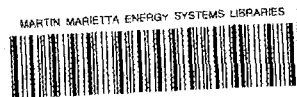


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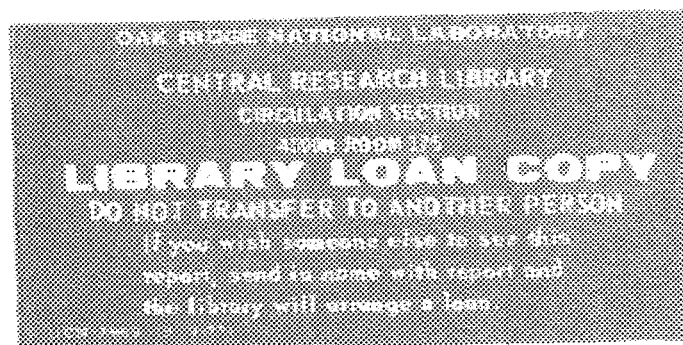


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ORNL/TM-10333

Microcomputer-Based Vehicle Routing and Scheduling—An Overview

A. J. Klein



Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes--Printed Copy: A04; Microfiche A01

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Data Systems Engineering Organization
Microcomputer-Based Vehicle Routing and Scheduling—An Overview

A. J. Klein

Report Prepared for
Navy Military Sealift Command,
Department of Navy
under
Interagency Agreement 1521-1521-A1

Date Published: August 1987

Prepared by
Data Systems Research and Development
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MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

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CONTENTS

	Page
LIST OF FIGURES	v
LIST OF TABLES	vii
ABSTRACT	ix
1. INTRODUCTION	1
2. STRATEGY	3
3. OVERVIEW OF PACKAGES	5
3.1 VERY INEXPENSIVE PACKAGES	7
3.2 VERY EXPENSIVE PACKAGES	8
3.3 REMAINING VEHICLE-ROUTING AND SCHEDULING PACKAGES	10
4. KEY CHARACTERISTICS OF VEHICLE ROUTING AND SCHEDULING	11
4.1 TRAVEL TIMES	11
4.2 CUSTOMER (STOP) DATA	15
4.3 ROUTES	16
4.4 VEHICLES	19
4.5 INTERVENTION CAPABILITIES	20
4.6 GRAPHICS	20
5. CONCLUSIONS	21
6. DEMONSTRATION PACKAGES	23
6.1 FLEET ROUTER	23
6.2 TRUCKSTOPS	27
6.3 MICRO VEH PLAN	30
6.4 DSS	34
7. TEST RESULTS	37

LIST OF FIGURES

Figure		Page
1.	Vehicle-routing solution sequence	5
2	Example of a barrier	14
3	Basic single-vehicle-routing problem	17
4	Backhaul problem	18
5	General pickup and delivery problem	18

LIST OF TABLES

Table		Page
1	Microcomputer vehicle-routing packages	2
2	Breakdown of software packages	8
3	Summary characteristics of demonstration packages	24
4	Demonstration software performance comparisons	37

ABSTRACT

Commercially available vehicle-routing and scheduling packages were surveyed to assess capabilities, categorize key characteristics, compare individual packages, and select candidate software for additional testing. Among the key characteristics addressed were backhauling, distance and vehicle travel-time calculation, geocoding, speed zones, natural barriers, time-window constraints, vehicle/stop matching constraints, and other constraints such as vehicle/driver operating costs. The survey included review of vendor literature, telephone interviews, site visits to review software, and the testing of demonstration packages on a set of sample distribution networks. Thirteen packages were reviewed; these were categorized by price and performance as follows: (1) inexpensive packages (costing \$2000 or less), which solve the basic vehicle-routing problem but are somewhat limited in their ability to handle large numbers of vehicles and stops; (2) medium-priced systems (from \$5000 to \$20,000), which offer more capability to handle constraints such as multiple pickup and delivery, time windows, and multiple depots and provide manual intervention capability and enhanced graphics; (3) very expensive systems (from \$50,000 to about \$150,000), which can handle real-time situations in scheduling last-minute route changes and employ sophisticated graphics tools to change route schedules interactively. Out of the 13 packages, four demonstration vehicle-routing packages were obtained for testing of 4 sample networks; two of the packages were found to be capable of solving most vehicle-routing problem constraints for two versions of 21-city and 30-city networks.

1. INTRODUCTION

The use of the microcomputer for business and industry applications has accelerated tremendously within the last few years. Along with this increased use has been the growth of microcomputer-based software tailored to the specific needs of the end user. One can see this development in the area of vehicle routing and scheduling—there has been a virtual explosion of such software only within the last two to three years. Companies that distribute their goods to a vast number of customers and still employ manual scheduling techniques for dispatching vehicles are obvious candidates for adopting microcomputer vehicle-routing software for their business operations.

Current research has shown that most fleet operators can achieve 10–15% reductions in fleet miles traveled through use of advanced scheduling techniques. This reduction can represent significant savings for even the smallest of fleets when one considers the average cost of running a vehicle is \$1.00 to \$1.50 per mile.¹

The development and use of vehicle-routing and scheduling software is only now rapidly coming into its own. Before about 1980, only large, expensive mainframe vehicle-routing and scheduling applications existed. These systems were suitable only for relatively large companies having well-staffed, in-house data processing or management information system technical support groups. However, as businesses started to implement microcomputer business software applications in the early 1980s, smaller investments in equipment, personnel, and training meant that microcomputer-based vehicle-routing systems could benefit smaller companies, particularly those without an extensive automated data processing (ADP) support staff. Moreover, these systems are designed for the end user's needs (i.e., the vehicle dispatcher or scheduler within the organization's distribution group).

The impetus for this overview of vehicle-routing and scheduling packages has been the work associated with upgrading a major software program for the Navy Military Sealift Command (MSC). The program, called the Sealift Contingency Planning System (SEACOP), is an automated strategic planning model that assists MSC transportation analysts in developing systematic methods for the utilization of available ships to respond most efficiently to an overseas military emergency involving U.S. forces. A major subsystem within SEACOP, called the Scheduler Subsystem, generates movement tables for accomplishing sealift to areas specified by the Commanders in Chief in an operational plan (OPLAN). The Scheduler Subsystem manages information pertaining to ship characteristics; port characteristics; unit and resupply movement requirements; port-to-port distance tables; and operations planning data to schedule ship arrivals and departures, cargo destinations, and routes to be taken by ships. In its routing and scheduling of ships to match the requirements of an OPLAN to the shipping resources available for use, the Scheduler Subsystem employs many of the same heuristic transportation algorithms used by the commercially available packages surveyed in this paper. Thus, a study of the commercially available vehicle-routing and scheduling packages, their characteristics, routing, graphics, and user intervention capabilities, is very helpful in establishing desired characteristics and capabilities for microcomputer-based ship-routing and scheduling software applicable to MSC planning and analysis needs apart from a mainframe environment.

