maintenance offices. Deciding when to establish a new field office and where to put this new office is often a difficult process. The decision is usually subjective in nature, with no way to measure the efficiency of alternate locations. For any state, the existing configuration of offices may reflect the historical pattern of state development, political pressures, degree of control exerted by the central office, or all of these.

A statistical technique is used in Alabama to compare alternate locations of field maintenance offices. The technique is called the *p*-median model, and it may be applied either to existing or proposed locations.

NEED FOR MODELING

Sophisticated modeling has been widely accepted in the business world. Business managers use the modeling process to forecast trends, to evaluate various management scenarios, and to help make difficult decisions when there is insufficient data for direct evaluation of the situation. A number of models have been developed for such uses by the business community. As computers have increased in capacity and sophistication, the models have done likewise. At the current time, some models use extremely large data bases and apply increasingly complex statistical procedures to overcome incompleteness or irregularities of the data and to examine increasingly large numbers of scenarios.

Highway engineers have traditionally made good use of computers as part of the engineering design process, and for accumulation, use, and reporting of data. Increasingly, engineers are using computers as management tools. Maintenance management systems and bridge management systems are two good examples of highway management through computer applications. Several bridge management systems use sophisticated operations research techniques to analyze incomplete data sets (called fuzzy data) and to make complex decisions regarding optimization of funding for bridge treatment.

APPLICATIONS TO HIGHWAY FIELD OFFICES

Field offices are normally placed so that employees have reasonable access to all roadway locations, and so that the public has good access to a highway manager. Enough offices should be close together so that employee travel time to the work site is reasonably minimized. On the other hand, there should not be too many field offices because the administrative overhead becomes too large a portion of the overall highway budget. The most efficient arrangement usually has a minimum number of field offices located in the optimum locations so that employees can readily cover the entire roadway network.

It seems logical that modeling techniques could be used to pick the optimum locations of field offices. Because the problem involves multiple trips from field offices to different nodes in the transportation system, it lends itself to the *p*-median technique.

One use for modeling might be to choose where to place a new county-level maintenance office in a location where there had previously been none. Trial locations of the office could be modeled to determine which location minimized overall travel from the office to the various roadway sections. Similarly, the current offices in several counties could be studied for closure with the replacement by a single office serving several counties. In this case, the added expense of constructing the new office and the added expenses of longer employee travel routes could be balanced against the savings generated by the closure of the multiple existing field offices.

The modeling process can be customized to fit individual states or individual regions within a state. For example, measures of economic development and growth (population, income per capita, dollars of manufacturing per capita, etc.) can be

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added to the model to evaluate the need for future offices in areas of high growth. It is also possible to use such models to devise plans for the highway agency for future reshaping of its field office network through additions, closures, and relocations of offices.

SIMPLIFIED DESCRIPTION OF THE *p*-MEDIAN MODEL

Several examples will illustrate the nature of the *p*-median model. This discrete model has been used to establish the optimum locations for medical facilities in rural India, to identify the best pattern for neighborhood schools, and to predict the best locations for commercial and merchandising outlets. In general, the model measures accessibility of a facility that is delivering a service to a widespread audience.

The *p*-median methodology attempts to find an optimum set of locations for facilities by minimizing the distances between these facilities and the audience that they serve. In the context of highway maintenance offices, the model has the following characteristics:

1. All demands for service are assigned to the closest facility.
2. Each demand for service is located at a node within the transportation network.
3. The number of facilities (maintenance field offices) is a fixed value for each scenario to be modeled.
4. The model attempts to reach equilibrium by minimizing the distances between the service facilities and the adjacent nodes.
5. Trial locations of service facilities are established and nodes are assigned to them. The nodes are then reassigned to various facilities until the optimum locations and patterns are identified.
6. The physical distances between nodes and service facilities can be weighted to reflect the attractiveness of one node over another.
7. The model calculates an objective function for each possible pattern and attempts to find the best configuration by optimizing this function.

