Efficient Personnel Management for Winter Highway Maintenance

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The focus of this research was the development of a model for addressing the problem of reassignment of snow removal personnel for the LaPorte District Office of the Indiana Department of Highways. This consists of assigning transfer personnel to winter snow removal routes so as to minimize the total distance that the workforce as a whole must travel to work during snow emergencies while keeping to a minimum the number of state-owned vehicles that must be issued for this purpose. During the course of this work, a third objective was identified, which addressed the issue of equity in assignment strategy. A methodology was developed for determining a feasible assignment strategy that minimized the maximum distance that any individual would be required to travel to work. The result of this work is a microcomputer-based model that can greatly improve personnel management strategies for winter highway maintenance operations. The model structure, solution procedure, and interpretation of model results are discussed.

The maintenance of the nation's highway system requires personnel trained in the use of a wide range of equipment. The efficiency of operations such as road surface repair, painting and labeling, mowing and weed control, and signal maintenance depends in part on the manner in which these personnel are assigned to job sites. This is particularly important in developing a strategy for winter snow and ice control, where the public safety depends on a rapid mobilization of the workforce.

Winter snow and ice control is extremely labor intensive. Because of an insufficient number of permanent maintenance personnel to staff all routes, snow and ice control operations for most of the northern states require a seasonal reassignment of personnel from summer activities such as construction inspection and materials testing to winter snowplow operation. This avoids the problem of seasonal hirings and firings but may disrupt normal work patterns, because workers may be assigned to work out of different site locations for the winter season. Most important, the way in which these job reassignments are made may have a dramatic effect on the overall cost and efficiency of snow and ice control.

When up to 150 persons must be reassigned to up to 20 different job sites, each with an expected demand for workers, the problem of determining an efficient assignment strategy becomes severe. First, the number of possible different assignment strategies is extremely large. Second, there may be multiple and conflicting objectives in developing criteria for judging a particular assignment strategy. Finally, the use of sophisticated operations research techniques for aiding the design of assignment strategies may not be justfied on the basis of the computational requirements of such models; until recently, optimization procedures capable of solving such management problems required expensive computer hardware and software as well as specialized expertise in modeling.

The design and development of a model for aiding maintenance engineers in making decisions about personnel reassignment are described. The model was developed for the Indiana Department of Highways for use in staffing distributed site locations with sufficient personnel to conduct winter roadway maintenance. The model is small enough to be solved by using modern microcomputer technology and can be used by managers with little or no previous experience in systems modeling. In addition to generating efficient solutions to the personnel reassignment problem, the model also provides valuable and explicit information about the quality of any particular solution.

After a brief overview of related research, the specific problem addressed by this work will be presented. The general structure of the model developed to solve this problem and a discussion of interpreting the model results will be presented. Readers interested in a more detailed discussion of model design and solution procedure are referred to work by Wright et al. *(1)*, and those wishing more information about the microcomputer implementation of the model may wish to see work by Wright and Egly *(2)*.

MODELING SNOW AND ICE CONTROL MANAGEMENT

The removal of snow and ice from the nation's highways is an expensive undertaking. For example, clearing of state-maintained roads cost an estimated $334 million in 1976 *(3)*. Considering the expenditures involved, small improvements in operational procedures and the selection of appropriate alternatives can produce substantial savings. As stated by Minsk *(4)*, "Decision makers need better information and methodology to make economic determinations of snow-removal system operation and effectiveness."

Snow and ice removal operations have occasionally been studied from the broad systems perspective. Minsk *(4)* identified many of the parameters pertinent to establishing a framework for the systematic management of snow removal activities. Climatic elements, traffic quantities, equipment capabilities, and the road network were all included in the system description. Personnel management practices, however,

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were left outside the system boundary. In another study *(5)*, a statewide snow and ice control program was dissected into small functional parts. These portions were examined for potential cost savings, and one area, the analysis of various staffing and shift arrangements, was given a high probability of success; improved personnel management could produce an estimated 5 percent reduction in staff expenditures. Responsibility for personnel scheduling was delegated to district-level administrations. The topic was targeted for further research but no concrete suggestions for improvements in the area were offered.

