Evaluation of Computer-Generated Routes for Improved Snow and Ice Control

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A route design decision support system was developed for maintenance engineers of the Indiana Department of Transportation (INDOT) to use in designing snow and ice control service routes. This system, known as CASPER—Computer Aided System for Planning Efficient Routes—incorporates a multiple objective heuristic optimization procedure to identify routes that have excellent serviceability and efficient resource usage. Routes designed using CASPER were placed into service and carefully evaluated by INDOT maintenance officials. The evaluation showed a significant improvement in network service and, at the same time, a 10 percent reduction in the size of the service fleet required. Cost savings to date are conservatively estimated at $5 million and are expected to exceed $14 million projected over a 10-year period when the system is implemented statewide.

The efficiency of Department of Transportation (DOT) winter maintenance activities depends, to a large degree, on the routes the maintenance personnel use to conduct these important operations. The snow route design problem faced by most DOT maintenance engineers may be characterized as follows:

> Given a partition of the transportation network to be serviced using resources issued from a single depot located on that partition, find the noninferior set of configurations for N service routes that collectively service that network partition.

Recent research aimed at improving the configuration of winter service routes for the Indiana Department of Transportation (INDOT) demonstrated that significant cost savings may be realized through the systematic integration of operations research methodologies with spatial network data [geographic information systems (GIS)] to solve this routing problem (*1*).

The decision support system that was developed to address the snow vehicle routing problem is called CASPER—Computer-Aided System for Planning Efficient Routes. Upon completion of the CASPER system prototype in the fall of 1992, a systematic testing procedure was started in early 1993. Through this process, INDOT maintenance engineers used CASPER to produce detailed snow route designs for a portion of the transportation network that was previously serviced by 430 service vehicles. The new route configurations produced using CASPER for the same service area required only 396 service vehicles. The new routes were put into service during the 1993–94 snow season and were shown to provide significantly better service than the original routes.

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WINTER NETWORK MAINTENANCE PROBLEM

Maintenance operations within INDOT are administered from six district offices, each of which is further divided into five or six subdistricts. Each subdistrict oversees operations that are conducted from five to six service depots (also called units). Each unit is responsible for providing service to a portion of the network using a fleet of trucks, each servicing a specific route. Logistically, route designations may be quite complicated and interrelated. For example, consider a small hypothetical service area that is to be serviced using two vehicles, as shown in Figure 1. Two different routes are shown: a black route and a gray route. Service travel for both routes is shown with solid lines, and deadhead travel is indicated by dashed lines. For example, upon initiation of the snow fighting operation, both trucks leave the service depot heading due west with the black route performing service (spreading and/or plowing) to Point A, and the gray route deadheading. At Point A the truck servicing the black route turns north while continuing to service the road surface, and the truck servicing the gray route continues east and initiates service. Because this service district includes a portion of an interstate, tandem service (service by both vehicles together) is required. Consequently, the vehicles must meet at the on-ramp entrance (Point B) to initiate this service. Tandem servicing might continue in a southeasterly direction to Point C (a median turnaround location) at which the vehicles reverse direction. Leaving the interstate portion of their routes near Point B, the vehicles separate and continue servicing/deadheading on their respective routes, returning to the service depot for replenishment of their supplies. If additional servicing or clean-up activities are needed, the routes are repeated until the operation is completed.

The number of routes assigned to a depot ranges from 5 to 15 and are class dependent. INDOT uses a method of road classification based on the average daily traffic (ADT). There are three classes of roads. Class I roads have an ADT of 5,000 vehicles or more; Class II roads are those with an ADT between 1,000 and 5,000 vehicles; and Class III roads have an ADT of 1,000 vehicles or fewer. Routes take the class of the highest ranked road segment they contain. Routes should preferably be homogeneous with respect to class. When some mixing of classes is unavoidable, it is preferable to avoid mixing Class I roads with Class III roads.

Travel by service vehicles on the network is classified as either (*a*) service travel, with the truck plowing snow off the roadway and/or the truck spreading material on the roadway or (*b*) deadhead travel, with the truck traversing that road segment in order to travel to another location to begin servicing another road segment. Deadhead travel generally allows higher travel speeds, while different service types (plowing versus spreading) may have different speed requirements. A major goal of route design within INDOT, especially for snow and ice control operations, is to minimize the amount of deadhead travel.

