INTERACTIVE DESIGN OF SERVICE ROUTES

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ABSTRACT: The design of transportation-network service routes is both combinatorially complex and fraught with multiple and conflicting management objectives. The focus of this work is the design and development of a computer-aided system for assisting in the design of network service routes. The system integrates: (1) Spatial network data; (2) multiobjective heuristic optimization techniques; and (3) an interactive, user-controlled graphical interface. The result is a systematic methodology for evaluating route configurations that facilitates the identification of solutions that reduce service-resource requirements while at the same time improve the overall level of service to the network. Although this research was motivated by the need to design winter snow- and ice-control service routes in Indiana, the approach is generalizable to a wide variety of applications requiring service to the edges (road segments) of a network such as crack sealing, pothole repair, painting and striping, weed control, and scheduled inspection. The structure and function of this system are discussed, as well as an evaluation of its use to date by Indiana Department of Transportation maintenance engineers.

INTRODUCTION

An important, though often neglected, factor in the development of strategies for the delivery of public services is the design of service routes. The value of effective route design in the public sector relates not only to the cost of service provided, but also to a variety of intangible benefits such as quality and equity of service. While the importance of effective route design has been documented, as have the potential benefits resulting from route improvements, instances of implemented public-sector routing systems are rare. The magnitude and complexity of most public-sector routing problems have precluded the development of general-purpose, or even application-specific route-design systems.

Regardless of the domain of application, routing problems may be classified in terms of the particular objectives and constraints inherent in a specific problem. Whereas private-sector routing problems are generally evaluated in economic terms—minimize cost, maximize net benefits, etc.—public-sector vehicle-routing problems are more often motivated by a desire to improve service or public welfare (Stricker 1970). Although there do exist complex constraints in routing problems faced by private organizations, the maximizing of benefits or the minimizing of costs is usually the ultimate and singular goal of most private-sector routing problems. However, minimizing costs is not the only, nor is it usually the most important, concern in public-sector routing problems (cost in the public sector is generally treated as a budgetary constraint). Commonly, the objectives most important in the provision of public services relate to social well being, and thus may be difficult to quantify. Also, public-sector problems tend to reflect

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multiple, frequently conflicting, and often simultaneous objectives (Stricker 1970; Bodin et al. 1983).

Public-sector service-route design is generally more difficult than its private-sector counterpart because the decision-making environment within which routing and the delivery of services take place is more complex. First, uncertainties may exist about the level of demand for services, or demand may experience significant, and often unpredictable changes over time. Second, important but intangible objectives, such as the public's safety and satisfaction with the quality of service are difficult to measure, yet these objectives may be the most important when delivering public services. Third, even in cases where the system is well understood, and sufficiently good analytical procedures are available to model that system, public-sector problems are more likely to be characterized by multiple and often conflicting objectives.

Because of the complexity and magnitude of the winter snow- and ice-control serivce-route–design problem faced by the state of Indiana, a research project was commissioned to design and develop a computer-support environment within which existing service routes could be evaluated explicitly, and new ones developed. The result is a prototype spatial decision support system (SDSS) that has become known as the Computer Aided System for Planning Efficient Routes (CASPER). The system has been used successfully in the redesign of service routes for approximately one-third of the network maintained by the state of Indiana, and the remaining areas of the state are scheduled to be evaluated in the near future. Though the use of CASPER is still largely experimental, verifiable economic benefits to the state of Indiana have already reached several million dollars.

This research is presented in several sections. Following a description of the winter service-route–design problem faced by Indiana, as well as most northern states, the technical literature about route-design methodologies relevant to this research is reviewed. Then the analytical framework of CASPER is presented including a discussion of: (1) The spatial database requirements of the system; (2) the systems analytical model elements and atoms; and (3) system flow control and user responsibilities. The paper concludes by documenting preliminary results from the use of CASPER by Indiana Department of Transportation (INDOT) maintenance engineers, and a prognosis for future use.

SNOW-ROUTE DESIGN IN INDIANA

Snow and ice control during the winter months in Indiana is, by several measures, a major operation (*Field Operations* 1985). INDOT must routinely maintain some 18,369 km (11,414 mi) of roadway throughout the state. Because each traffic lane must receive service, this translates into more than 46,400 lane km (29,000 lane mi). The resources needed for this operation include nearly 1,500 trained personnel and some 1,200 maintenance vehicles. The cost is enormous—over $14,000,000 was budgeted by the state of Indiana to support the operation during the 1990–91 winter season.

The overall goals of winter operations are to provide safe public-driving surfaces, efficient use of maintenance vehicles and personnel, and effective use of materials. Each road segment in the state's transportation network is routinely rated based on average daily traffic (ADT), and wintertime service requirements (measured by frequency of service and type of service) are based on these ratings. During snow events, Class I roads (ADT greater

than 5,000) receive continuous service including plowing and the application of materials (salt, chemicals, and abrasives) as needed to keep the road surface bare; generally every 2 h during an ongoing snow event. Class II roads (ADT between 1,000 and 5,000) receive continuous plowing and sufficient chemicals and abrasives to maintain bare wet pavement in the center portion of the roadway; generally every 3 h. Class III roads (ADT less than 1,000) receive enough service to keep the routes passable, with chemical treatment only for hills, curves, and intersections; generally every 4 h. The design of service routes, including deadhead travel segments, are based significantly on this "time-to-service" parameter.