The typical state highway agency has multiple levels of field offices. Typically, this involves several district offices reporting to one larger division office, which in turn reports to the headquarters of the agency. The *p*-median model has now been modified to handle multiple levels of facilities. The hierarchical facility version of *p*-median has several characteristics in addition to those for the normal version, as follows:

1. There are multiple levels of facilities such that each facility level provides different but related services.
2. The service levels form a nested facility hierarchy.
3. The presence of a higher-level facility in a region requires that more than one lower-level facility also be located in that region.
4. For a given number of facilities and for a given ratio of higher-order to lower-order facilities, the model selects the optimum locations of the higher-order facilities with an optimum pattern of lower-order facilities clustered around them.

The concept of the *p*-median technique is simple to grasp. Given a fixed number of facilities, it finds a set of locations that minimizes the total system of travel between the facilities and the network that they serve. The model operates by starting with trial locations and calculating the total travel. One at a time, the model then exchanges nodes in and out of the current solution set until the objective value is optimized. For the hierarchical problem with two levels of facilities, the model starts by calculating travel for a fixed set of primary offices. Then a level change procedure is used to find optimum locations for the lower-level offices. The model then switches levels and returns to find another optimum configuration of higher-level offices, then switches back to find a matching set of second-level offices. This procedure is repeated until the objective function is minimized for all locations of first-level and second-level facilities. Obviously for simulation of an entire state, this procedure can involve an extremely large number of manipulations and calculations.

The basic premise of trial-and-error location of offices to minimize travel can be enhanced through analytical techniques. In the next section, the theoretical basis for the *p*-median methodology and heuristic and bounding procedure techniques used to improve the modeling process are described.

THEORETICAL BASIS OF THE *p*-MEDIAN MODEL

The highway maintenance office location problem is a generalization of the *p*-median problem. It can be formulated as a binary linear programming problem as follows:

Minimize

$$\sum_{i=1}^{n} \sum_{j=1}^{n} a_i d_{ij} x_{ij} \tag{1}$$

subject to

$$\sum_{j=1}^{n} X_{ij} = 1 \qquad \text{for } i \varepsilon I \tag{2}$$

$$\sum_{j=1}^{n} Y_j = P \tag{3}$$

$$X_{ij} \leq Y_j \qquad \text{for } i \varepsilon I,\ j \varepsilon J \tag{4}$$

$$X_{ij},\ Y_j\ \varepsilon\ \{0, 1\} \tag{5}$$

where

J = set of potential facility sites;
I = set of demand nodes ($I = J$);
n = number of demand nodes;
Y_j = 1 if a facility is located at Node j, 0 otherwise;
X_{ij} = 1 if the demand at Node i is assigned to a facility at Node j, 0 otherwise;
a_i = population (or weight) at Node i;
d_{ij} = distance traveled (cost incurred) if the demand at Node i assigns to a facility at Node j; and
P = number of facilities to be located.

This formulation is a slight modification of the ReVelle and Swain (*1*) formulation of the p-median problem. Implicit in this formulation is the assumption that all demand is located at the nodes of the transportation network. The objective function (Equation 1) of the formulation minimizes weighted distance. The constraint set (Equation 2) ensures that each demand node is assigned to one and only one facility node. Assignment is limited to open facilities (Equation 4). The number of open facilities is limited to p by constraint (Equation 3). The final constraint set (Equation 5) is the binary requirement. If the facility variables Y_j are binary, then it can be shown that the assignment variables X_{ij} are also binary, so the restrictions on the X_{ij} variables can be relaxed to nonnegativity requirements.