Much of the research related to snow and ice removal operations has focused on the design of optimal snowplowing and chemical-spreading routes. Simulation *(6,7)*, mathematical programming *(8)*, and graph theory *(9)* techniques have all been applied to this portion of the problem. Although this is an interesting topic, routing solutions are not particularly relevant to the reallocation of the work force unless these solutions alter route structures to the extent that the demand for snow and ice removal personnel shifts from one site to another.

Cifelli et al. *(10)* developed parameters and equations to estimate the manpower and equipment requirements of road-clearing operations. These formulas were designed to provide for equitable allocation of existing equipment from the service-level perspective. The number of employees needed to maintain a highway network and the cost of such operations could be estimated through the application of these equations, which considered not only the base manpower requirements of the equipment involved, but also employee benefit time and personnel attrition rates. Provisions for allocating these personnel were not part of that research; the reassignment or transfer of employees was not considered.

Manpower scheduling and allocation separate from the issue of snow and ice removal has been studied within the private sector on a much larger scale. United Airlines *(11)*, for example, developed the Station Manpower Planning System (SMPS) in 1983. This system combined integer and linear programming with network optimization techniques to develop work schedules for 4,000 employees, approximately 8 percent of United Airlines' work force. Although the model addressed the reallocation of excess manpower, this issue was but a small part of a much larger scheduling problem. With the support of several subordinate elements, the SMPS scheduling module solved a matrix of around 5,000 columns, 1,000 rows, and 20,000 elements on an IBM 9081 computer. Thus, the solution techniques employed were not suited to the microcomputer environment.

On a smaller scale, Baker et al. *(12)* considered manpower allocation in terms of cyclic shift scheduling. The problem was to find the minimum number of employees needed to staff a job where the demand for personnel changed in a cyclic pattern. Shifts ran for 8 hr and manpower requirements changed every 4 hr. An algorithm was developed that allowed the generation of solutions "by hand" for small problems. Cyclic shifting cannot, however, be extrapolated to account for personnel requirements that change seasonally.

Satpute *(13)* developed the model Personnel Allocation using Linear Programming (PALP) in the late 1970s. This formulation could be used to assign individuals, grouped into "employee categories" on the basis of their qualifications, to tasks requiring specific skill levels. Associated with the tasks were estimates of the time to job completion and the number of personnel required. Costs (matrix elements) were developed for the assignment of individuals from various skill categories (rows) to specific jobs (columns) and the formulation was driven by a "minimize cost" objective. The model was developed in general terms and could be applied to a broad range of assignment problems. Models such as PALP may become very popular in the microcomputer era.

Even before microcomputer technologies advanced to their present level, researchers began to investigate the issues associated with moving large programs to small machines. Rooney et al. *(14)* examined the problem on the basis of storage, translation, and economic issues. This was, however, an extreme example. A large program was transferred to an intentionally undersized microcomputer system. Storage problems were a major focus of the work, but translation difficulties relating the essential differences between the FORTRAN and BASIC programming languages were also highlighted. A conclusion was that "squeezing large codes onto small machines is now [1982] governed by economics, not necessity."

Some of the concerns involved in moving linear programming software to microcomputers were enumerated by McKay *(15)*. Although this work did not deal with a specific example, it did provide a reminder that different algorithms, while all falling under the general heading of "linear programming," can have very different storage requirements. If the revised simplex is selected over the full-tableau method, for example, storing the inverse matrix in the form of eta vectors and using decomposition techniques to limit the size of these vectors may reduce storage requirements to about 10 to 20 percent of that required to store the explicit inverse. McKay *(15)* estimated that "it would be reasonable to expect a capacity of up to about 150 rows on a machine with an address limit of 64kb and a hardware floating point unit." Finally, in a direct reference to microcomputer technology, McKay states: "Prices of hardware are now sufficiently low that it is usually cheaper to buy a machine of suitable size rather than to spend a great deal of effort in fitting a program into a smaller machine."