The INDOT snow and ice control policy is reflected in a set of prespecified service routes, which generally do not change significantly from one snow season to the next (*Field Operations* 1985). These routes are administered out of field-unit sites that also serve as depots for service vehicles and material storage. On the order of six units are administered out of INDOT subdistrict offices, which are in turn administered out of six district offices in the state. It is the responsibility of the subdistrict superintendent and the unit foreman to dispatch trucks for snow- and ice-control tasks along these predetermined routes. In most cases, route design is not an activity that needs to be conducted in real time, or even on a regular basis. Because the design of routes is a major determining factor of overall quality of service, and because the system is not flexible enough to accommodate changes during the winter season, it is important that the complexities and uncertainties associated with the operation be considered as explicitly as possible during route design and periodic reevaluation of service routes.

Operational Objectives and Constraints

The quality of service is usually measured by the time to clear for each individual route. Better quality will be achieved when shorter time is required to complete servicing a route, as more service can be provided per unit time. Yet shorter routes implies more routes will be needed to service a given partition of the network, which means more vehicles are needed. This conflicts with another goal of INDOT, that of minimizing operational costs. A typical service vehicle, including plow and spreading attachments, materials bins, and traction gear costs between $70,000 and $120,000.

Minimizing deadhead travel (travel over the network with no service being performed) is another important objective in the overall winter operation for two important reasons. First, and most important, the shorter the total deadhead travel on the network, the more time that a vehicle is providing service, and the more efficient is the service operation. Second, management is concerned with public reaction to the quality of service provided; traditionally, the most intense and frequent of all citizen complaints directed at winter operations relates directly to the amount of deadhead travel in a particular area.

Road class homogeneity is a third major factor in the effectiveness with which the snow- and ice-control operation is conducted. Resources are allocated to the network based on the historic importance of individual road segments. A lower class (say, class II) road will be treated as a higher class (say, class I) road, if this lower class road segment is included in a service route having higher class road segments. This class upgrading usually implies excessive resource usage, nonequity of service provided by class type, and most important, deterioration of overall service quality and increased cost. While many existing routes within the state include at least some mixing of

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class types, most operations engineers agree that reducing this ratio would improve effectiveness of operations.

Overall Efficiency and Effectiveness of Route Design

In designing an overall management strategy for snow and ice control, a number of difficult questions may be posed: What is the best set of routes for maintenance vehicles so as to maximize service level while keeping overall deadhead miles as low as possible? What characteristics of individual routes are most important in terms of overall safety of operation? What contingencies should be provided to compensate for the uncertainties of storm intensity? What characteristics should individual routes have in order to address the projected human resource (driver) availability or specific personnel capabilities? These questions and more should be considered in the design of an effective strategy for conducting winter road maintenance. Questions such as these are addressed within the structured analysis framework provided by CASPER.

It is clear that the factors that determine the quality of service provided through the winter operation depend as much on intangible objectives as on tangible ones. Furthermore, from a modeling standpoint, a great number of very "low level" system components must be considered; factors such as differences in storm type and intensity, vehicle maneuverability, physical nuances of the network, and differences in personnel skills. Because of these considerations, a practical approach to the design of a routing system such as the one produced through this research requires the ability to incorporate precise, but possibly not yet known, system intricacies. The models developed through this research are thus properly perceived as mechanisms to aid the experienced and knowledgeable operations engineer, rather than dictating implementable solutions.

The route designer's challenge is to obtain, to the maximum extent possible, class homogeneity and service quality, while minimizing deadhead travel distance and the number of trucks and personnel needed. Management goals relative to route design are to form a collection of routes that are efficient in terms of the time to provide service, and compact in terms of the regions that they cover. An optimal collection of routes involves the definition of a travel sequence of road segments that minimizes the total time required to traverse the route when considering different travel speeds. The other perspective of an optimal collection of routes for the region being serviced involves determining a minimum number of routes for which the total travel time is minimized (Bodin et al. 1989).

PREVIOUS SNOW–ROUTE-DESIGN RESEARCH

The problem of winter-service route design as described previously can be posed as a capacitated arc routing problem on a directed graph and has been proven NP-hard (Wang 1992). This suggests that the chances of finding a polynomial time algorithm is small. Consequently, the most successful implementations of the technology are likely to be based on heuristic rather than exact procedures. Nonetheless, limited work directed at solving this very difficult problem has been ongoing for several decades.

Stricker (1970) addresses the problem of urban snow removal using the Chinese postman problem (CPP) as the basic model. In his analysis of the snow-plowing problem, he reveals shortcomings of the CPP model with respect to real-world constraints such as the need for multiple plows and

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multiple lane roads. Cook and Alprin (1976) propose a closest street heuristic (or dynamic routing of spreader trucks) to address the urban snow- and ice-removal problem based on the assumption that there are no priorities associated with roads. Tucker and Clohan (1979) employ a simulation model to solve the same problem. The routing module (not really a model) in their simulation model provides a simple computer-graph–based environment for users to design routes manually, and a preliminary way to predict the time needed to finish a particular route.