Some high points in the history of the p-median problem will now be noted. Hakimi (*2*) described the problem and gave a proof that if all demand is located at the nodes of the transportation network then an optimal facility set will exist consisting of nodes. Tietz and Bart (*3*) developed an exchange heuristic for the p-median problem that starts with an initial configuration and exchanges nodes not in the current configuration with nodes in the current configuration until no one-at-a-time exchange will reduce weighted distance. ReVelle and Swain (*1*) formulated the problem as a binary linear program and discovered that if the constraint set (Equation 5) is relaxed to nonnegativity conditions before the formulation is solved, natural binary solutions are obtained in many cases. Corneujols et al. (*4*) and Narula et al. (*5*) developed an efficient solution procedure for the p-median problem on the basis of subgradient optimization of a Lagrangian dual. In both cases, the Lagrangian dual was developed by multiplying each assignment constraint (Equation 2) by a nonnegative multiplier and appending it to the objective function (Equation 1).

The p-median problem is often used to analyze public sector locational decisions in which the cost of facilities or the benefits of services are difficult to estimate with precision. Sometimes, the actual number of facilities that should be established is one of the decisions to be made, in which case the formulation can be solved for various values of p, and a tradeoff curve can be drawn between the number of facilities and weighted distance. Weighted distance is used as a surrogate for the aggregate level of service in the locational system. Thus, a tradeoff curve between the number of facilities and weighted distance allows an evaluation of the improvement in service that results from additional facilities.

Hierarchical Median Model

The p-median problem has been applied in many different contexts; however, there are a number of situations that require extensions of the basic p-median model to allow for such factors as multiple time states, nonclosest facility service, a coverage objective, and facilities of different types. A more complete account of these generalizations of the p-median problem is given by Church and Weaver (*6*) and the references contained therein. The problem of locating district offices and division offices of a state highway department can be modeled as an extended median problem known as the "nested hierarchical median problem." The hierarchical median model was developed by Weaver and Church (*7*) as a general multiple-level model. The problem here is modeled as a two-level hierarchical locational system, and a two-level formulation will be given. Special-purpose solution procedures for the nested hierarchical median will be outlined for the two-level case. A more general formulation and more complete account of the solution procedures is given by Weaver and Church (*7*), who include an account of the nested hierarchical median model's relationship to other models in the location literature.

Two-level hierarchical facilities provide two types of services in a manner such that there is a hierarchical relationship between the first-level facilities and the second-level facilities. The location of a second-level facility at a site requires that a first-level facility also be located at the site. In the context of highway department district and division offices, first-level facilities are district offices and second-level facilities are division offices. Division offices are only located in counties with district offices so this problem can be modeled as a nested hierarchical median problem.

The two-level nested hierarchical median model can be formulated as a binary linear program as follows:

Minimize

$$\sum_{k=1}^{2} \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ik} d_{ij} X_{ijk} \quad (6)$$

subject to

$$\sum_{j=1}^{n} X_{ijk} = 1 \qquad \text{for } i \varepsilon I,\ k = 1, 2 \quad (7)$$

$$\sum_{j=1}^{n} Y_{jk} = P_k \qquad \text{for } k = 1, 2 \quad (8)$$

$$X_{ijk} \le Y_{jk} \qquad \text{for } i \varepsilon I,\ j \varepsilon J,\ k = 1, 2 \quad (9)$$

$$Y_{j2} \le Y_{j1} \qquad \text{for } j \varepsilon J \quad (10)$$

$$X_{ijk},\ Y_{jk}\ \varepsilon\ \{0, 1\} \quad (11)$$

where

a_{ik} = demand at Node i for k-level service;
P_k = number of k-level facilities to be located ($P_2 \le P_1$);
Y_{jk} = 1 if a k-level facility is located at Node j, 0 otherwise; and
X_{ijk} = 1 if the demand for k-level service at Node i is assigned to a facility at Node j, 0 otherwise.

The objective function (Equation 6) again minimizes weighted distance, but here it is weighted to both first-level and second-level facilities. The constraint set (Equation 1) ensures that all demand nodes are assigned to exactly one first-level facility and one second-level facility. Assignment of demand nodes to facilities can take place only if a facility of the proper level is open as a result of the constraint set (Equation 9). Exactly P_1 first-level and P_2 second-level facilities will be opened because of the constraint set (Equation 8).