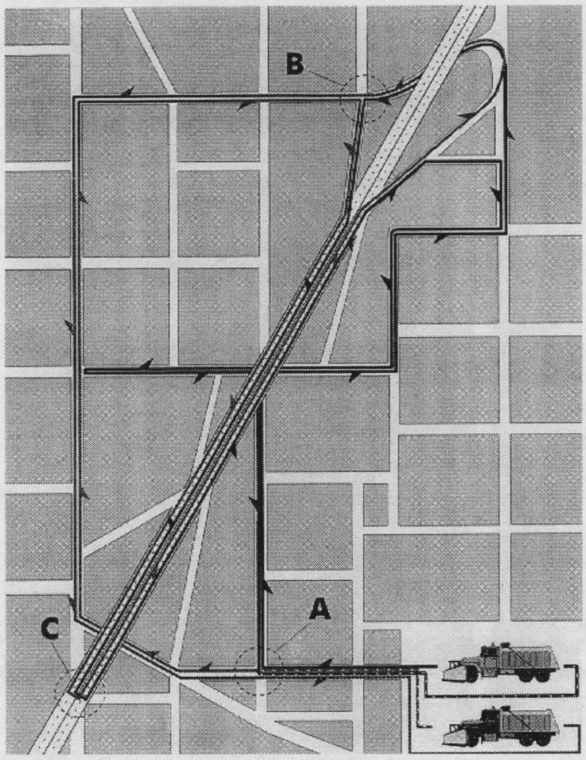

FIGURE 1 Schematic representation of the multivehicle, single-depot snow route design problem.

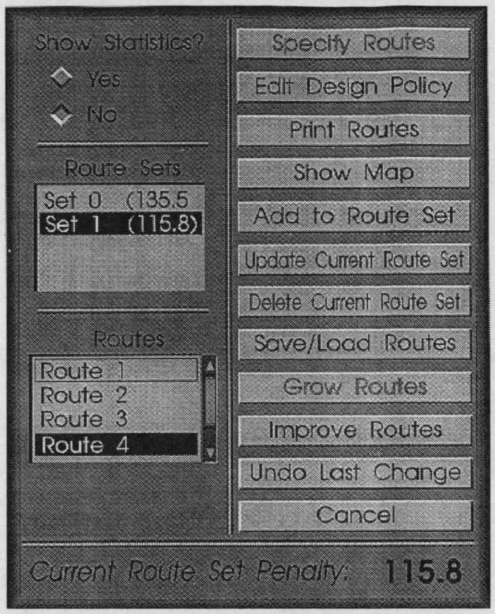

FIGURE 2 Main route design dialogue box within the CASPER graphical user interface.

INDOT's guidelines indicate that good Class I routes should receive service every 2 hr and Class II and III routes every 3 hr. The routes are, therefore, designed to be 2 and 3 hr long so that consecutive passes on the same routes achieve the required frequency.

CASPER ROUTE DESIGN SYSTEM

CASPER was designed and developed to assist in the design of a set of feasible routes originating and terminating at a specific depot to service a preselected portion of the network. In the current implementation, the selected portion of the network conforms to the boundaries of the unit partitions that have evolved through the years. In generating a feasible route set from which to proceed, CASPER estimates the number of trucks required to service the area based on the number of lane miles requiring service, the average service speed, and the service time limitations on that length of the route. Arcs (road segments) are then assigned to each truck such that the trucks provide mutually exclusive and collectively exhaustive coverage of the network. A one-step-ahead search is used to guide route growth in the direction that looks most promising. A shortest-path–based method is used to determine the minimum possible time required to finish servicing the current route should a particular arc be accommodated in the route.

Starting from the initial set of routes, CASPER can be used to improve the routes in a manual mode or an automated mode, much like using an intelligent computer aided design (CAD) system to plan a physical facility layout. The user may select from a number of design modules using a convenient graphical user interface. A typical design dialogue box is shown in Figure 2, with press bars to invoke models and CAD display routines on the left-hand side of the menu, and routing statistics and route sets on the right. The routes designed in either case are assigned a value based on a penalty structure with user-specified weights for the different objectives. The total penalty score for the "current" route set is displayed at the bottom of the dialogue box shown in Figure 2.