Since their emergence some 15 years ago, microprocessor-based computers have drastically changed the potential for integrating analytical models into the public decision-making process. Indeed, advances in computer technology have not ceased to accelerate during this period. Today modern microcomputers far exceed the capabilities of the multimillion-dollar mainframe computers of the early 1970s. Furthermore, research in the areas of hardware architecture *(15)*, networking *(16)*, and artificial intelligence and knowledge-based systems *(7)* suggests that the past influence of computers may be small compared with what might be expected in the future.

These developments will bring new capabilities to a wide range of the public sector at a time when new levels of efficiency are essential. However, hardware is only one side of the issue; the full impact of this technological surge will not be felt until the applications software is available. As Minsk *(4)* pointed out: "System optimization by computer modeling needs further work and refinement and translation into a practical format for wide use by large and small winter maintenance organizations."

OPTIMIZING WINTER PERSONNEL ASSIGNMENTS

The responsibility for the removal of snow and ice from the Indiana Interstate highway system during the winter lies with the Indiana Department of Highways (IDoH). Maintenance operations are conducted out of six separate district offices, each having up to three subdistrict offices *(17)*. Available winter maintenance personnel are assigned to one of up to 20 site locations where vehicles and other equipment are housed. Plowing and abrasive-spreading routes emanate from these facilities.

The assignment of workers to site locations is guided by two related objectives. First, it is desirable that workers be assigned to sites so that the total distance traveled by all workers to all job sites is as small as possible. If the distance that a worker must drive is great, it is possible that he or she might be unable to report to work in extreme emergency conditions. The second major objective in snow and ice control is one of equity; it is desirable to provide a uniform level of service throughout the service area and to distribute the workload as evenly as possible among the work force. This objective is achieved if the distance traveled by each worker to his or her job assignment is close to that of other workers or if the distance traveled by the worker traveling farthest is as small as possible (minimizing the deviation in travel distances may result in assignments to distances greater than necessary or, in some cases, assignments where workers are passing each other on the way to the job site).

In addition to these two major objectives, the design of efficient reassignment strategies must observe resource limitations. A major resource limitation to winter maintenance for IDoH is the availability of state-owned vehicles that can be issued to workers. The policy of IDoH is that if a person is assigned to a site that is not the closest site to his or her home station, and if that is more than 15 mi away, that person must be given use of a state-owned vehicle (see Figure 1). It is important that any reassignment strategy adhere to this policy and still observe a limit on available vehicles.

The personnel reassignment problem may be stated as follows: Find that strategy for the reassignment of summer personnel to snow removal units during the winter such that the total distance traveled by all workers to their respective job sites is as small as possible while keeping the maximum distance traveled by any one worker as small as possible and that requires the issuance of no more vehicles than are currently available. The problem may be complicated by other factors such as worker seniority or other concerns that restrict the range of sites to which an individual worker may be assigned. An effective management tool must be able to accommodate such contingencies.

A technique has been developed for solving the personnel reassignment problem. The methodology employs multiobjective optimization to generate a tradeoff relationship between the objectives of minimizing total travel distance and minimizing maximum travel distance. Demand for workers at each job site and limitations on vehicles are treated as system constraints. The model is solved using a variation of the constraint method of multiobjective optimization discussed by Cohon *(18)* and has thus been titled Systematic Analysis of Noninferior Transfer Assignments (SANTA).