As noted in the preceding, these vehicle-routing and scheduling packages are very responsive to the end-user's needs and have opened up vast savings opportunities from the standpoint of time,

control, computer, and personnel resources. As more businesses realize the advantages of microcomputer-based vehicle routing and scheduling, the number of such packages is bound to increase. As it turns out, there are at least 13 vehicle-routing packages commercially available for microcomputer application. Table 1 provides summary information on vehicle-routing packages. The purpose of this report is to describe the author's experiences with these packages.

Table 1. Microcomputer vehicle-routing packages

Package	Distributor	Phone	Price	Required hardware
Roadshow	Routing Technology Software, Inc. 7315 Wisconsin Ave. Bethesda, MD 20817	(301) 469-3130	\$30,000-\$110,000	IBM PC-XT or AT with 512K
Dispatch/Control	Trans Tech Services 6000 Stoneridge Rd. Suite 240 Pleasanton, CA 94566	(415) 463-1400	Basic System—\$55,000 Advanced System—\$145,000	Appollo family of super micros
Distribution Scheduling System (DSS)	Systems Research, Inc. 1919 Indiana Lane Manhattan, KS 66502	(913) 539-8338	\$750	IBM PC-XT or AT with 512K
E-Z Router	Productivity Specialists, Inc. (PSI) Two Crossroads of Commerce Rolling Meadows, IL 60008	(312) 870-8667	\$22,000-\$40,000, depending on site customization	IBM PC-XT/AT
Fleet Router	DASTEK P.O. Box 440125 Houston, TX 77244	(713) 531-1718	\$995	IBM PC with 256K
Micro Veh Plan	United Management Consultants 9900 Main Street Suite 300 Fairfax, VA 22031	(703) 691-4080	\$1,995	IBM PC-XT or AT Burroughs B20 Series of Micros
NetSolve	Distinct Management Consultant 10750 Hickory Ridge Rd. Columbia, MD 21044	(301) 596-3100	\$495	IBM PC-XT or AT with 512K
Roadnet	Roadnet Systems Corp. 117 Lakefront Drive Hunt Valley, MD 21030	(301) 666-0399	\$5,000	IBM PC-XT or AT with 512K
RouteAssist	Logistics Resources Leaseway Transportation 3700 Park East Drive Cleveland, OH 44122	(216) 464-3300	\$10,000 plus \$500 per month	IBM PC-XT or AT
Routemaster	Applied Operations Research Inc. 22056 Saticoy St. Canoga Park, CA 91303	(818) 888-336	\$495	Almost any micro
Routeplanner	Columbia Software P.O. Box 2235 Columbia, MD 21045	(301) 997-3100	\$70	Apple II +
Trucks	Logistics Decisions Systems, STSC, Inc. 2115 East Jefferson St. Rockville, MD 20852	(301) 984-5488	\$21,500 base price and up, depending on customer size	IBM PC/XT/AT with 640K
Truckstops	MicroAnalytics, Inc. 2054 N. 14th St. Arlington, VA 22201	(703) 841-0414	\$1,995	IBM PC/XT/AT with 256K

2. STRATEGY

Certain limitations are inherent in a survey such as this. First, the costs of acquiring all codes for a comprehensive evaluation is prohibitively high. Therefore, only those packages having demonstration diskettes were actually used in a "hands-on" mode. Unfortunately, these made up only 4 of the 13 available packages. For the remainder of the packages, literature and phone inquiries were used to assemble the data. The accuracy of this information may therefore be somewhat less reliable than that of the four "test-driven" packages. Second, existing codes are being updated and improved and new ones are continually emerging in the burgeoning microcomputer software marketplace. Third, each code may solve the same vehicle-routing and scheduling problem but with differing objectives in mind. For example, one code may first seek to minimize the number of vehicles used in a network and then to minimize the number of miles traveled, whereas a second code may try to assign vehicles to routes so that all customers will be serviced with the minimum distance traveled. Thus, direct comparisons of routes developed by different codes may be somewhat misleading.

With these limitations in mind, the following plan was developed. Each code's vehicle-routing features, as obtained through vendor information and phone inquiries, were listed and compared. In some cases, sufficient information was not available to make a good comparison. In the case of the demonstration diskettes, test problems were run in an attempt to compare the route-optimization efficiency of these codes. These test problems were limited by the number of nodes that the demonstration diskettes would allow. Results are shown in Sect. 7.

In addition to quality of the solution reached, each package was also evaluated on characteristics such as time-window constraints for individual stops, backhauling capability, multiple pickups and deliveries on a route, multiple terminals, cargo/stop matching, etc. This evaluation is presented in Sect 6.

3. OVERVIEW OF PACKAGES

All codes will solve the basic single-depot vehicle-routing problem. This problem is to find a set of delivery routes to a set of customer locations for vehicles housed at a central depot that minimizes total distance traveled or total fleet travel time. The customers are represented as nodes in a network whose demand is deterministic and is known in advance.

Also assumed in the basic vehicle-routing problem is that each vehicle has the same fixed capacity and can operate each day for a specified length of time. Most vehicle-routing packages use what is known as a "two-phase" method of heuristics to solve the basic vehicle-routing problem. In phase 1, customers are served by vehicles without specifying the sequence. In phase 2, routes are obtained for each vehicle using a traveling-salesman heuristic that seeks to find the minimum cost or distance route sequence.² The solution method for a typical vehicle-routing package is shown in Fig. 1.