The constraint set also ensures that a second-level facility will not be opened at a site unless a first-level facility is also opened at the site (Equation 10); Equation 11 is the binary requirement. The constraint that is required to enforce the nesting property makes the model more difficult to solve (Equation 10). Without the nesting constraint set (Equation 11), the formulation (Equations 6 through 9 and Equation 11) can be solved as two independent p-median problems.

Solution of the Nested Hierarchical Median Problem

The formulation for the two-level hierarchical median problem can be solved with commercial mathematical programming software such as IBM's MPSX/MIP. The difficulty of such a solution approach lies in the problem size. The formulation has $2n^2 + 2n$ decision variables of which $2n$ (the facility variables) must be explicitly required to be binary. The number of constraints is $2n^2 + 3n + 2$. For the problem of location of the highway district and division offices, when all 67 Alabama counties were considered potential facility sites, the resulting mixed-integer programming problem had 9,112 variables (of which 134 were required to be binary) and 9,181 constraints. Even with today's computing tools, this problem is large, especially when it is considered that in many cases one wants to solve the formulation for several different values of the parameters, such as the number of facilities (P_1, P_2) and demand weights (a_{ik}), so that not just one large mixed-integer linear program must be solved, but many such problems.

Efficient special-purpose solution procedures that have been developed for the p-median problem have been modified for the hierarchical median problem. Two approaches have been shown experimentally to generally obtain good results in a reasonable amount of computer time for the p-median problem. These approaches are the primal exchange heuristic and Lagrangian bounding. When both approaches are used together, optimal or near-optimal results are generally obtained for problems on the basis of actual spatial data sets. The modifications required for the p-median procedures are described later. A more complete account has been provided by Weaver and Church (*7*).

The exchange heuristic for the p-median problem was developed by Teitz and Bart (*3*). The heuristic, which starts with an initial facility set, partitions the nodes of the transportation network into facility nodes and nonfacility nodes. The effect of exchanging each node in the facility set with a node in the nonfacility set is determined. If an exchange reduces weighted distance, the change is made. After all nodes in the initial nonfacility set have been considered for exchange into the facility set, a cycle is complete. The heuristic then repeats the preceding steps, using the facility set of the first cycle as its starting set. This continues until no cycle produces an improvement in the model (i.e., no reduction in weighted travel distance). Modifying the exchange heuristic to solve the nested hierarchical median model proceeds by letting second-level facility locations be determined by their place in the facility list and by making the necessary changes in objective function evaluations. However, if these are the only modifications made, there is a possibility that facilities may be in the facility set at the wrong level. The heuristic can be improved by changing the level of facilities at the end of each cycle if such changes reduce weighted distance. This modified heuristic has been shown to obtain an optimal or near-optimal result for several moderately sized data sets (*7*).

Another solution approach that can be used alone or after the exchange heuristic is Lagrangian bounding. A Lagrangian dual (LD) (of Equations 6–11) is formed by multiplying each assignment constraint (Equation 7) by a nonnegativity multiplier μ_{ik} and appending the result to the objective function. After simplification and modification of the binary requirements (Equation 11), the following LD results:

Maximize

$$LD(\mu) = \text{Min} \sum_k \sum_i \sum_j (a_{ik} - \mu_{ik})X_{ijk} + \sum_i \sum_k \mu_{ik} \quad (12)$$

subject to

$$\sum_j Y_{jk} = P_k \quad \text{for } k = 1, 2 \quad (13)$$

$$X_{ijk} \leq Y_{jk} \quad \text{for } i \varepsilon I, j \varepsilon J, k = 1, 2 \quad (14)$$

$$Y_{j2} \leq Y_{j1} \quad \text{for } j \varepsilon J \quad (15)$$

$$(X_{ij2}, Y_{j2}) \ \varepsilon \ \{0, 1\} \quad (16)$$

$$(X_{ij1}, Y_{j1}) \ \varepsilon \ \{0, 1, 2\} \quad (17)$$

$$Y_{j1} \leq Y_{j2} + 1 \quad (18)$$

For any set of multipliers μ_{ik}, the formulation (Equations 12–18) determines a valid bound on the primal problem (Equations 6–11). The binary requirement for first-level assignments and facilities are relaxed in Equations 17 and 18 to make the dual easier to solve. For a fixed set of multipliers, the dual problem is solved as follows:

Define

$$E_{j1} = \sum_{i=1}^{n} \min(0, a_{i1}d_{ij} - \mu_{i1}) \quad \text{and} \quad (19)$$

$$E_{j2} = E_{ji} + \sum_{i=1}^{n} \min(0, a_{i2}d_{ij} - \mu_{i2}) \quad (20)$$

Determine the P_2 smallest E_{j2} values and $P_1 - P_2$ smallest E_{j1} values; add the sum of these E_{jk} values just determined to the sum of the multipliers, and the value of the dual is determined. The solution of the dual may not be primal feasible, but a feasible completion of this dual solution is easily constructed using E_{jk} values. For any set of multipliers μ_{ik}, a valid lower bound is determined and a feasible completion is available that can be compared to the best primal solution found so far (by the exchange heuristic or the bounding procedure). The task then is to determine a set of multipliers that maximizes the dual lower bound. This procedure can be accomplished by subgradient optimization as in Narula et al. (*5*) or Weaver and Church (*8,9*). The bounding procedure is terminated when the lower bound is within a specified tolerance of the best primal value identified or after a fixed number of interactions. When the exchange heuristic followed by Lagrangian bounding was used to solve the highway district and division office location formulations, optimal or near-optimal solutions were always obtained.

APPLICATION OF *p*-MEDIAN METHODOLOGY

An example will be given to illustrate one use of modeling in examining the location of field offices. In this case, the *p*-median study was used for two purposes: (a) to evaluate the optimum number of division offices in Alabama and (b) to identify the best locations for these offices. In Alabama, the lower-level facilities are called district offices. Typically, three to six districts report to a division. Currently, the Alabama Highway Department has nine division offices.

Operation of the Model

For this study, the higher-level service facilities were division offices. The lower-level service facilities were district offices. The accessibility function was defined as the distance in miles between the various county seats in the state.

The physical distances between county seats were weighted by various factors that were felt to possibly influence highway maintenance costs and the level of service for maintenance. Factors that were examined in this trial study included centerline miles of state route, lane-miles of state route, vehicle-miles of travel, Alabama Highway Department historical maintenance cost records, population density, and income per capita. A series of constraints were also devised to simulate geographical and other real-world situations (indirect travel routes caused by rivers or mountains, spatial development patterns, etc.).

The model was operated separately with each of the parameters used to weight the accessibility of field office locations. The model was run many times for each parameter to determine the effect of increasing or reducing the number of field offices. Typically, scenarios were tested starting with four division offices around the state and progressing until 10 or 12 division offices had been studied. In each case, the optimum locations of division offices were plotted and the value of the objective function was tabulated for further study.

Results of *p*-Median Study

The *p*-median technique was used to establish an optimum number of division offices by tabulating the objective function from a series of computer runs. Adding more division offices reduces total travel because each district office becomes closer to a division office. At some point, so many division offices will have been added that there is almost no change in overall travel. This effect is shown in Table 1 and on Figure 1. The researchers examined the marginal change in the objective function as a technique for determining the best number of division offices. From Figure 1, a level of efficiency was noted after seven offices had been placed in the state because the marginal change reached a plateau. When there were seven, eight, or nine divisions in the state, the marginal change in objective value was relatively constant at about 4 percent. However, as a 10th office was added, the marginal change dropped drastically to about 2 percent, where it reached a new plateau. The drop from 4 to 2 percent indicates that exceeding nine division offices would not be as effective in minimizing travel as additions up to that time.

The effectiveness of adding additional division offices is highly dependent on the shape and density of the road network. Once the road network is in place, the optimum location for maintenance offices becomes a matter of minimizing travel over this network. In urban or semiurban locations where there are many miles of roads and alternate routes, the model will examine multitudes of locations to find the optimum travel configuration between offices. In underdeveloped rural areas, there will be few trial locations and the model can quickly choose the optimum locations.