The penalty score that drives the design process is pre-established by the user and is a function of the three design objectives discussed previously: (*a*) minimize deadhead travel distance, (*b*) maximize road class continuity, and (*c*) minimize deviation from target service times. The user provides weights or relative priorities for these objectives by setting values (sliders) in a "routing policy" dialogue box (Figure 3). The user may also establish design constraints, such as restrictions on mixing road classes, and tandem servicing restrictions. The user may also elect to fix or "freeze" individual routes such that the model may not make subsequent changes automatically.

In the automatic mode, CASPER uses Tabu Search, a strategy that has achieved impressive success in many combinatorial optimization problems (*2,3*). The search moves to an improved solution in the neighborhood of the current solution, except when the current solution is a local optimum. Tabu Search, unlike purely improving search strategies, avoids getting trapped at a local optimum by allowing nonimproving moves out of the vicinity of a local optimum. Cycling is avoided by forbidding moves likely to take the search back to the recently visited local optimum. At any time during the process, the best solution found is called the incumbent solution. The user explores the solution space using this procedure repeatedly until he or she is satisfied that the incumbent solution is close to optimal or until some preset maximum number of iterations has been reached.

A tabu list is a list of moves that are forbidden. The tabu list is of limited length, and once it is filled, any addition to the list causes the oldest member on the list to be deleted from the list. The length of the tabu list determines the length of the cycles that are prevented and is a parameter that needs to be carefully selected based on the

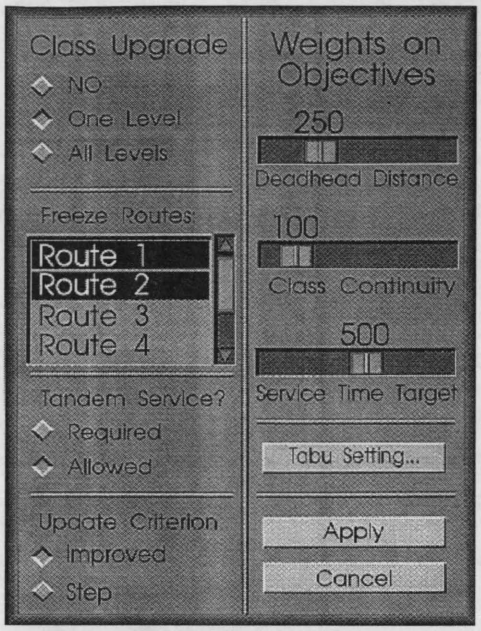

FIGURE 3 Route design policy dialogue box of the CASPER graphical user interface.

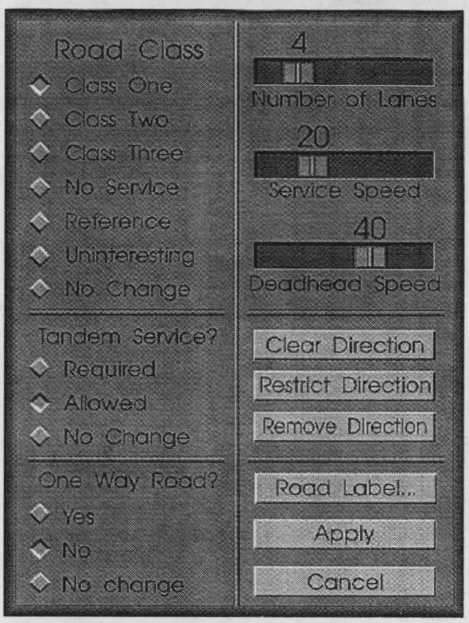

FIGURE 4 Design template for road classification in the CASPER graphical user interface.

application. Aspiration criteria provide conditions under which the tabu restrictions may be overridden. The tabu lists and aspiration criteria provide a control mechanism to constrain and free the search procedure. The user may change the tabu lists and aspiration criteria through the design policy dialogue box of the graphical user interface (Figure 3).