More recently, Haslam (1988) developed a seed-node–based greedy "route growth heuristic" for extensive rural areas. Haslam's algorithm relies on users' experiences to pick these seed nodes judiciously. While preliminary results using this approach were shown to be promising—this work also used network data for the state of Indiana—Haslam concluded that additional technologies will have to be incorporated into this approach before it can be used practically for most public-sector route design environments, particularly for more urban areas.

We conclude that the application of advanced analytical and numerical methods, and computer technologies to the problem of designing winter service routes is in its infancy. The ad-hoc methods previously mentioned have not been thoroughly evaluated, and are not generalizable to other operations or applications. General routing algorithms from the fields of operations research and management sciences are too general or abstract to capture the intricacies of this problem domain. And commercial geographic information systems (GIS) software, while extremely useful for displaying problem solutions (route sets), lacks the analytical tools necessary for finding efficient or effective route designs. Lastly, most of the work that has been discussed in the literature focuses on urban networks, not the rural areas that are the focus of the present research. A new framework for attacking this problem, and one that provides the foundation for the design and development of the CASPER route design prototype, is presented in the following section.

FRAMEWORK FOR MULTIOBJECTIVE ROUTE DESIGN

Consider a maintenance engineer who is presented with the task of developing a new snow- and ice-control route-design configuration for a portion of the intrastate-highway system. The motivation for this assignment might be economic; for example the desire to reduce the size of the service fleet in this region to avoid having to replace an obsolete piece of equipment. Alternately, the motivation might have to do with improving service—new construction of road segments over the past several years may have resulted in a deterioration of service to a route that has subsequently grown in length. Still another motivation might have to do with human resources—personnel turnover may have resulted in the loss of very senior (and experienced) vehicle operators who were traditionally assigned to more complex and operationally difficult or more important routes. Whatever the motivation, the maintenance engineer wishes to at least review the existing route configuration in a systematic manner, and probably make modifications that will become part of future operations.

The ideal system for use by this individual should include several essential elements and be capable of a minimal functional level of performance. Necessary elements include: (1) Sufficiently accurate and precise representation of the transportation network, including characteristics of each road segment as well as maneuver-specific node (intersection) information; (2)

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a model base containing appropriate data manipulation routines; and (3) a responsive visual interactive user interface having the appropriate level of user friendliness. Functionally, the system should facilitate the integration of model elements in a manner that is either meaningful to the decision maker in response to specific commands and instructions, or that is able to monitor the route design process, and provide nonprocedural feedback about the quality of a given design. Furthermore, the system should be able to conform to the design "style" of the user. One user may wish to approach the design task by first looking at existing routes, and using a variety of route manipulation "tools" discover improvements, while another user may wish to begin the process by articulating a set of desirable characteristics for service routes, and have the system automatically generate some good starting configurations prior to "hands-on" manipulation towards improvement.

These criteria guided the design and development of the prototype network decision support system resulting from this research. Like its namesake "CASPER: the friendly ghost," this route design system is a bit intimidating at first; particularly for individuals not familiar with high-end computer technology. But after becoming more familiar with the system, users are able to understand that CASPER is not a threat, but a great help in addressing the very complex problems associated with route design.

Fig. 1 presents the general framework of the CASPER route-design system. A user-friendly interface acts as the communication media between users and CASPER. With the assistance of this interface, users can manipulate data, design routes, and control the behavior of CASPER, while CASPER solicits appropriate user inputs and displays intermediate results graphically to users. The spatial network database can be accessed and modified by users via a data-filtering module. Users can elect to "toggle" automatic route design modules, invoke computer-aided-design–type (CAD-type) operators to change route configurations manually, or a combination of both. The central automatic design module will find and launch the appropriate models/tools in the model base to meet user's requests. The
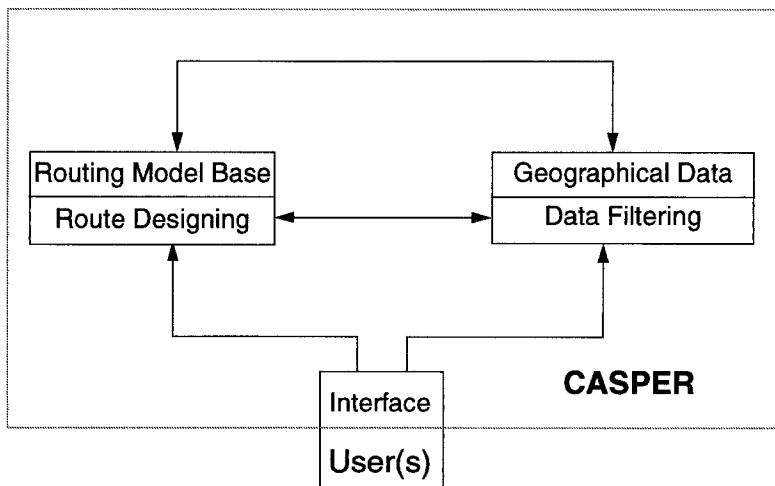

FIG. 1.   CASPER Route Design Framework

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connection between route-design modules and the data-filtering module provides users with a way of manipulating data during the route-design procedures. Similarly, a direct connection from the database to the routing model base allows tools resident in this model base to gather information without invoking the intermediate data filtering module. With this as a general description of CASPER, the structure and function of the data and models base components of the system are discussed in more detail herein.