When determining the optimum number of locations for offices, the marginal change curve (Figure 1) is usually balanced against the cost of division offices to find an optimum value for number of field offices, such that the cost for construction of the offices and the overhead for running them when combined with the operating cost of maintaining roads has reached a minimum value. This point may be found through an analytical analysis or by simply combining a plot of the change in objective value with a plot of the cost for adding new division offices.

TABLE 1 CHANGES IN OBJECTIVE VALUE FOR INCREASES IN THE NUMBER OF DIVISION OFFICES

Number of Division Offices	Objective Value	Marginal Change
4	423,946	--
5	378,984	- 10.6%
6	353,995	- 5.9%
7	335,848	- 4.3%
8	318,685	- 4.0%
9	302,873	- 3.8%
10	291,821	- 2.3%
11	281,244	- 2.3%
12	271,919	- 2.0%

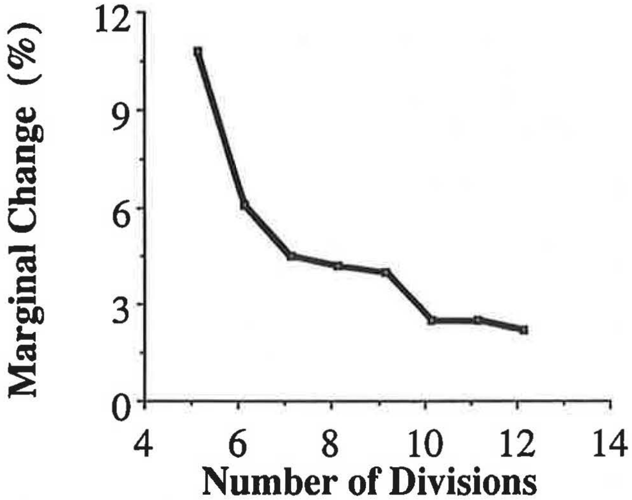

FIGURE 1 Marginal change in objective values.

Optimum Office Locations

Two figures indicate the results of *p*-median studies. Figure 2 shows the search for the optimum number of division offices. Figure 3 shows the effects of using several weighting factors to modify the distances between service facilities to reflect the attractiveness of some sites over others.

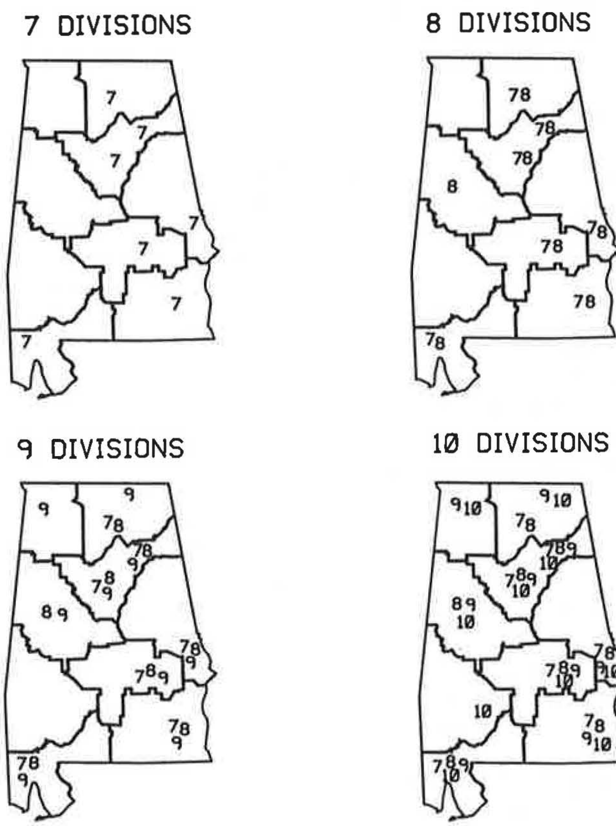

FIGURE 2 Existing division boundaries and changes in optimum locations with increased offices.