CASPER uses a spatial description of the network based on the U.S. Geological Survey Digital Line Graph (DLG) data. In addition to the network connectivity provided by the DLG data, information related to routing is needed to design feasible routes. Such information includes the road classification based on ADT, number of lanes in each direction, vehicle travel speeds while servicing and deadheading, points where the trucks fitted with snow plows can maneuver a U-turn safely and conveniently, depot locations, and direction restrictions. Direction restrictions include one-way roads as well as certain intersections (such as at an entrance ramp) in which left turns are not allowed. The CASPER prototype includes mechanisms for reclassifying standard DLG data files to develop these data bases. This is accomplished by users who are knowledgeable about the service areas and who compose data templates describing the relevant features of individual road segments and network nodes (intersections, turnaround areas, etc.). Dialogue boxes used for data-base development are shown in Figures 4 and 5, for roadway and node classification, respectively.

It is emphasized that the data discussed above are an integral part of the CASPER methodology. The success of the system results from the use of explicit objectives within the search heuristic to converge on good solutions and the ability of a knowledgeable user to select the best solution among them based on additional constraints and requirements specific to the particular area. The level of detail reflected by the spatial representation of the network is essential for the user to evaluate different options.

The multi-objective snow route design problem can be summarized as a multi-objective optimization model having the following form:

Objectives:

- Minimize the deviation from the target service times.
- Minimize deadhead.
- Maximize road class homogeneity.

Constraints:

- Each arc must be serviced only as part of one route.
- Routes must be designed to be continuous.
- Contributions toward the route service times must be appropriately calculated based on whether the arc is being serviced or being used to deadhead over.
- Routes should start and end at the depot.
- Subtours must not be allowed.

CASPER incorporates this model into a framework that allows a user who is knowledgeable about the winter maintenance operation to design efficient route configurations. The specific algorithm used in CASPER is summarized as six iterative steps (*4*):

1. Generate an initial feasible solution and designate this as the current solution. This is also the incumbent solution or best solution found so far.
2. The neighborhood of the current solution is the set of solutions differing from the current solution by a pair of arcs. Generate possible candidate solutions to move to in the neighborhood of the current solution.
3. Select the best admissible candidate. The best admissible candidate is the candidate solution showing the greatest improvement (or least worsening if the current solution is a local minimum) that (*a*) is not forbidden (tabu) or (*b*) is forbidden but satisfies the aspiration criteria.
4. Make the best admissible candidate the current solution. Update the incumbent solution if it is better than the incumbent solution currently stored.

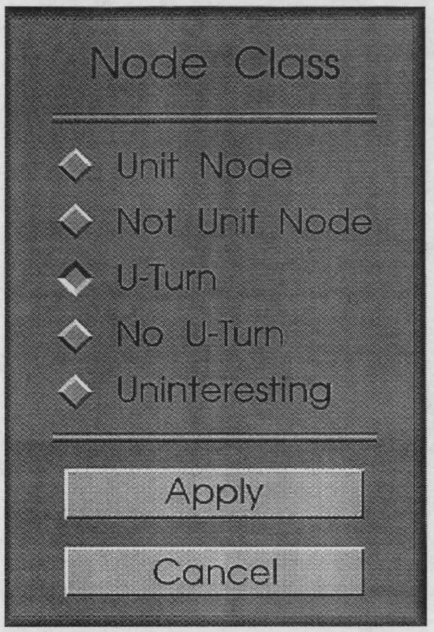

FIGURE 5 Design template for node classification in the CASPER graphical user interface.

5. Update the tabu list by adding the best admissible solution used. The tabu list is of limited length; therefore, the oldest member on the list is deleted if the list length maximum has been reached.

6. Check whether the stopping criterion (specified number of iterations or satisfactory solution) is met. If not go to Step 2. Else stop.

The six-step search procedure is driven by penalties assessed according to model objectives described earlier and is consistent with user-specified weights on those objectives. The following section discusses the use of the model to date within the state of Indiana.

ROUTE DESIGN PROCEDURE

To achieve a comprehensive evaluation of the CASPER route design system, the initial design of service routes was planned as a three-phase procedure. First, a team of researchers and maintenance engineers established a uniform design policy that would be used for all service areas. Second, routes would be designed by teams consisting of local maintenance personnel and a project manager who would participate in all design activities. Third, new routes would be placed into service for a winter season, after which maintenance personnel would be interviewed as to the quality and efficiency of service in comparison to previous routes. Each of these phases is discussed below.