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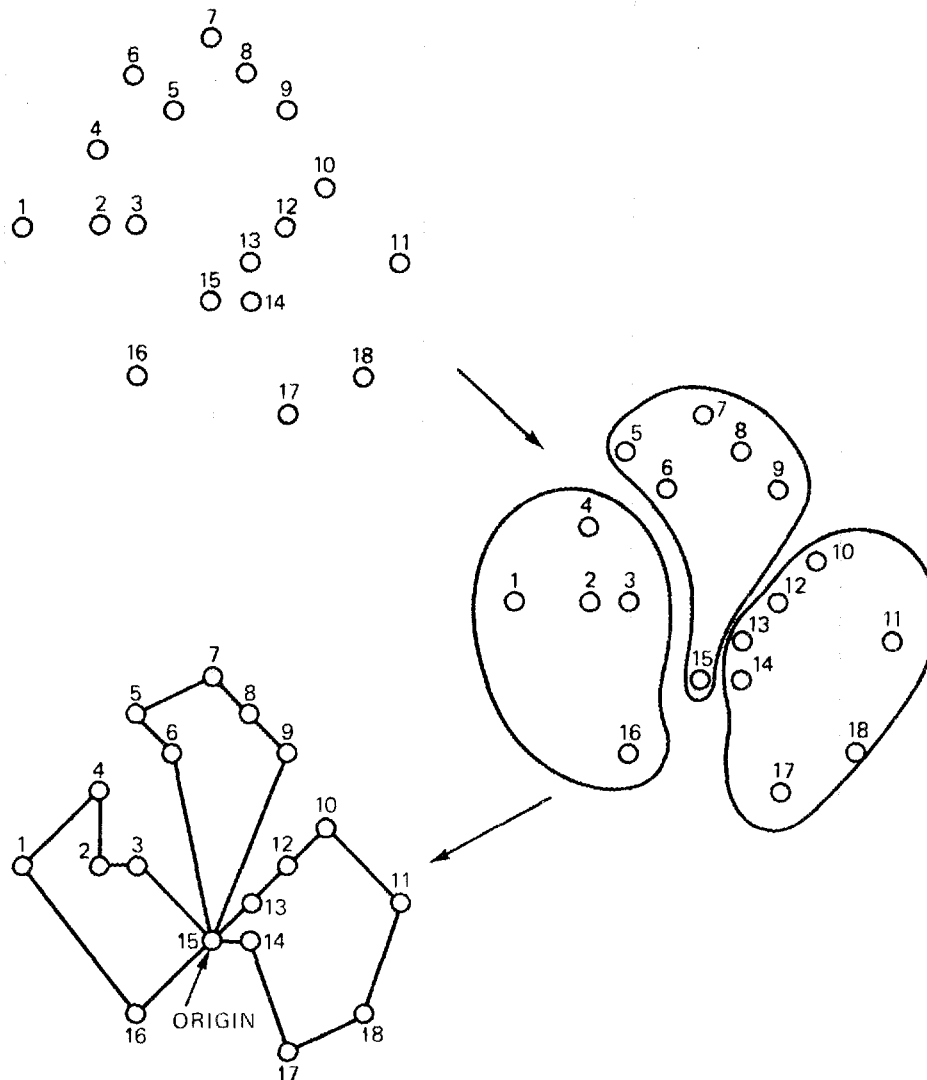


Fig. 1. Vehicle-routing solution sequence.

Although the amount and type of input required for individual packages varies, there are certain basic requirements for all codes. At a minimum, customer and depot locations must be entered using latitude/longitude or some sort of x-y grid coordinates, except in the case of very expensive packages in which geocoding is employed. Each customer's demand (weight or volume) must be identified. Vehicle types, sizes, and capacities must be identified as well. In addition to these basic input requirements, other data may be entered, such as grid scaling factors, speed zone considerations, natural barriers, stop times for each customer (which can be fixed or in terms of quantity/time for pickup or delivery), maximum distance or travel times for vehicles before requiring layover or break [in accordance with Department of Transportation (DOT) regulations], cost factors (per mile, per hour, and overtime), and unloading times.

Obviously, a considerable amount of data has to be entered to set up a network before these codes are operational. The amount of data, however, would not be any greater than that required by a dispatcher if he were to route the vehicles manually. Some of the more user-friendly codes have global updating capabilities that reduce the time and effort for this initial data entry, especially when some of the entries are repetitive. For example, if all stops in the network have the same time-window for delivery, rather than retrieving each individual stop record and entering the data each time, the code allows a global update of the time-window information to be made. This drastically reduces the amount of keyboard manipulation required.³

The basic vehicle-routing and scheduling problem becomes more complex as real-world constraints are imposed. For example, the fleet may be heterogeneous, having various sizes and capacities of vehicles available. There may be customer-defined time constraints on deliveries or pickups at customer sites. There may be multiple routes for a vehicle, backhaul considerations, more than one depot, restrictions on the type of vehicle that may handle certain cargo, multicommodity capacities for each vehicle, lunchbreak and overtime considerations for drivers, etc.

To deal with the various classes of problems, Bodin et al.⁴ have suggested a taxonomy of vehicle-routing and scheduling problems that classifies each problem on the basis of 12 characteristics (A--L):

- A. Time to service a particular node
 - 1. time specified and fixed in advance
(vehicle-scheduling problem)
 - 2. time windows (combined vehicle routing and scheduling)
 - 3. time unspecified (vehicle routing)
- B. Number of depots
 - 1. one depot
 - 2. more than one depot
- C. Type of fleet available
 - 1. homogeneous fleet
 - 2. heterogeneous fleet
- D. Size of fleet available
 - 1. one vehicle
 - 2. more than one vehicle
- E. Nature of demands
 - 1. deterministic
 - 2. stochastic

- F. Location of demands
 - 1. at nodes
 - 2. on arcs
 - 3. mixed
- G. Underlying network
 - 1. undirected (symmetric distance matrix)
 - 2. directed (unsymmetric distance matrix)
 - 3. mixed
- H. Vehicle capacity constraints
 - 1. imposed—all the same
 - 2. imposed—not all the same
 - 3. not imposed
- I. Maximum vehicle route times
 - 1. imposed—all the same
 - 2. imposed—not all the same
 - 3. not imposed
- J. Costs
 - 1. variable or routing costs
 - 2. fixed operating or vehicle costs
- K. Operations
 - 1. pickups only
 - 2. deliveries only
 - 3. mixed
- L. Objective
 - 1. minimize routing costs
 - 2. minimize sum of fixed and variable costs
 - 3. minimize number of vehicles

As might be expected, the more expensive packages can handle more of the Bodin characteristics. Thus, a natural breakdown of the microcomputer systems is based on price. Generally speaking, the inexpensive vehicle-routing packages cost less than \$2000, the more expensive routing systems range between \$5000 and \$20,000, and the very expensive packages cost anywhere from \$50,000 to \$145,000 (inclusive of vendor installation, customization, training, and support). This breakdown is shown in Table 2.