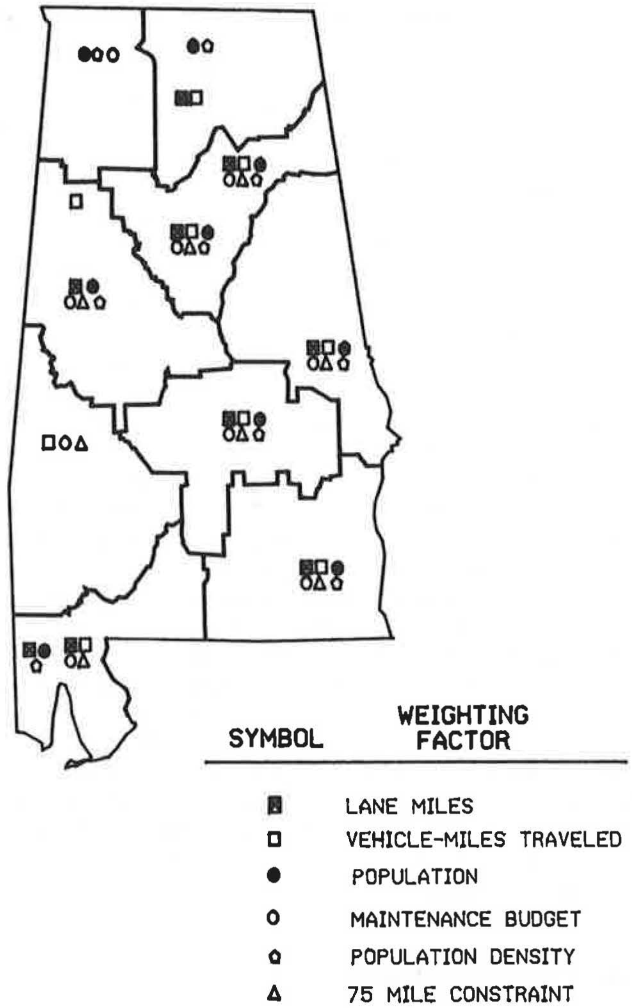

FIGURE 3 Existing division boundaries and optimum locations for nine division offices.

Number of Division Offices

The model can be used to determine the optimum locations for any given number of division offices. The number of offices can be varied through several scenarios to measure the effectiveness of various levels of field offices. This method can be used to find the best number of offices by examining marginal changes in objective value. Another use for such a study is to analyze the growth of field offices, in response to historical changes in population, miles of road, and other factors. This type of study is shown in Figure 2.

The fitness of any particular location for an office can be assessed by noting when it first appeared in the solution set, and how consistently the location remained in the solution set from scenario to scenario. Figure 2 shows a series of scenarios seeking the optimum locations for 7 to 10 division offices, using population as the weighting factor. After the modeling had been completed, six locations were found to have been assigned division offices for all scenarios. These sites might be considered excellent candidates for permanent division offices. One other location was assigned division offices in three of the scenarios and would also be considered a good permanent site. Three additional locations received division offices in two of the scenarios, while one site was only assigned an office in one scenario. The modeling process could be extended by increasing or decreasing the number of offices until the user obtained a good feel for the situation being studied and the attractiveness of various sites as possible field office locations.

Adding division offices in consecutive scenarios provided a step-by-step picture of the expansion of the highway agency. Experienced highway managers assisted the research staff in understanding the results of the modeling by recalling the historical additions of offices and relating these changes to factors like population growth, construction of new roads, etc.

Each scenario must be examined in detail during the evaluation process. Drastic changes may occur between consecutive computer runs. For example, going from seven field offices to eight offices is not as simple as choosing the best site for the next office. It may involve changes to many of the previous locations in order to accommodate the added division office. For example, adding a new office at the north end of a state may squeeze the remaining offices toward the south end of the state to balance travel among all offices. If a state already had seven field offices, the model may indicate that six of the existing offices should be relocated to add an eighth office. Although the model showed eight offices to be the best number and the most efficient arrangement, the highway agency would have to close and reconstruct so many existing offices that the net result would not be cost effective. The user must interpret the model carefully to understand its limitations and implications.