Database Development

For the application of vehicle routing over the state highway network, a complete spatial description of the network is used by CASPER. This description must include all major intersections in each district, adjacency information that indicates which intersections are joined directly by which roads, and the lengths of each of these roads. Planning for snow and ice control requires additional information, such as the average daily traffic, the number of lanes of every roadway, and more complete descriptions of intersections, including features such as turn lanes or traffic-control devices.

A major activity in support of this work has been to explore available digital-map data sources, and to find the best methods to convert these data to a usable network representation. The most promising format for this application is a vector format in which roadways are represented as polylines; a set of short segments connecting two intersections. The source for vector data thus far has been the U.S. Geological Survey digital-line-graph (DLG) format. Roadway information is available for the entire state of Indiana, and all other states of the United States at a 1:100,000 scale.

The use of these data for route design and analysis is hindered by two distinct factors. First, the DLG data set includes considerably more data than are needed for route design. Second, the classifications and characteristics attributes used by USGS may not be satisfactory for a given route-design problem. For example, USGS does not classify intersection nodes as being inappropriate for maneuvering a snow removal vehicle through a U-turn. Existing map representations of the highway network could be used as a data source for optimization, although the complexity of these data could prove difficult in the definition of solution methods. Only with intelligent and efficient filtering and reclassification are these data a useful resource in practical route-design and network-logistics applications.

Prior to the use of the CASPER prototype, a comprehensive database containing this information was required, and has since been developed for the entire state of Indiana. An efficient and "smart" data-filtering/classification module was developed and integrated into CASPER. The interactive DLG-3 data filter consists of three separate, but related functions: (1) Input of the original DLG-3 data files; (2) interactive reclassification of road and node (intersection) objects; and (3) output of reclassified data files in DLG-3 format. The basic structure of these procedures is illustrated in Fig. 2. Local transportation network experts (field engineers in INDOT organization; maintenance engineers in our figure) are the key components in this data-filter/classification process. The maintenance engineers are usually those individuals who are responsible for snow-route design within each district, and who have extensive knowledge and experience within his/her area of responsibility. A user-friendly interface was developed to help users to provide this essential information. The user develops a "template" representation of the node (intersection) or arc (road segment) that the user
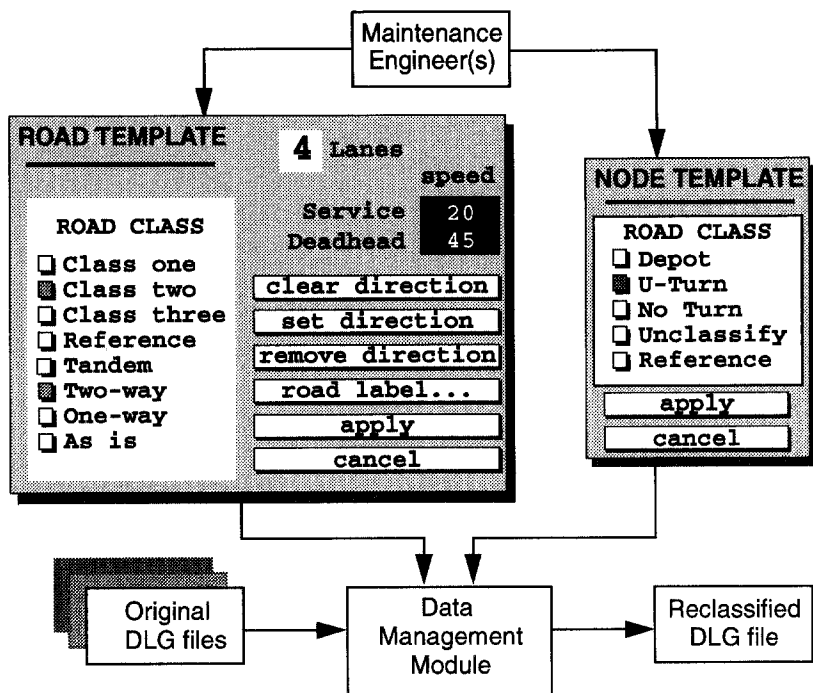
FIG. 2. Maintenance Engineer's Role in Database Development

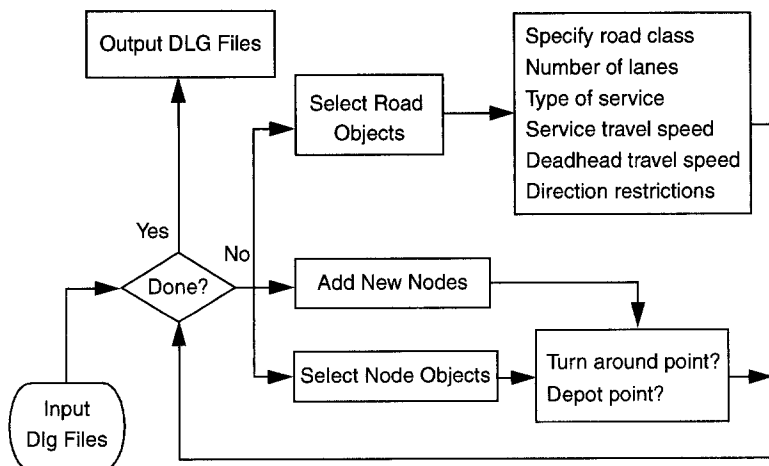**FIG. 3. Flowchart of Data Filtering/Classification Procedure**

desires to reclassify, then imposes that template on the target database graphics objects.