3.1 VERY INEXPENSIVE PACKAGES

Netsolve, Routeplanner, and Routemaster are all very inexpensive (less than \$500), but they solve only the traveling-salesman type of problem and not the more general vehicle-routing problem. Consequently, these three codes are in a separate category and are not considered in any detail. They are included in Table 2, however, for the sake of completeness. Netsolve, in addition to the traveling-salesman problem, will solve transportation, assignment, and minimum spanning-tree problems. One disadvantage of Netsolve is that the entire distance matrix must be entered in network fashion [i.e., the node-to-node cost (or distance)]. The user does not have the option of entering just the x-y coordinates and letting the program calculate the distance matrix. To use Netsolve, a Fortran routine was written to calculate the distance matrix given the x-y coordinates of

Table 2. Breakdown of software packages

Category	Type of package	Code trade name	Comments
I	Very inexpensive (traveling-salesman problem)	Netsolve Routemaster Routeplanner	Also solves transportation, assignment, minimum spanning-tree problems
II	Inexpensive vehicle-routing	DSS Fleet Router Micro Veh Plan Truckstops	
III	Expensive vehicle-routing	E-Z Router Roadnet RouteAssist Trucks	
IV	Very expensive vehicle-routing	Road Show Dispatch/Control	

the stops, and it was formatted as an input file. Once data are entered properly, however, Netsolve works well. There are three heuristics from which to choose: (1) farthest insertion, (2) cheapest insertion, and (3) nearest neighbor. The limit on the number of arcs in Netsolve is 1000, which means that the number of stops allowable is about 45. Routeplanner seems to offer an optimal procedure for solving small traveling-salesman problems. Routemaster can handle larger problems and employs a heuristic of some kind.

The remainder of the discussion in this report will deal with codes in categories II, III, and IV. Demonstration diskettes were obtained for the category II codes, and sample networks were run. Information was obtained from literature review and vendors for codes in categories III and IV. Category IV, which includes Roadshow and Dispatch/Control, is the high end of the vehicle-routing and scheduling software market. This particular market includes products that solve the real-time vehicle-routing problem, employing interactive graphics that use (1) computer-generated maps to do "what if" studies on alternative route combinations and (2) geocoding instead of manually input x-y coordinates to identify customer locations. They are discussed next.

3.2 VERY EXPENSIVE PACKAGES

3.2.1 Roadshow

Roadshow, from Routing Technology Software, Inc. (RTSI), is a relatively new vehicle-routing, scheduling, and dispatching system that supports the real-time management and special situation requirements of the dispatcher and fleet manager. Roadshow operates on an IBM PC/AT with dual display screens and enhanced graphics capability. It employs interactive graphics that allows last-minute delivery routes changes to be made with the aid of a mouse. The user can review the routes presented on the map screen and, at the same time, evaluate the comparative cost and logistics data on Roadshow's text screen. If a change is desired (to add, delete, reassign stops to a different route, resequence, etc.), the user moves the mouse to the appropriate stop and presses a button. A new route is generated, and the associated costs are displayed on the companion screen. Several

alternative routes can be evaluated quickly. Roadshow employs expert-system programming techniques with learning features that incorporate past driver performance in an attempt to improve the scheduling efficiency of future routes. Map data is geocoded by RTSI for the particular dispatching area in question. The user simply provides the street address of each customer, and Roadshow identifies the latitude/longitude coordinates from the geocoded data base provided.

Roadshow can handle most constraints for the general vehicle-routing problem, including:

- vehicle/driver constraints
 - vehicle capacity
 - availability
 - cost considerations
 - driver incentives
 - driver hour limits and DOT work rules
 - vehicle-driver matching
 - vehicle-commodity restrictions
 - tractor-trailer assignments
- delivery site constraints
 - multiple delivery windows
 - driver-truck restrictions
 - variable stop times
 - backhaul
 - variable setup times

Extensive documentation, education, and installation support is received with the package. As part of the installation process, RTSI will spend time at the customer's site to collect the necessary vehicle, stop, driver, and other data to ensure that the system will be running as quickly as possible.

3.2.2 Dispatch/Control

Dispatch/Control is intended to help motor-carrier dispatchers route vehicles around areas in efficient pickup-and-delivery operations. It is one of the few packages that will solve the real-time vehicle-routing problem. Customers demanding delivery or pickup are known in advance, usually the day before, and information is entered about the weight, cubic dimensions, number of packages, etc., and customer identification. Also, information must be given about time windows for customer pickup or delivery, vehicle availability, and other factors. Tentative vehicle routes are then developed in advance of the day's activities. Customers can also call in for same-day service. These customers are added to the existing routes, or new routes are created to handle the additional customers. Before leaving the terminal, the driver receives a printed schedule of stops with expected

arrival/departure times, customer service windows, and delivery volume. This provides management and drivers with documentation of expected performance.

Dispatch/Control will handle all the constraints listed for Roadshow (Sect. 3.1). The customer location data are based on extensive geocoding provided for the service territory by Transtech. This eliminates the time-consuming and largely clerical task of plotting customer locations for various routes from grid maps and inputting coordinate data into the vehicle-routing program. In addition to a built-in data base of all valid street addresses in the service area, Dispatch/Control offers an impressive set of graphics capabilities and is highly interactive. The dispatcher may override the computer's routing decisions at any time by shifting stops from one route to another by using a touch-screen. The system depicts the revised routings on its map display, using different colors to differentiate between pickups and deliveries. The dispatcher can also perform "what if" analyses on proposed changes to a route. The system evaluates changes to a route in terms of customer service windows, driver work rules, capacity requirements, stop service time, vehicle travel time, and other constraints. Any problems that may occur in the route are highlighted in an exception report so that other alternatives may be examined.

3.3 REMAINING VEHICLE-ROUTING AND SCHEDULING PACKAGES

Of the remaining eight microcomputer packages, only four have demonstration diskettes available. All four of these were tested, which included DSS, Fleet Router, Truckstops, and Micro Veh Plan. The other codes are in the expensive category and available vendor information plus literature was used to compile characteristics.

The four demonstration systems were tested using sample networks from Christofides *Distribution Management*.⁵ Section 5 describes in detail the key features of these four systems and some of the results of this network testing. Section 4 provides a description of the key characteristics of vehicle routing and scheduling and how they apply to the remaining packages.