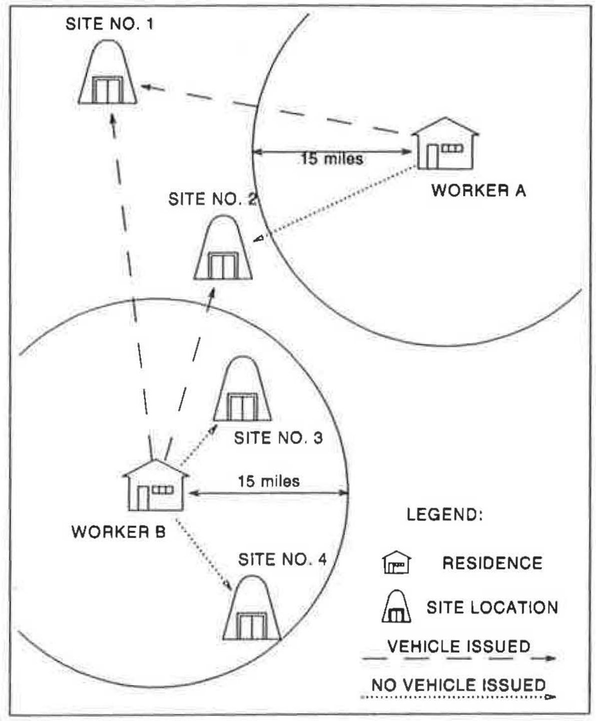

FIGURE 1 Schematic representation of IDoH vehicle assignment policy.

The formulation for the personnel reassignment problem that minimizes maximum travel distance is presented in Table 1. Let *DMAX* be a decision variable representing the maximum travel distance at optimality. The objective function (Equation 1) seeks the assignment strategy that makes this as small as possible. *DMAX* is actually defined by Equation 2, which ensures that *DMAX* is at least as great as each assigned travel

TABLE 1 MODEL FORMULATION FOR MINIMIZING MAXIMUM DISTANCE

$$\text{Minimize } Z = DMAX \quad (1)$$

$$\text{s.t.} \quad DMAX - \sum_{j \in N_i} d_{ij} x_{ij} \geq 0 \quad \forall i \quad (2)$$

$$\sum_{j \in N_i} x_{ij} \leq 1 \quad \forall i \quad (3)$$

$$\sum_{i} x_{ij} \geq T_j \quad \forall j \quad (4)$$

$$\sum_{i} \sum_{j \in N_i} A_{ij} x_{ij} \leq C \quad (5)$$

$$x_{ij} = \{0,1\} \quad \forall i, j \in N_i \quad (6)$$

where:

$A_{ij} = \begin{cases} 1, \text{ if the assignment of worker i to unit j requires a vehicle} \\ 0, \text{ otherwise} \end{cases}$

C = Number of vehicles available fo assignment

D = Maximum allowable travel distance

DMAX = The maximum assigned travel distance

d_{ij} = The distance worker i would travel if assigned to unit location j (miles)

i = The index on workers

j = The index on jobsites

$N_i = \{j \mid d_{ij} \leq D\}$

T_j = Demand for workers at unit location j

$x_{ij} = \begin{cases} 1, \text{ if worker i is assigned to unit j} \\ 0, \text{ otherwise} \end{cases}$

distance $d_{ij}x_{ij}$ when $x_{ij} = 1$ and therefore equal to the largest. Note that the only eligible assignments are those that would require travel of distances shorter than some absolute maximum regardless of whether a state vehicle is assigned. Equation 3 restricts an assignment from being made more than once,

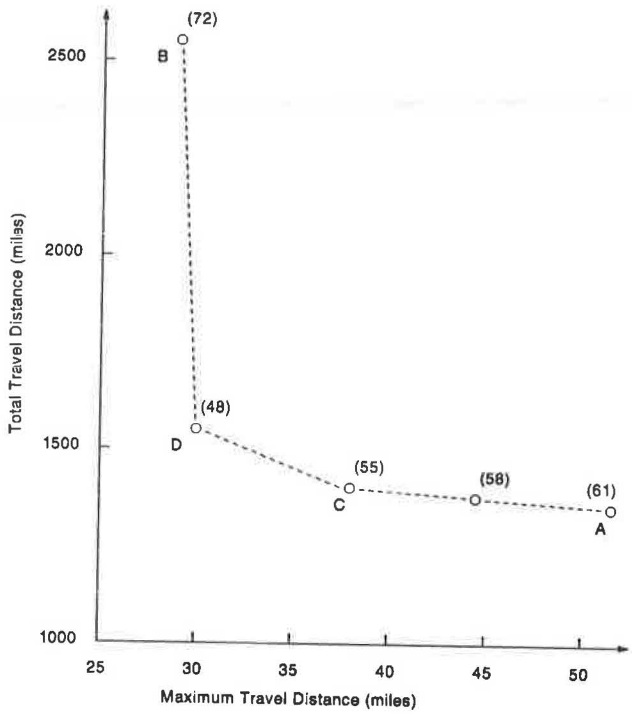

FIGURE 2 Tradeoff curve for distance objectives.

whereas Equation 4 ensures that demand for workers at each job site is met. Equation 5 is included to prevent the use of more state-owned vehicles than are available. Equation 6 imposes integrality restrictions on the solution space.