Fig. 3 illustrates the logic of this data-filtering/classification process. Users may either select existing road or node objects, or elect to add new nodes into the database. If node or road objects are selected, a template dialogue

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box is available for users to specify the characteristics of the selected objects (examples of these dialogue boxes are shown in Fig. 2). For example, the user may declare the selected road objects as a class I road having two lanes, a travel speed while servicing of 24 km/h (15 mi/hr), and a deadhead speed of 48 km/h (30 mi/hr). A similar procedure is used to classify node objects (turn maneuvers, etc.). The process continues iteratively until the entire network has been reclassified, or verified. A preliminary CAD capability is included in CASPER to allow users to create new nodes in the database, such as the crossover locations along interstate highways, intermediate salt-storage facilities, or other relevant objects that may not be georeferenced in the DLG data set as acquired from USGS. Upon completion of the data-filtering/reclassification process for a unit or subdistrict, other maintenance engineers who are familiar with other portions of the network would repeat the process for their areas of responsibility. Modifications to these parameters of the database may also be made during route design.

Model Elements and Integration

To assist users in designing efficient routes and to accommodate different users' decision-making styles, a local improvement heuristic-driven route design model has been developed. The rationale behind local improvement is that given a current solution, an improved solution may lie within the neighborhood of that solution. At the termination of systematic search procedure, the best solution found is considered the optimal solution. A major problem in the design of the local improvement heuristic to avoid the circumstance where a search is trapped in a local optimum. The search strategy adapted for use in CASPER is the "Tabu search" first articulated by Glover (1990). A summary of that algorithm is presented in Appendix I. The interested reader is referred to Wang (1992) for a more detailed discussion of the application of Glover's Tabu search procedure to problems of snow-route design.

Because of the complexity and intricacies in winter service route design, an effective modeling environment within this domain must provide enough freedom for users to design their own search strategies and to override system recommendations at any time. By specifying the trade-off among the objectives and allowing modification of the local improvement evaluation criteria, users need to be able to emphasize different objectives in different situations and determine more precisely, the model's searching range and direction. Users must also be able to override the routes suggested by the system and modify routes manually in order to address specific, and unanticipated considerations.

The structure of the local improvement route design model within CASPER is illustrated in Fig. 4. The first step in the route-design process is to specify the target routing area (the subnetwork and depot for which routes are to be designed). Currently, only a single depot is allowed in the selected area. A graph consisting of nodes and directed arcs is then created automatically based on the area selected. Alternately, the user might elect to use the existing set of routes for a particular area as a feasible starting point. The remainder of this discussion assumes that the user has elected to design a completely new set of service routes.

An empirical analysis is performed to estimate the number of vehicles needed and to determine the associated class of each route. An ad-hoc heuristic procedure for generating such an initial route is presented in Wang
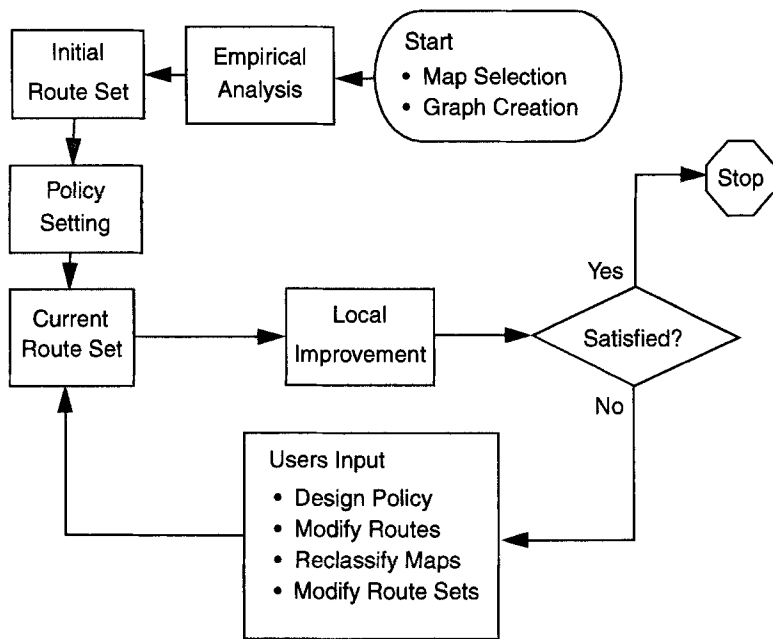
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┌──────────┐      ┌──────────┐      ╭─────────────────╮
│ Initial  │◄─────│Empirical │◄─────│ Start           │
│Route Set │      │Analysis  │      │ • Map Selection │
└──────────┘      └──────────┘      │ • Graph Creation│
      │                             ╰─────────────────╯
      ▼
┌──────────┐
│ Policy   │                                              ┌─────╮
│ Setting  │                                          ┌──►│Stop │
└──────────┘                                          │   ╰─────╯
      │                                            Yes │
      ▼                                                │
┌──────────┐      ┌──────────┐           ◇────────────┘
│ Current  │─────►│  Local   │──────►    ◇  Satisfied?  ◇
│Route Set │      │Improvement│          ◇────────────┐
└──────────┘      └──────────┘                     No │
      ▲                                                │
      │      ┌─────────────────────┐                   │
      │      │ Users Input         │                   │
      └──────│ • Design Policy     │◄──────────────────┘
             │ • Modify Routes     │
             │ • Reclassify Maps   │
             │ • Modify Route Sets │
             └─────────────────────┘
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FIG. 4.   Flow Control within Model Base