4. KEY CHARACTERISTICS OF VEHICLE ROUTING AND SCHEDULING

4.1 TRAVEL TIMES

4.1.1 Vehicle Travel Time Calculations

One of the most important considerations in a vehicle-routing package is the calculation of realistic travel times. If customer locations are given as x-y coordinates, a straight-line distance between two points can easily be calculated. All codes surveyed accept stop locations in x-y coordinates, and three of the four inexpensive codes (DSS, Micro Veh Plan, and Truckstops), plus all of the expensive codes, have conversion routines that can handle latitude/longitude coordinates as well. However, it is too simplistic to assume that travel times are linearly proportional to Euclidean distances. If this were the case, travel time would be independent of location. That is, it would take the same amount of time to traverse a mile in the country, suburbs, or in the city, which is obviously not the case. The need for realistic travel times becomes particularly acute for travel within cities, where delivery windows for customers may be short, for example, between 15 minutes and an hour. Therefore, some means must be found to make adjustments for the different environments to be encountered in a vehicle route. This is generally done through the use of speed zones, travel standards, and natural-barrier routines and, in the case of the very expensive codes, geocoding at the block-face level. The additional information and setup required by the systems to enter this kind of data involves a great deal of manual input and time, but the accuracy of the travel times is worth the effort. Once entered, this data need not be changed unless new routes or stops are added.

4.1.2 Accuracy of Distance Calculation

The accuracy of travel-time calculations is only as good as the location coordinates used as input for calculating distances. The use of latitude/longitude coordinates, with minor modification, usually can serve very well as the stop locations of most codes. Some codes, DSS and RouteAssist in particular, offer the user a zip code option to identify stop locations instead of entering x-y or latitude/longitude coordinates. The zip codes are converted internally to latitude/longitude, and distances are calculated in straight-line fashion. This is adequate if there are not too many stops within the same zip code.

There are a number of data bases available for listings of latitude/longitude coordinate information. For example, the U.S. Geological Survey publishes an index to the U.S. National Atlas that includes the latitude and longitude coordinates for virtually all cities and towns in the United States. Unfortunately, there is no automated method of extracting this latitude/longitude information from the U.S. Geological Survey data and having it input into the various vehicle-routing and scheduling systems.

Some packages, generally the more expensive ones, offer a location coordinate data base, which is a subset of the the U.S. Geological Survey data base. This location coordinate data base provided with the vehicle-routing package can be tailored for a specific service area. An interface routine to access this location coordinate data base is provided by the vendor so that the data can be read by the main scheduling program. This additional location data base and corresponding access software usually costs extra. Of the four systems tested, only Micro Veh Plan and Truckstops offered this type of automated latitude/longitude data retrieval. All the more expensive codes either have the

capability to interface with an external data base for extraction of coordinate information or provide a geocoded data base that automatically retrieves coordinate information. Geocoding is described later in this section.

If more accuracy in distance computation is desired, there are data bases available for extremely detailed latitude/longitude information of stop locations, including detailed street information and zip codes. Highway information data bases for accurate readings of the network links include Rand McNally's Milemaker and Logistics Systems' Compu Guide.⁶ However, such data bases tend to be somewhat expensive and are usually oriented to mainframes. The user generally has to access information in one operation and input it into the program in another. Using a suitable computerized location data base, a clerical person should be able to generate over 1000 coordinates per day. Most often, fleet operators or distribution companies will use detailed maps of their service regions that have latitude and longitude notation to generate coordinates. Each point is located on the map and a certain amount of interpolation is done to read the coordinates, which are then manually input into the vehicle-routing and scheduling program.² This can be a tedious operation, and many companies prefer contracting this type of service.

Somewhat easier than transcribing location data and inputting it into a program is to use a digitizer, an electronic key pad equipped with a cursor device such as a mouse or light pen. The cursor device is positioned over the stop location, and the coordinates of the point are transmitted to the microcomputer. Both Truckstops and Micro Veh Plan (of the inexpensive packages) offer links to a digitizer to automatically input stop location and distance coordinates. All of the more expensive codes offer this digitizer interface, if desired.

4.1.3 Geocoding

Using latitude/longitude listings is an effective procedure as long as the cities or towns available in the listing provide sufficient detail for the user's purposes. This is generally the case for companies involved in intercity delivery operations, but not so for companies whose deliveries are primarily local. For example, if delivery is made to a chain of stores throughout the Carolinas, the occasional occurrence of two or three deliveries in Raleigh with the same coordinates probably doesn't do much harm. If, however, the company routinely performs all its deliveries in the greater Washington-Baltimore area, for example, city and town locations will not give sufficient detail for accurate routing. This can be overcome through a technique called geocoding.

Geocoding is a computer-based routing method that matches customer addresses with specific map latitude/longitude coordinates. The geocoded data base contains all valid streets and street addresses within a given distribution area. The geocoding process requires meticulous attention to detail and is a time-consuming task when routing vehicles in high-density metropolitan areas. Generally, it is not practical for a single computer user to geocode an entire service area. Therefore, geocoded data bases for particular metropolitan areas are usually provided by the vendor supplying the vehicle-routing software as part of the full purchase price. Of the systems surveyed, only the most expensive, Transtech's Dispatch/Control and RTSI's Roadshow, provide geocoding support.

Geocoding provides the most accuracy when combined with a street/highway model. Each address is given its own latitude/longitude coordinate, and the street/highway model is used to calculate distances from one point to another. Because the travel model represents real highways and streets, it accounts for natural barriers (e.g., lakes, rivers) and calculates true distances, not straight-line distances as do less-expensive dispatching systems that employ an x-y coordinate

system for customer locations. The combination of geocoding and a street/highway model is the most accurate way to calculate customer-to-customer travel times.⁷

In addition to providing accuracy of distances, geocoding is also flexible and simple to use when adding new customers or changing existing routes. The user simply enters the street address of the new customer, and the system immediately identifies the location from the address. There is no need to look up a map coordinate. Used in conjunction with a computer graphics system, geocoding offers speed, accuracy, and simplicity in generating routing structures interactively. Daily modifications of existing routes can be made if required, based on the actual customers to be serviced on that day. In summary, geocoding is the best as far as ease of setup, ease of adding new customers, and accuracy of computed travel times. The obvious drawback is the high price of such systems—about \$100K for a company having a fair-sized distribution operation.

4.1.4 Network-Based Travel Times

Network-based travel times provide the most accuracy in estimating travel time because each network link (node to node) is coded with the actual data from previous trips. However, inputting data this way requires a considerable investment of time and money. Some systems allow for a combination of both actual network distance or time and x-y coordinates. Among the inexpensive codes, Micro Veh Plan has the capability to enter actual network-based distance for each customer link. Truckstops provides a distance file interface as an extra option, but the other two inexpensive codes, Fleet Router and DSS, do not have this capability. Among the expensive codes, Roadnet and Trucks use network-based distances or travel times in one way or another.