A similar model formulation may be used to address the problem of minimizing maximum travel distance [see report by Wright et al. *(2)*] and together a tradeoff relationship between these two objectives may be generated. An example of this relationship is presented in Figure 2. Each point on the curve in Figure 2 represents a unique personnel assignment profile. Endpoints of the curve represent solutions that result in the shortest overall travel distance (Point A) and shortest maximum travel distance (Point B), whereas the interior points are compromise solutions. The numbers adjacent to each solution indicate the number of vehicles required for that solution. By knowing that the points presented in such a figure represent all efficient solutions, the maintenance engineer responsible for snow control may select the solution that best represents his objectives in personnel management (Figure 2).

INTERPRETATION OF MODEL RESULTS

The SANTA model as implemented in a microcomputer environment *(2)* can be used to generate efficient personnel reassignment strategies like those presented in Figure 2. Each point on the graph of "noninferior" solutions represents a specific personel assignment profile with a unique cost and pattern of resource use. For each solution, a complete multipage assignment report is provided. Figures 3–5 and Table 2 present an example of these assignment reports, the report from the solution corresponding to Point C on Figure 2.

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             DISTANCE SUMMARY                          VEHICLE SUMMARY
             -------- -------                          ------- -------

     MAXIMUM ALLOWED =     38.0              STATE VEHICLES:
                                               NUMBER AVAILABLE:       55
      TOTAL DISTANCE =   1853.1                TOT. ALLOCATED =        55
                                               TOTAL DISTANCE =    1405.0
    AVERAGE DISTANCE =     14.8                AVERAGE DISTANCE =    25.5

    MAXIMUM DISTANCE =     38.0              PRIVATELY OWNED:
                                               TOTAL DISTANCE =     448.1
        DEV DISTANCE =     38.0                AVERAGE DISTANCE =     6.4

                               ONE-WAY DISTANCE PROFILE

          INTERVAL 0    5    10   15   20   25   30   35   40   45   50
 TOTAL    (miles)  +--------------------------------------------------+
                   |         |         |         |         |          |
 (36)     0 -  5   |PPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPP       |    .     |
 (17)     5 - 10   |PPPPPPPPPPPPPPPPP .    |    .    |    .    |    .     |
 (17)    10 - 15   |PPPPPPPPPPPPPPPP*     |    .    |    .    |    .     |
 (18)    15 - 20   |P*****************    |    .    |    .    |    .     |
 (13)    20 - 25   |*************    .    |    .    |    .    |    .     |
 ( 6)    25 - 10   |******   |    .    |    .    |    .    |    .     |
 ( 9)    10 - 15   |*********|    .    |    .    |    .    |    .     |
 ( 9)    15 - 40   |*********|    .    |    .    |    .    |    .     |
                   +--------------------------------------------------+
                   0    5    10   15   20   25   30   35   40   45   50

                        NUMBER OF EMPLOYEES IN EACH INTERVAL

                              P - PERSONAL VEHICLE
                              * - STATE VEHICLE
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FIGURE 3 Assignment summary statistics format.

POSSIBLE ALTERNATE ASSIGNMENTS

Baillieul R	to UNIT 4301	Lietzan W	to UNIT 4501
Bell B	to UNIT 4301	Ludwig J	to UNIT 4502
Carey R	to UNIT 4101	Rynearson K	to UNIT 4103
Ewing R	to UNIT 4102	Standifer L	to UNIT 4702
Gastineau D	to UNIT 4402	Stigen L	to UNIT 4102
Kinsey M	to UNIT 4202	Strom J	to UNIT 4701
Leinbach E	to UNIT 4501	Weatherwax K	to UNIT 4201

FIGURE 4 Alternative assignments report format.