(1992). This initial route set becomes the "current route set" automatically as it is generated. The local improvement procedure can then be invoked by the users in an attempt to find an improved route. Two possible outcomes may result from triggering the improvement procedure: (1) An improved solution is found; or (2) an improved solution is not found after a user specified number of iterations. If the user is satisfied with the outcome, the procedure simply stops and outputs the best routes found. Otherwise, users may provide additional information (the specific mechanism for providing this input is discussed in detail later) reflecting personal preferences or different ideas, and then trigger the local improvement procedure again. These procedures (local improvement and users input) will be repeated until a satisfactory solution is found.

The forcing function behind the local improvement procedure with CASPER computes a penalty score for individual route configurations based on three design objectives: (1) Minimum deviation from target service travel time for a route; (2) minimum deadhead distance within a route; and (3) maximum road class homogeneity within a route. All these measurements are converted into the same unit of measurement (penalty score) with user-provided weights on objectives. This penalty score thus reflects the route-design goals of the individual using the system (a winter-maintenance service engineer responsible for the operation in a particular region), and serves as an explicit measure of the relative differences among different route configurations within a given service area.

By iteratively evaluating the current route, users are able to "direct" and "control" the local improvement search direction by changing policy settings, modifying routes manually, or reclassifying data. It is assumed that each new (improved) solution will stimulate thoughts and ideas from users

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regarding the quality of routes. Experienced users are able to identify the "good" and "bad" parts of current routes, and to guide the system accordingly. At any point in this process, a current route may be saved and "marked" for later consideration and comparison with other route sets.

The policy specification involves the setting of weighted parameters that are associated with the objectives discussed previously, and the specification of other criteria used by the improvement heuristics. The following parameters may be set or modified and manipulated by the user to control the design policy:

- The values of the weighted parameters associated with design objectives.
- The maximum number of search attempts to find an improved solution under the current policy.
- The class upgrade limitation. As indicated before, a class upgrade (e.g., from class II to class I) will take place when a lower class route (a class II route) accommodates a higher class road (a class I road). This limitation specifies whether class upgrading is allowed and to what extent. For example, users can specify that only the upgrade to the next highest class is allowed. Under this restriction, a class III route can be upgraded to class II but not to class I.
- Routes that are not allowed to be modified. Occasionally, users are satisfied with some of the routes and do not desire further modifications. In this case, users can declare these routes to be frozen and no additional modification is allowed (automatically). Thus, no arc will be swapped into or out of these "good" routes.

In addition to modifying the policy setting to direct the search, users may want to modify routes manually to address important intangible concerns. These concerns, such as the locations of sharp curves, steep slopes, poorly designed intersections, important residence areas, and individual driver's experiences, are usually missing from the available data and their importance, impact, and trade-off with the other objectives are usually difficult to measure accurately. It is likely that these subjective issues are most difficult to address adequately in a predefined model and probably will not be raised and identified until users have a chance to evaluate routes. For example, users may want to assign manually a class II road with steep side slopes to a class I route. By doing this, a certain degree of class continuity is sacrificed in exchange for a higher degree of public safety. It is infeasible to be able to anticipate all such circumstances, or to generalize them among different service areas or different personnel experiences.

Another option is provided by allowing users to go back to the database and modify road and node attributes during route-designing procedures. Occasionally, it is desirable for users to modify data attributes after evaluating current routes so that these changes will be accommodated in the next improvement iteration. For example, users may want to declare some new points as (no) turn-around locations or to modify the traveling speed or the class for some road objects. Severe drifting conditions on a particular road segment may best be handled by different travel speeds in different directions on the same road. This does not mean that errors exist in the data, but rather allows a mechanism by which users can change some of his/her previous subjective judgments.

The total number of snow- and ice-removal vehicles required to service

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a specific subnetwork is the major factor in determining overall costs and thus it is usually desirable to minimize the number of vehicles used to provide an adequate level of service and without sacrificing public safety significantly. In some instances, it may become clear that the total number of required vehicles could be reduced. For example, three 1.2-h-long class I routes are likely to be replaced by two 1.8-h-long routes. When such a situation occurs, users can select a route to be "deleted" and each arc served by that route will automatically be assigned to the appropriate route(s) based on the current policy setting.

By coupling the aforementioned tools, and with the flexibility provided by CASPER, users are able to direct the route improvement search direction, and interact with the system at any time. Different users' decision-making styles and other intangible concerns may be accommodated in this manner. For example, for some users the highest priority may be the objective of reducing deadhead distance. After achieving a small deadhead distance, users may put more emphasis on the objective of class continuity in an attempt to balance these two objectives. At the same time, the capability of allowing users to override and modify the outcome of local improvement procedures and to reclassify data offer a greater degree of flexibility for users to reflect the real-world situations and personal preferences.