4.1.5 Speed Zones and Travel Standards

Truckstops, DSS, Fleet Router, RouteAssist, and E-Z Router all use speed zones to more accurately reflect travel times. Fleet Router has the most extensive capability in this area, having up to 15 speed zones that the user may input to simulate driving conditions between and within zones the user specifies. Other codes use “environmental” or travel standards for specifying routing operations. For example, the Trucks package allows the user to establish one set of parameters to apply in good weather under normal conditions, another to take into account rain-or snow-caused delays, another to accommodate rush-hour conditions in urban areas, another for holiday schedules, etc. By specifying such detailed environments, the user presumably has a better chance of obtaining accurate travel times between customer locations.

Micro Veh Plan, on the other hand, does not use speed zone information but employs three travel-standard types that correspond to formulas that predict travel time for any given travel link. The travel-time formula is a combination of a fixed time per stop and a variable time per mile. By using data relating time traveled and distance between delivery points, a regression analysis can develop a travel formula that would be applicable to a particular environment, for example, rural deliveries. This is somewhat more cumbersome to use than simply entering average mile-per-hour figures for given speed zones.

Summarizing, the use of speed zones and travel standards allows the user to specify more accurately the travel times associated with each network link. Speed zones are the easiest and most common way of handling the various driving conditions found within a typical service region. The use of environmental or travel standards probably offers more accuracy but also is more costly in terms of data analysis to develop parameters and additional input and maintenance.

4.1.6 Natural Barriers

In addition to speed zones, DSS, Truckstops, and Fleet Router have natural barrier routines that allow the user to simulate barriers such as rivers and lakes in a straight-line fashion, linking specified coordinate points or zones. To calculate distance between customers separated by a barrier, the system routes the vehicle in parallel with the barrier until a transit point or the end of the barrier is reached, at which point the vehicle is then routed to the destination point in a straight line. Truckstops and Fleet Router both have barrier routines that use x-y coordinates to locate barrier segments. DSS identifies a barrier through identification of the zone numbers it spans. Because a zone may be an area, rather than a single point, this method of identifying barrier locations may be somewhat less accurate than use of x-y coordinates. It should be noted that as the number of barriers or transit points increases, the amount of execution time required to compute intercustomer distances and transit times increases. This is because the system must examine many alternative routes around the barrier before it can decide on the best or minimum-time route. It is, therefore, best to define only those barriers that represent significant diversions for vehicles, for example, more than 15 min. Another point to consider is whether the improved accuracy provided by using barriers outweighs the inaccuracies that arise from variations in traffic conditions. Expensive codes such as Dispatch/Control and Roadshow do not use barrier routines because these codes are based on extensive geocoding, which takes barriers into account and can calculate true distances. An example of a barrier is shown in Fig. 2.

ORNL-DWG 86-18406

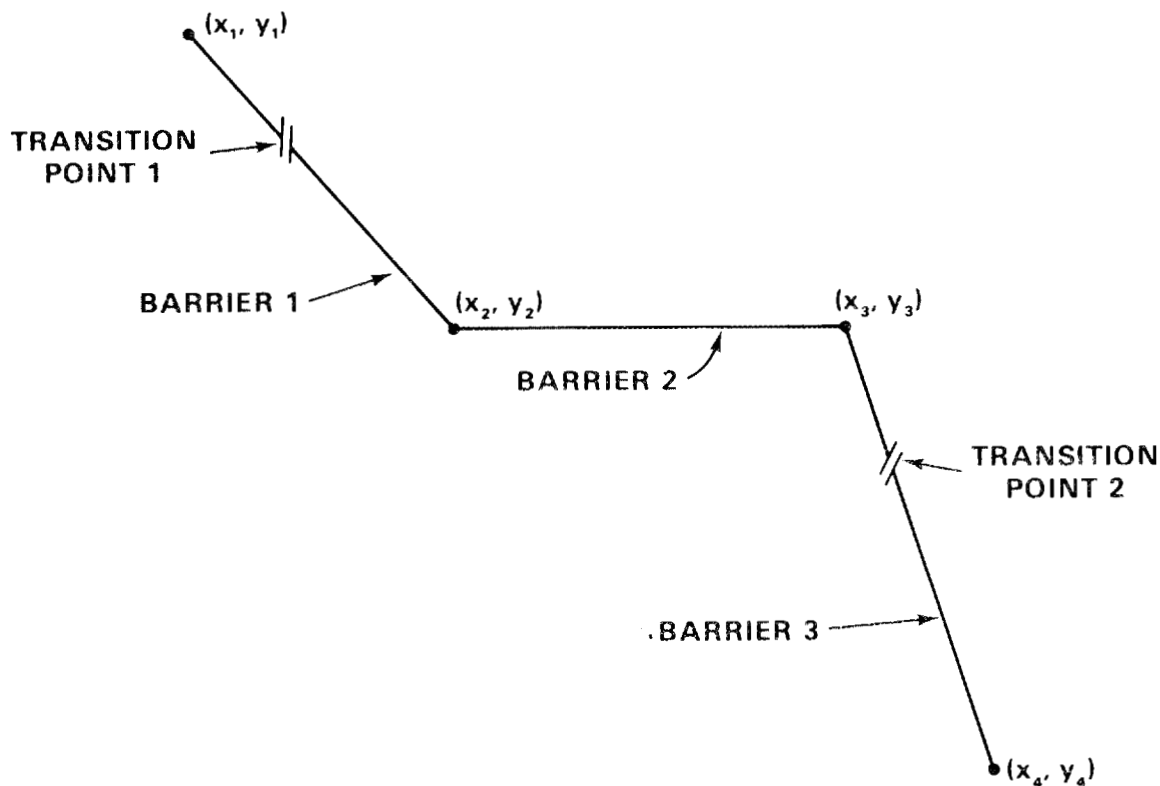


Fig. 2. Example of a barrier.

4.1.7 Distance Calculation Method

In addition to barrier routines that may improve the accuracy of the distance calculations, some codes allow for calculation of the distances to be done in either straight-line (or crow-fly) or rectilinear (or right-angle) fashion. For example, the latter approach might be preferable in a dense-traffic situation at the block-face level in the city, where many right-angle turns are the rule. Experience has shown that the straight-line method should be used unless the rectilinear nature of the roads is overwhelming. The straight-line distance calculation method would be preferable for intercity or country driving conditions. Of the codes tested, DSS and Truckstops have the capability to calculate distance in rectilinear fashion; Micro Veh Plan and Fleet Router do not. All of the more expensive codes have the capability to calculate distances using both methods.