Establishing a Design Policy

Before INDOT could begin designing snow routes for the state, a design policy and protocol for using the prototype software had to be established. CASPER was originally conceived to design routes with a flexible user-definable policy. That is, CASPER designs routes based on several objectives for which the user has the ability to set relative levels of importance. Specifically, the amount of deadhead mileage, adherence to class continuity, and time limit for each class of route can each be given a value on a scale of 0 to 100 that defines how important that objective is relative to the other two.

At a meeting held before the beginning of the route design process for the state, it was decided to design the state's first set of routes with a uniform and fixed policy. This three-part policy is commonly referred to as the CASPER penalty function.

The CASPER penalty function is used by the route designer to help evaluate the "*goodness*" of any given set of routes. After several discussions with INDOT personnel and testing in a typical district, the following criteria were used to determine the penalty score for all routes designed by INDOT. As discussed previously, any given route's penalty score comprises three contributing factors: total service time, deadhead distance, and class continuity.

Total Service Time

Class I routes have a target service time of 2 hr, and class II and III routes have a target service time of 3 hr. Service times are based on a deadhead speed of 64.4 km/hr (40 m/hr) and a service speed of 32.2 km/hr (20 m/hr). For Class I routes, a penalty value of 0 is assessed for routes that have a service time between 90 and 120 min, corresponding to the ideal service time window. For Class II and III routes, the ideal service time window with 0 penalty value is between 150 and 165 min. For any class route, if the service time is either below or above the ideal service time window, then a cubic function is used to determine the penalty value based on the number of minutes the route is below or above the lower or upper bound of the window. For example, if a Class I route has a service time of 85 min, then the total service time penalty value contribution to the route's total penalty score would be $5^3 = 125$ points for the 5 min the route was below the lower bound of the ideal service time window (90 min).

Deadhead Distance

For any class route, 1 deadhead mi (1.6 km) equals one penalty point for each deadhead mile in the route.

Class Continuity

For any class route, the number of off-class miles in the route divided by 3 equals the number of penalty points for the route. The value 3 was chosen to cause deadhead mileage to be roughly three times more important than class continuity or the number of off-class miles in a route.

This penalty structure causes total service time to be the most important consideration when designing routes. If a route is more than 10 min above or below the ideal service time window, then its penalty score will be at least 1,000 and deadhead or class continuity will not significantly affect the penalty score. It should also be noted that the function is exponential, which creates the potential for very large penalty values. Deadhead and class continuity become the dominant factor when the route is within the ideal service time window or very close.

Design Process

Following the completion of the CASPER prototype route design system, a team of maintenance engineers was assembled to redesign service routes for INDOT. This team consisted of

- A project leader, who would have major design responsibility within the entire state and had extensive experience with winter maintenance operations;
- Two to three maintenance personnel with local or regional knowledge at the subdistrict level; and
- A technician for assisting with data and computer operations.

Model parameters (including weights on objectives), constraint settings, and tabu search parameters were kept constant throughout the operation to ensure that a uniform design policy was used for evaluative purposes.

During the winter season following the redesign of service routes for the northern districts of INDOT, the routes were put into service and later evaluated by INDOT maintenance personnel. The following section describes the performance of the new routes based on the design objectives used.

Performance Based on Design Objectives

Service routes were developed using CASPER for several units in the four northern districts of Indiana: LaPorte, Ft. Wayne, Crawfordsville, and Greenfield. The effectiveness of CASPER in identifying efficient service routes within the context presented above is summarized in Table 1. A total of 430 routes were redesigned for four northern INDOT district offices: LaPorte, Ft. Wayne, Crawfordsville, and Greenfield. In each case, the aggregate penalty score was reduced by a considerable margin—95 percent to 99 percent.