The first page of each report (Figure 3) presents a summary for the current solution for the districtwide solution. The Distance Summary presents statistics that may be of interest to the personnel manager, including the maximum travel distance allowed by the model, the total (one-way) travel distance by all workers, the average travel distance, the maximum travel distance assigned by the model, and the maximum deviation in distances (the difference in travel distance between the worker who travels the farthest and the one who travels the shortest distance to work). The Vehicle Summary provides summary information about the requirements for state-owned vehicles dictated by the current solution in comparison with privately owned vehicles. At the bottom of the first page of output, a histogram showing the overall assignment profile is provided indicating the distance frequency for the current assignment. The assignment summary provides the decision maker with an efficient means of comparing different assignment strategies.

The second page of the assignment report (Figure 4) provides a list of possible alternative assignments that were "discovered" by the solution process *(1)*. For example, with the current solution, it would be possible to make an assignment for worker Carey (to Unit 4101) that is equally as good as his current assignment (Unit 4302 from Table 2). Finding this new assignment profile would require rerunning the SANTA model and "fixing" worker Carey to Unit 4101, a capability that is available with this model. The list of possible alternative assignments is provided so that the personnel manager may exercise some degree of subjective judgment in making assignments without drastically changing the quality of the overall solution.

The actual personnel site assignments are listed beginning on the third page of the assignment report form (Table 2). This is simply an alphabetical listing of workers, their site assignments, and mileage to work and an indication as to whether a vehicle must be assigned. The same information is provided organized by subdistrict and unit location (Figure 5).

The overall assignment report is provided for each feasible solution determined by the model. The model is designed to be executed on an IBM PC/XT or AT running the DOS 3.0 operating system and supported by a math coprocessor

TABLE 2 JOBSITE ASSIGNMENT REPORT FORMAT

ASSIGNMENT REPORT

	EMPLOYEE	UNIT	MILES		EMPLOYEE	UNIT	MILES
*	Allen K	4102	19.0	*	Howard H	4502	21.0
	Alverez A	4701	9.0	*	Hudson M	4102	34.0
	Arens B	4103	4.0	*	Insco F	4501	28.0
*	Armstrong D	4702	24.0		Jacks R	4103	1.0
	Atkinson T	4202	2.0		Jackson J	4701	9.0
	Baillieul R	4602	1.0		James L	4601	15.0
	Baker D	4302	7.0	*	Johnson B	4702	32.0
	Barta M	4701	11.0		Johnson R	4701	11.0
*	Bell B	4302	29.0		Jones J	4701	9.0
*	Berg K	4702	37.0		Jones T	4701	9.0
*	Bohm D	4102	34.0	*	Kemp J	4702	16.0
	Bradfield R	4702	16.0	*	Kinsey M	4201	22.0
	Brown K	4101	12.0		Kroening R	4103	1.0
*	Cain E	4402	21.0	*	Kruzick C	4102	34.0
*	Carey R	4302	29.0	*	Lamb M	4301	36.0
	Chrzan R	4302	3.0		Lane K	4302	12.0
*	Collins M	4702	24.0		Larson C	4701	1.0
	Crane S	4101	1.0		Leinbach E	4102	10.0
*	Dalka C	4501	32.0	*	Lemay R	4502	21.0
	Donovan P	4302	2.0		Lemons E	4701	10.0
	Edging S	4301	4.0		Lestinsky S	4101	5.0
*	Egolf B	4702	27.0	*	Lietzan W	4502	16.0
*	Ekovich A	4502	15.0		Link H	4101	1.0
*	England W	4502	21.0	*	Lorenz R	4501	37.0
	Epley B	4502	5.0		Lotter R	4101	1.0
	.	.	.		.	.	.
	.	.	.		.	.	.
	.	.	.		.	.	.