4.1.8 Scale Factor

All codes tested have the capability for the user to enter a scaling factor that converts grid units (the x-y coordinate units) into actual miles. The use of straight-line or right-angle calculation methods will produce a distance that is based simply on the grid units. The grid-based distance must be multiplied by a scaling factor to produce an estimate of the actual miles driven on that leg of the trip. Experience indicates that for North America, straight-line miles should be scaled up 10–20% to correspond reasonably accurately with odometer or hub miles; 20% is the more typical scaling factor for eastern metropolitan areas, whereas 10% is typical for midwestern rural areas. To develop the scaling factor, a company uses the actual odometer data for a set of vehicle routes and compares that with the straight-line or rectilinear distances (depending on which method was used) derived from the vehicle-routing software with the scaling factor set at one. The ratio of calculated over actual distance is the scaling factor. Some of the vendors provide consulting services to develop accurate scaling factors using regression analysis techniques. These vendors claim they are able to produce mileage estimates that are accurate to 2–3% of actual distances 90–95% of the time.

4.2 CUSTOMER (STOP) DATA

4.2.1 Time Windows

A time window indicates the time when a delivery or pickup can be made at a customer location. A hard time window restricts the delivery to the specified interval of time only, whereas a soft time window allows the vehicle to miss the interval.⁴ For the soft time window, a penalty is assessed based the number of minutes early or late. In some situations, customers may have multiple time windows, for example 9:00–11:00 a.m. and 2:00–4:00 p.m. In addition, the open time (close time) for a customer is defined to be the absolute earliest time (latest time) that a delivery can take place. Of the four codes tested, DSS, Truckstops, and Micro Veh Plan have hard time window capabilities. Truckstops and Micro Veh Plan allow two hard time windows per stop; DSS accommodates one hard time window. A summary is shown below.

Time window	Code trade name
Hard	DSS, E-Z Router, Micro Veh Plan, RouteAssist, Truckstops, Trucks
Soft	Roadnet
None	Fleet Router

4.2.2 Delivery Times

All codes allow the delivery time at each customer location to be a fixed amount that is specified in advance or a variable amount that is estimated by a formula of the type

$$\text{Delivery time for customer } i = A(i) + B(i) \times \text{Demand}(i),$$

where $A(i)$ is the fixed amount of time required to deliver goods, $B(i)$ is the time required to deliver one unit of goods, and $\text{Demand}(i)$ is the actual demand to be delivered to customer i . The unit of goods may be weight (CWT), volume (CUFT), pallets, No. of containers, etc. This information must be entered for each customer location. Some codes have the capability to handle multiple types of goods, in which case the user may specify different delivery times for each type. If delivery times are not specified, the code will default to a value the user specifies (in a general parameter file) that has been set for all stops.

4.2.3 Vehicle/Stop Restrictions

Often, individual stops can restrict selected truck types. Most vehicle-routing packages have the capability to enter requirement codes that indicate that the stop must be loaded uniquely on a vehicle having the matching code. The vehicle/stop restriction is important in the case where certain types of trucks can be turned away from or rejected by certain stops because of dock-size limitations or parking problems. DSS, Truckstops, and Micro Veh Plan (among the inexpensive codes) and all the expensive codes have a vehicle/stop restriction capability. Some of the codes even allow for specifying whether the stop is considered a tail load (i.e., the first stop on the route, on the "tail" of the truck), or a head load (i.e., the last stop on the route, in the "head" of the truck). The use of these special restriction codes introduces a significant additional level of complexity into the vehicle-routing calculation and requires a certain amount of care to implement effectively.

4.2.4 Multiple-Depot Capability

If a distribution company has several depots in its operations, the dispatcher may wish to know which one may most effectively serve a fleet of vehicles having several routes in a service region. In this case, vehicles or routes are not assigned a priori to a particular depot; the vehicle-routing program makes this assignment based on the most efficient and economical routing schedules that can be constructed. Of the packages surveyed, only DSS has true multiple-depot capability. That is, it selects the "best" depot to serve a set of scheduled vehicle routes. In the other codes, the stops are initially assigned to a given depot, from which the constructed routes start and end.

4.3 ROUTES

4.3.1 Backhauling

The backhaul is the segment of the vehicle delivery trip from the last customer delivery location back to the depot. Usually, the vehicle is empty when it makes this return trip. This creates an unprofitable segment of vehicle utilization on each vehicle trip. Thus, being able to utilize the vehicle for making a pickup on this leg constitutes a good opportunity to increase the profitability of the distribution operation.

On a backhauling route, deliveries assigned to a vehicle are carried out first. Once the vehicle is empty, it is designated to make some pickups and transport the goods picked up back to the depot. The simple backhaul problem assumes no more than one pickup (backhaul) assigned to a route; the multiple backhaul problem assumes more than one.

Of the inexpensive codes, only Fleet Router does not provide backhauling capability. Of the more expensive codes, Roadnet and Router do not have backhauling capabilities. The remaining six codes can handle both simple and multiple backhaul problems.

4.3.2 Pickup and Delivery

A somewhat more general case than the backhaul problem is the pickup and delivery problem. In the pickup and delivery problem, the vehicle is scheduled to pick up a customer or goods at one location for delivery to a second location, not necessarily the depot. Such operations occur in messenger and limousine services. One vendor reports that this type of operation is employed by a major soft-drink retailer in making deliveries of products to distribution warehouses located throughout the bottler's region. Micro Veh Plan is the only inexpensive code that handles the general pickup and delivery problem. Among expensive codes, E-Z Router appears to be the only system capable of dealing with this problem. The simple vehicle-routing, backhaul, and general pickup and delivery problems are illustrated in Figs. 3-5, respectively.