More dramatic than the overall improved level of service afforded by the redesigned service routes is the reduction in overall cost of the entire operation, as shown by Table 2. In that table, data are presented for two route configurations for the region: (*a*) the routes in place before the use of CASPER and (*b*) the routes redesigned using CASPER, which are now used. The total number of routes to provide service to a constant area has been reduced by 34 (see Columns 2 and 6 in Table 2). Using an estimated cost per route over a 10-year period of $140,000, the total cost reduction indicated for the routes designed so far amounts to $5 million. Here the cost per route (truck) is the sum of vehicle cost, cost of mounted equipment, annual maintenance cost, fuel cost for winter service, and labor cost for maintenance (present value of cost flow over 10 years).

Total cost savings resulting from the redesign of all service routes are estimated to be at least $15 million.

TABLE 1 Evaluation Using CASPER's Penalty Structure

District	Penalty Scores	
	Previous routes	CASPER routes
Greenfield	673943.3	7818.3
LaPorte	7887880.9	196433.6
Ft.Wayne	2360264.0	48877.0
Crawfordsville	10285596.8	534522.4

Although the service routes developed using CASPER clearly dominate those previously employed by INDOT, a more detailed comparison of the routes before and after CASPER uncovers an interesting paradox. Consistently, the design team was willing to sacrifice two objectives—minimize deadhead distance and enforce class continuity—in favor of the third objective—minimize deviation from the target service times. As is shown in Table 2, the contribution to the overall penalty for deadhead distance and class homogeneity objectives usually increased, in general, during the use of CASPER. For example, in Crawfordsville district, which contains about 7,240 km (4,500 lane mi) of road, the earlier route configuration used 144 service routes with a total of 2,070 km (1,286 lane mi) of deadhead and 862 km (536 lane mi) of off-class road segments. Following the use of CASPER to redesign routes for the same network partition, the resulting deadhead and off-class miles increased to 2,267 km (1,408 mi) and 1,609 km (1,000 mi), respectively. Yet the overall penalty score decreased from more than 10 million to 550,000 (Table 1). When questioned about this seeming contradiction, in the stated policy used in model design versus policy used in route design, the response for the new route designs was enlightening: "All routes should receive the highest level of treatment maintaining bare pavements for as long as possible. The lower level of service for class II and class III roads comes into play only when it is impossible to maintain class I level of service for the entire region. As such, for these routes that are meant to be used for 'average' storms, the class continuity requirement is not as binding. Real time adjustments can then be made as required based on the actual intensity and areal extent of the snow event. As such, the requirement for class continuity in the routes designed for the average storm is not as important."

"The problem with deadheading is mostly connected with the public perception. Deadheading is viewed to be evidence of inefficient operation, and complaints arise when citizens observe trucks deadheading over road segments that have not been serviced. With improvement in the overall quality of the set of service routes designed, citizens are likely to be less frustrated. It is a fact that deadhead can never be totally eliminated using the existing depots or a comparable number of depots. However, any other means to reduce deadhead are worth considering."

The departure from the stated policy in the matter of class continuity was acceptable because a higher level of service was being provided. The stated policy was interpreted to be the least acceptable level of service. On the other hand, a reduction in deadhead would be desirable.

Characteristics of CASPER Solutions

Although the performance of the CASPER methodology can be evaluated explicitly using the penalty structure with specified weights on objectives or costs associated with the operation, an evaluation of other characteristics of the routes designed in different units reveals additional considerations. The premise of this research is that some factors, such as reduction of deadhead travel, might better be addressed at the partitioning level, and factors that are not considered in CASPER, such as compactness of the area served by a given depot, can affect the quality of the routes designed. A study of the route design with respect to some of these factors reveals information about the decision makers' acceptance levels for certain routing criteria and features of favorable network topology. This information can be used to improve the base data

TABLE 2 Comparison of Snow Removal Operations in Districts Before and After Redesign Using CASPER

District	Before CASPER				After CASPER			
	# of routes	Total Distance (km[a])			# of routes	Total Distance (km)		
		Service	Deadhead	Off-class		Service	Deadhead	Off-class
Greenfield	57	2929.6	7312.6	681.2	58	2850.0	857.5	769.4
La Porte	113	5595.7	2312.0	406.8	99	5394.1	1673.4	1225.2
Ft.Wayne	116	5687.0	1907.7	975.0	108	5683.9	2045.7	1644.6
Crawfordsville	144	7238.4	2070.6	862.3	131	7251.1	2266.6	1609.2

a. 1 km = 0.62 miles

(network partitions) that are subsequently used by CASPER in designing routes.