* State Vehicle Issued

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                    SUMMARY FOR SUBDISTRICT 4500

UNIT:  4501      DEMAND:    7             SUBDISTRICT LISTING
----------------------------              -------------------
 1. * Dalka C                32.0          1. Dalka C          4501
 2. * Henrichs G             28.0          2. Ekovich A        4502
 3. * Insco F                28.0          3. England W        4502
 4. * Lorenz R               37.0          4. Epley B          4502
 5. * Marshall W             37.0          5. Hammons J        4502
 6. * Mougin M               36.0          6. Henrichs G       4501
 7. * Ropp W                 30.0          7. Henry L          4502
                                           8. Howard H         4502
                                           9. Insco F          4501
                                          10. Lemay R          4502
UNIT:  4502      DEMAND:   12             11. Lietzan W        4502
----------------------------              12. Lorenz R         4501
 1. * Ekovich A              15.0         13. Marshall W       4501
 2. * England W              21.0         14. Mougin M         4501
 3.   Epley B                 5.0         15. Pope J           4502
 4. * Hammons J              21.0         16. Ropp W           4501
 5. * Henry L                21.0         17. Rundzaitis A     4502
 6. * Howard H               21.0         18. Rynearson K      4502
 7. * Lemay R                21.0         19. White D          4502
 8. * Lietzan W              16.0
 9.   Pope J                  4.0
10.   Rundzaitis A            5.0
11. * Rynearson K            21.0
12.   White D                 3.0
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FIGURE 5 Unit-specific assignment report format.

TABLE 3 EVALUATION OF MODEL RESULTS

Item	Season	
	1983–1984[a]	1984–1985[b]
Personnel	85	118
Vehicles	75	48
Total distance (mi)	2,017	1,540
Maximum distance (mi)	56	30
Average Distance (mi)	24	13

[a]Solution used for the 1983–1984 winter season developed without the SANTA model.
[b]Solution used for the 1984–1985 winter season developed using the SANTA model.

[optional but very important for reasonable performance *(19)*]. Each solution requires approximately 15 min of running time *(2)*. Experience has shown that the entire noninferior solution for a given assignment problem may be generated by using SANTA in a matter of a few hours, even by an inexperienced user.

A dramatic indication of the value of the information provided by SANTA is provided in Table 3. Several assignment parameters are presented for each of two actual personnel assignments; the first, the 1983–1984 assignment for an IDoH district office and the second, the 1984–1985 assignment for the same district office. The 1983–1984 assignment strategy was generated manually, without the aid of a model of any kind, whereas the 1984–1985 solution was incorporated directly as generated by SANTA. (This solution corresponds to that indicated by Point D on Figure 2.) Though the requirements for personnel were different (85 in 1983–1984 compared with 118 in 1984–1985), the overall improvement in assignment effectiveness is clear. It has been estimated that the overall cost savings to the state were approximately $100,000 during the winter season for this single district alone *(1)*. Since that time, the model has been used by other district offices with similar results. Work is currently under way to link the model to a personnel database with the intent to help manage operations on a weekly or biweekly schedule.

CONCLUSIONS

The SANTA model has proven successful in its ability to aid personnel managers in making important decisions about the reassignment of summer highway construction workers to winter maintenance operations in the state of Indiana. The model is easy to use and able to be supported by relatively inexpensive computer hardware. Most important, SANTA provides the decision maker with an explicit indication for the range of choice available to develop useful personnel reassignment strategies.

Beyond the identification of efficient assignment strategies, SANTA may also be used to justify those strategies by its ability to give an explicit indication of the inferiority of other solutions. For example, the user may wish to demonstrate how the current solution is better than some other solution by running SANTA in a mode that allows specific assignments to be made. Still other possible uses for the model would be in personnel hiring decisions or to aid in making decisions about modifications to existing route designs and related demand for personnel.

Modern computer technology has advanced to the point where sophisticated modeling algorithms can be made available to decision makers at remote locations in a cost-effective manner. The SANTA model is an example of the successful incorporation of such technology into the arena of highway maintenance operations.

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