PRELIMINARY RESULTS

Following initial prototype system development, several unit sites were selected for testing the route-design capability of CASPER. The districts involved in this evaluation stage were the Crawfordsville and Greenfield Districts. The Carbondale unit was selected as a representative service unit for the Crawfordsville district, and route design was conducted by Michael A. Smith; former field engineer and the individual who designed the existing snow routes. In Greenfield district, two adjacent units, the Tipton unit and the Kokomo unit were selected, with designs being completed by Karl Kleinkort (the field engineer), Joe Olson (the subdistrict manager), and the foreman from each unit.

Crawfordsville District

Area Characteristics and Objectives
Currently, Crawfordsville District is suffering the shortage of human resources (drivers) and the available vehicles are just enough to cover all existing routes. When some vehicles break down during the winter season, a frequent occurrence, it causes serious operational and administrative problems, and service levels may be deteriorated significantly. Therefore, the major goal for service-route design within this district is to reduce the number of routes without sacrificing service level or public safety significantly.

Carbondale Unit Results
The comparisons of current routes and the routes design using CASPER is shown in Tables 1 and 2. Both of these tables contain data measuring the quality of two different route configurations for the Carbondale service unit. Table 1 presents a solution requiring seven individual routes, each represented as a row. The entries in the second column is the class associated with each route. The entries in columns 3–5 for a given route indicate a

TABLE 1.   Existing Routes for Carbondale Unit (Total Value: 148.1)

Route (1)	Route class (2)	Time (h) (3)	Deadhead (4)	Class continuous (5)	Value (6)
1	2	1.8	2.4	0.0	2.4
2	1	2.4	0.6	0.0	56.2
3	1	1.3	0.5	0.0	0.5
4	1	2.2	11.4	0.0	23.3
5	2	2.8	11.4	74.8	25.4
6	2	2.4	17.1	41.9	24.2
7	2	2.3	16.0	27.7	20.5

TABLE 2.   Routes Designed Using CASPER for Carbondale Unit (Total Value: 51.9)

Route (1)	Route class (2)	Time (h) (3)	Deadhead (4)	Class continuous (5)	Value (6)
1	1	1.9	0.6	0.0	1.0
2	1	1.5	0.5	0.0	0.5
3	1	2.2	0.5	0.0	7.7
4	2	3.2	17.1	54.2	32.1
5	2	3.2	2.1	0.0	5.0
6	3	2.5	5.6	0.0	5.6

penalty attainment level measured for that route for three important service criteria: service time, deadhead miles, and class continuity, respectively. The rightmost column is the penalty "score" as mapped through a penalty function established by the user, with the overall penalty score for that particular set of routes indicated as "total value." The smaller that number, the better the route configuration. For example, the seven-route solution shown in Table 1 has a total penalty value of 148.1.

Table 2 presents another solution, and one that is better than the previous solution in two important ways. First, the overall level of service is better (the total penalty score is only 51.9); and second, the solution requires one fewer route (six rather than seven). Given that each route requires capital equipment, the solution presented in Table 2 is not only better, but is less expensive than that presented in Table 1. The first solution is the route design used by INDOT for the Carbondale unit during the 1991–1992 and all previous winter seasons. The second is one designed by INDOT maintenance personnel using CASPER, and that was instituted for the 1992–1993 and subsequent seasons.

Greenfield District

Area Characteristics and Objectives

Though adjacent, the Greenfield District has very different characteristics from those of the Crawfordsville District. This district (at least, Tipton subdistrict) does not suffer the shortage of vehicles and human resources. Furthermore, additional vehicles are available for next winter season. Because of ample availability of operating resources, the goal of this district

is to utilize all of the available resources in an optimal manner in order to achieve the maximal service level. Also, some routes have been found to be practically infeasible during last year's practices. Another goal of this district is to improve these infeasible routes as well.

Tipton Unit Results

Tables 3 and 4 show the current routes and the routes produced with the aid of CASPER for the Tipton unit, respectively. At the first glance, it is surprising to note that the additional vehicle does not seem to improve service level significantly— total penalty reduction from 131.7 to 112.4. But in reality, at least one of the existing routes is infeasible based on INDOT's specified service policy; a three-hour class II route with a small deadhead distance, should be considered a "near-perfect" route according to INDOT's policies. However, this route becomes impossible to maintain when there is wind blowing and drifting the snow during a winter storm, which is the normal experience in this area. Under such weather conditions, when a truck finishes the south part of this route, the snow accumulated on the north part becomes impossible to service, often requiring road closure. This emphasizes the importance of having human (expert) involvement in service-route design. Only the experienced domain experts are able to recognize such fine points of route design and to address them appropriately. In this test, CASPER successfully helps users to correct an "infeasible" route, to accommodate users' request of having a seven-route solution, and to comfort the users' desire of totally controlling CASPER's route-improvement behavior.