Alternate Weighting Factors

It would be ideal if a single factor could be identified that always measured the effectiveness of alternate locations of maintenance offices. Where such a direct measurement or a surrogate measurement existed, it would be relatively simple to choose optimum locations. In the real world, a single factor can rarely be identified, and usually many possible influences (weighting factors) are considered for use in choosing office locations. Figure 3 shows one possible way to study surrogate measures of effectiveness both individually and in combination with other factors.

Figure 3 was prepared by formulating a scenario, then changing the weighting factors between consecutive computer runs. The optimum locations were plotted for each factor, then compared visually.

Figure 3 can be further analyzed to determine the role of each of the parameters used as weighting factors. For example, using current population values in each county as the weighting factor would yield a set of optimum locations. Next, miles of vehicle travel in each county could be used as the weighting factor and another set of offices identified. The two sets could be compared to each other and to the locations of existing field offices to evaluate the applicability of the factors and to calibrate the model. Large numbers of weighting factors could be tested to increase the effectiveness of the model.

When certain parameters are found to be reasonable surrogates for measuring the effectiveness of maintenance office locations, future values of the parameters could be investigated. The model could use estimated future values to show the effects of population growth, increased vehicle travel, or decreased maintenance budgets. The results of such scenarios can be used in planning future field office configurations of the highway agency.

A further illustration of the versatility of the model is shown on Figure 3. An artificial constraint was created to require that all district offices be located within 75 mi of a division office. This provided a way to reasonably minimize travel times for employees. For the case of nine division offices, the model was able to place the offices in locations that met the constraints. However, the constrained locations were in much different places from those selected by any other modeling effort. When the constraint was changed to 60 mi, finding nine locations that met the criteria was impossible. The model could have easily been expanded to study 100-mi constraints or other conditions. Such modeling provides background information to assist highway managers in making decisions regarding locating new field offices.

Summary of Examples

Two examples have been briefly presented to illustrate the modeling process and the types of results that may be expected. Both examples make it apparent that a scenario may be tailored to fit the local situation, and many conclusions may be drawn from the examples by careful study. Such adaptation may yield insights into the best locations for both existing and future field offices.

RESULTS

The purpose of the *p*-median modeling was to identify possible changes to increase efficiency in the location of high-level field maintenance offices of the Alabama Highway Department. The modeling was successful in defining one location that was a strong candidate for a new office, and in defining several existing offices that would be more efficient if relocated.

Following the *p*-median study, the researchers performed an intensive analysis of the travel savings provided through adoption of the new and relocated offices. This analysis was performed by an intensive, more conventional model that tracked travel to and from each roadway segment in a division. This second model provided quantitative estimates of travel savings; however, it was labor intensive and consumed huge amounts of computer time. The second model could not have been used to study all possible changes, but it did not have to be used in that manner because the *p*-median model had already defined the most realistic scenarios.

According to the final results of the research project, a new division office was not cost effective. Because a relocation of one division office with a consequent realignment of the boundaries of three affected divisions was found to be cost effective, the Alabama Highway Department is moving toward implementation of this latter recommendation.

CONCLUSION

The *p*-median model is widely used in the business industry to study the attractiveness between service facilities and the audience receiving services. The model has had demonstrated success in selecting optimum locations for business and government facilities, and it may be readily adapted to the highway field office problem.

The *p*-median model is easy to formulate, easy to calibrate, and relatively inexpensive to run. Many alternative scenarios may be examined quickly once the model has been formulated.

There are certain limitations to using the model. Surrogate measures must often be studied when directly measuring the effectiveness of office locations is impossible. The accuracy of conclusions drawn from use of the model may be limited by the appropriateness of the weighting factors and by the resourcefulness and experience of the persons interpreting the results.

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