In reviewing the route sets developed by CASPER and agreed upon by the design team, two factors surfaced as being most important favoring good designs: (a) the location of the unit with respect to the network partition to be serviced from that unit and (b) the size of the unit (number of service miles assigned to a particular unit). Of these factors, the former is intuitive but the latter is not.

It was generally agreed by the design team that the most important factor in achieving a good set of routes for a predetermined partition of the network was the location of the unit servicing that partition. Although difficult to quantify because both the location of the units and the network partition of each were fixed and constant through the design process, all agreed that designs for units that were centrally located were better than for those that were not. This result is not surprising. Given a fixed network partition, a central unit location will tend to reduce redundant travel in reaching the most distant road segments within the specified target times. Unit locations adjacent to multilane highways were also found to result in superior performance to those on more restricted access road segments.

Field Testing and Final Evaluation

An attempt had been made to redesign approximately one-third of the state's snow routes up to that point, and it was thought that the limited amount of resources available to the project would be better used in implementing an accounting system that would provide a means for evaluating the redesigned routes. Also, any new routes that would be designed that late in the year could not be implemented for the current season.

The preliminary results of using the CASPER prototype system required field testing and verification. It was anticipated that some units would require modifications to be made to their route sets and possibly even an entire redesign after the field testing. With the possibility of some units requiring an additional truck after redesign and others implementing new configurations, the net increases in improved efficiency should remain about the same.

One of the intangible benefits of the CASPER software system is the computer-based design and decision support environment that it provides its users. As the unit and subdistrict personnel become more familiar with the system and have the opportunity to customize or effect changes on its design, they will inevitably use it more often to perform analyses, designs, comparisons, and what-if or hypothetical testing of ideas. They will view the system as a valuable tool to manage their limited resources and provide a better level of service to the public.

INDOT maintenance management staff developed the CASPER snow route evaluation procedure and forms. This procedure established a four-step process by which each unit could provide feedback as to the usability and goodness of each route it had designed using CASPER. The goal of the process was to evaluate how effectively CASPER had designed routes by obtaining feedback from the unit foreman and snow plow driver levels.

The first step of the process was to document each new route. After each unit completed its CASPER session, color printouts were produced of the routes the unit had designed. These printouts were taken to the subdistrict offices, where they were used to create INDOT route documents (directions). INDOT documents each of its routes with a tabular and map representation form. The subdistrict and unit personnel were also asked to strictly adhere to each CASPER route with only one truck so that a true and accurate evaluation of the CASPER routes could be performed.

The second step in the procedure was to simply test the routes on a dry run basis and train the drivers. Each driver was to drive his or her route in dry pavement conditions so that they could learn and become comfortable with it. They could also document any problems that they might foresee with the route at that time, such as traversal time.

The third phase of the procedure was to formally document each traversal of each route during a snow event. A standard evaluation form was produced for this purpose. The form for each route consisted of spaces for the designed traversal time, actual traversal time, road condition, and whether the truck was plowing or spreading on that pass. A remarks section for documenting problems or the lack thereof also was included. Each driver completed these forms for every pass he or she made of his or her respective routes, and the subdistrict offices collected the forms.

The fourth and final part of the procedure was to synthesize the evaluation forms. If a route was found to be absolutely unusable, then the subdistrict was to locally fix the problem in whatever way it deemed necessary. All other documented problems were to be sent to the state office for compilation. With this information, the state could track and compile statistics on the effectiveness and usability of the CASPER routes.

The results for the 1992–93 snow season have been compiled for 262 routes (66 percent of the total number of routes redesigned), and 72 percent of the CASPER-designed routes were found to be acceptable. The subdistrict acceptance rates varied greatly from 23 to 100 percent. The reasons behind the large variance in acceptance

have yet to be fully investigated at this point, but the variance could be related to problems with the base data, the constant travel speeds that were assumed during the design, or minor problems that are being perceived as major.

At this writing, all remaining route design problems identified during testing have been resolved without the need for systematic redesign using CASPER. Work is in progress to develop models to redistrict service areas and to adapt this methodology to other maintenance activities

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