TABLE 3. Existing Routes for Tipton Unit (Total Value: 137.3)

Route (1)	Route class (2)	Time (h) (3)	Deadhead (4)	Class continuous (5)	Value (6)
1	1	1.8	8.1	0.0	8.1
2	1	1.8	8.1	0.0	8.1
3	2	3.0	2.4	0.0	3.0
4	1	2.3	0.0	57.2	56.2
5	2	2.5	10.3	44.6	33.6
6	2	2.5	22.6	0.0	22.6

TABLE 4. Routes Design Using CASPER for Tipton Unit (Total Value: 112.4)

Route (1)	Route class (2)	Time (h) (3)	Deadhead (4)	Class continuous (5)	Value (6)
1	1	1.9	0.0	0.0	1.0
2	1	1.8	8.1	0.0	8.1
3	2	2.0	18.4	0.0	27.6
4	2	2.5	22.6	0.0	22.6
5	2	2.0	1.3	0.0	1.3
6	2	2.5	10.3	44.6	33.6
7	1	1.5	0.0	64.8	19.0

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TABLE 5. Exiting Routes for Kokomo Unit (Total Value: 446.47)

Route (1)	Route class (2)	Time (h) (3)	Deadhead (4)	Class continuous (5)	Value (6)
1	1	2.0	15.0	0.0	15.0
2	1	2.1	1.5	46.4	23.5
3	1	2.6	9.5	54.3	318.9
4	1	1.9	6.5	0.0	6.5
5	1	2.4	17.3	0.0	82.6
6	1	1.4	0.0	0.0	0.0

TABLE 6. Routes Designed By CASPER for Kokomo Unit (Total Value: 53.6)

Route (1)	Route class (2)	Time (h) (3)	Deadhead (4)	Class continuous (5)	Value (6)
1	1	1.8	0.0	25.4	7.9
2	1	2.0	6.5	0.0	6.6
3	1	2.1	10.4	0.0	11.5
4	2	2.6	1.5	0.0	1.5
5	1	1.8	0.4	0.0	0.9
6	1	1.9	15.9	0.0	25.3

Kokomo Unit Results

Tables 5 and 6 compare the existing routes and the routes designed by CASPER for the Kokomo service unit. Unlike the Tipton unit, no additional vehicle is available for this area. The major goal is to maximize the service level by using all of available vehicles with a minimal operational cost. According to the statistics shown on these tables, the service level is improved significantly—improvement from 446.47 to 53.6 using CASPER.

Another interesting observation is that all current used routes are class I routes and one out of the six CASPER produced routes is a class II route. This difference indicates that the CASPER produced routes use resources (sand and abrasive materials) in a more effective manner; recall that unnecessary materials will be applied to the lower class roads when they are integrated to a higher class route. Again, the use of CASPER does manage to improve the overall service level while allowing resources to be utilized more efficiently.

CONCLUDING REMARKS

The CASPER service-route-design prototype represents a unique approach to the design of transportation service routes; one that places the maintenance engineer in the role of expert, and the computer suport system in the role of technical assistant or accountant. The result is a system that is both powerful and flexible, and that shows great promise in developing improved service routes on one hand, and possibly reducing the number of service routes necessary to achieve an acceptable level of service on the other. Consequently, the use of this methodology is likely to result in simultaneous benefits of improved service and significantly improved operating costs.

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Preliminary testing of CASPER has been conducted in the state of Indiana by the Indiana Department of Transportation. Approximately 40% of the rural service area of the state has undergone preliminary winter service route redesign, with approximately 8% reduction in the total number of routes necessary to service that network. In most instances, reduction in overall penalty scores (improved service levels) for these routes has been achieved. A systematic and comprehensive (quantitative) evaluation is presently being conducted by INDOT maintenance personnel and is expected to be completed by the time this paper appears in print. Total cost savings to the state directly attributable to the use of CASPER is expected to reach several millions of dollars.

APPENDIX I. CASPER LOCAL IMPROVEMENT ALGORITHM

The local improvement algorithm used within the CASPER route-design prototype is based on the Tabu search methodology first proposed by Glover (1989, 1990). The algorithm, as adapted to the problem of designing service routes on a transportation network, is presented as six iterative steps:

Step 1: Generate an initial solution and designate this as the current solution. A solution is a specific set of route designations that completely service a predesignated portion of a network.

Step 2: Generate possible candidates based on the current solution. A candidate is a solution that differs from the current solution by one or a pair of arcs.

Step 3: Select the best admissible candidate from the candidates generated.

Step 3.1: Arbitrarily pick a candidate and designate it as the current candidate. Reset the incumbent objective value.

Step 3.2: Evaluate the current candidate by a user-defined objective function.

Step 3.3: If the current candidate has a better objective value than the incumbent one, go to step 3.4; otherwise, go to step 3.7.

Step 3.4: Check whether this current candidate is included on the current Tabu list? If yes, go to step 3.5; otherwise, go to step 3.6. A candidate is on the current Tabu list if it has been an incumbent solution within the past n iterations of step 3.

Step 3.5: Perform the aspiration check. If pass, go to step 3.6; otherwise, go to step 3.7. An aspiration check is a user-defined mechanism for specifying conditions under which a solution on the Tabu list can become the incumbent solution.

Step 3.6: Make the current candidate as the incumbent admissible candidate and update the incumbent objective value.

Step 3.7: Check whether there is any candidate left. If yes, go to step 3.1; otherwise go to step 3.8.

Step 3.8: The inclement admissible candidate is the best admissible candidate.

Step 4: Make the best admissible candidate the current solution.
Step 5: Update the Tabu list.
Step 6: Check whether the stopping criterion—usually a specified total number

of iterations—is met. If not, go to step 2; otherwise, the search procedures terminate and a near-optimum solution is found.

APPENDIX II. REFERENCES

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