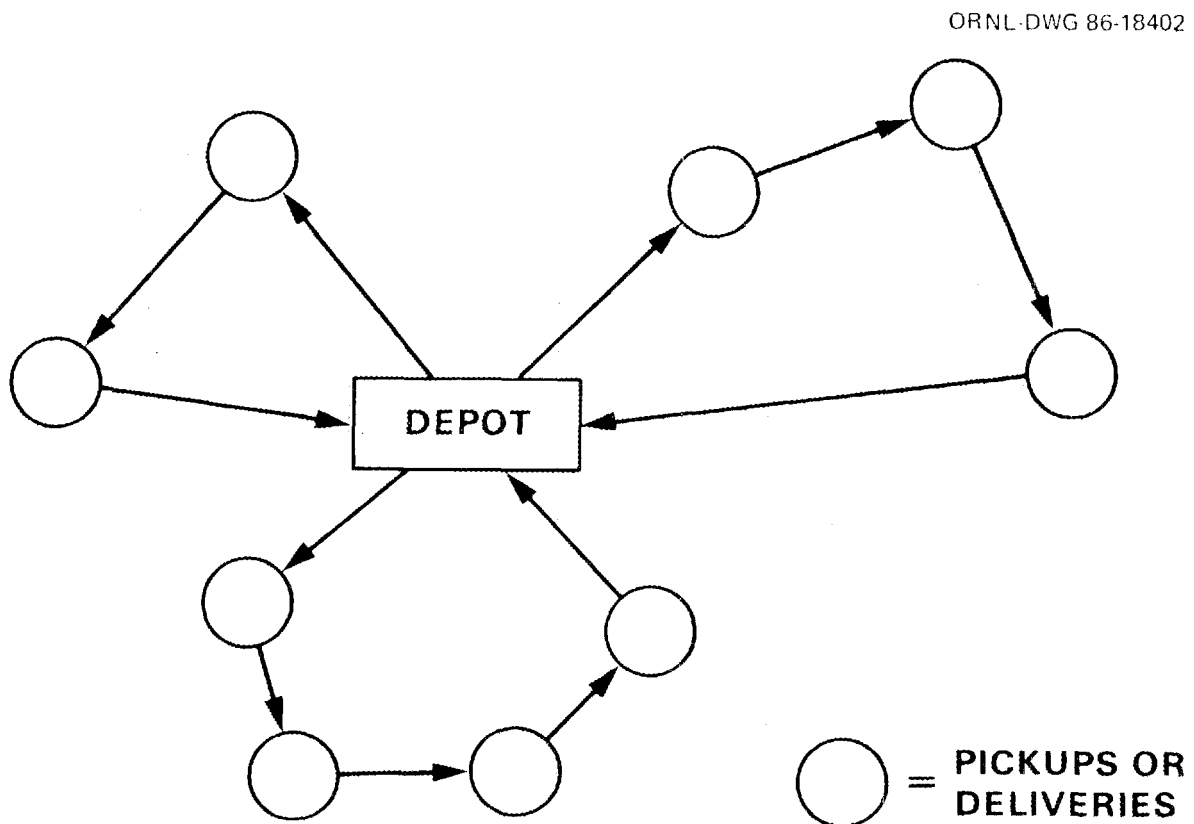
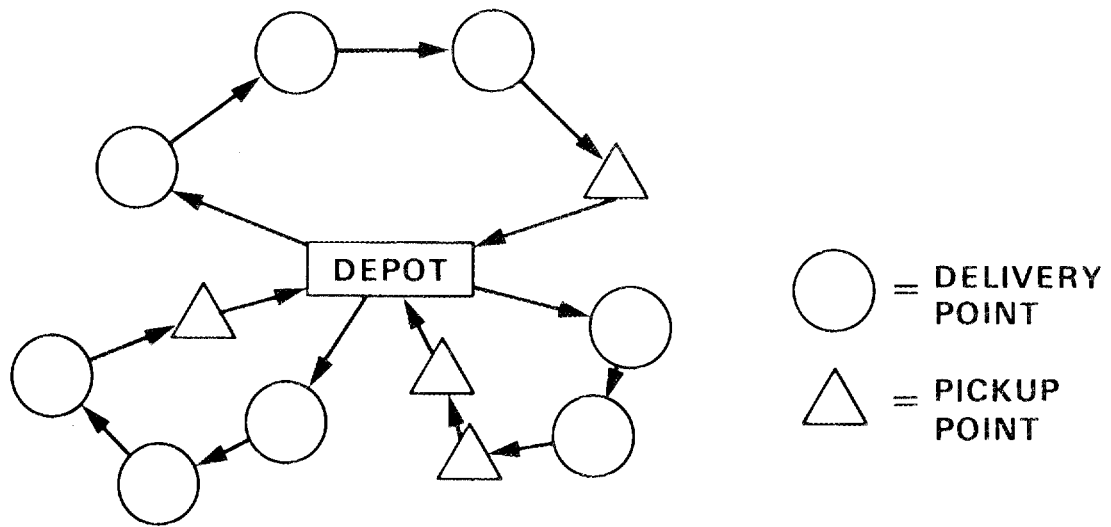
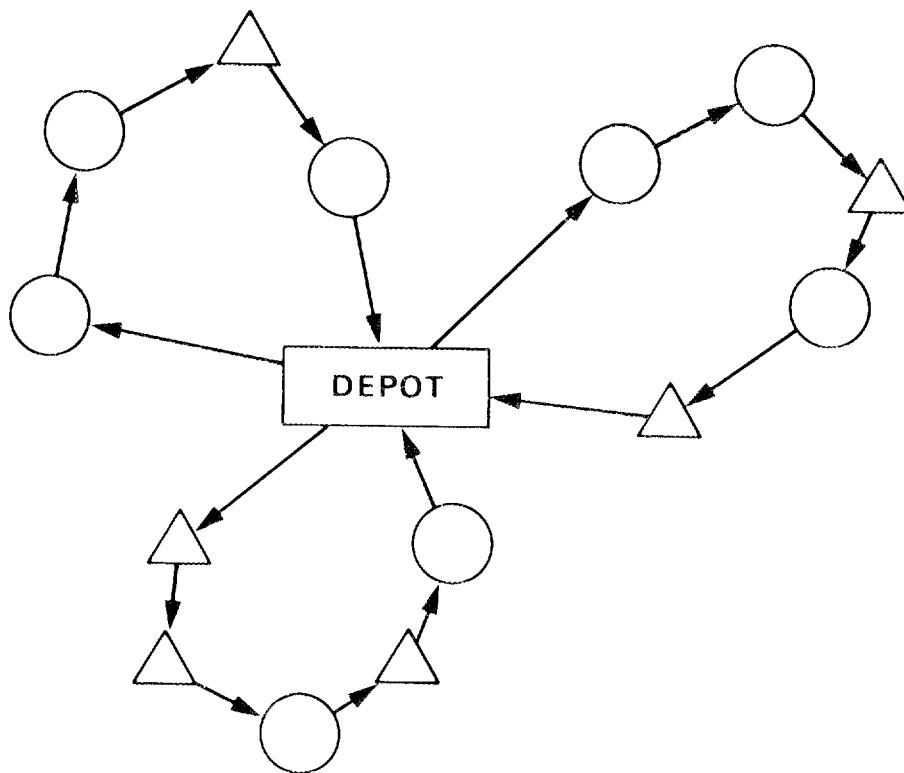


Fig. 3. Basic single-vehicle-routing problems

**Fig. 4. Backhaul problem.****Fig. 5. General pickup problem.**

4.3.3 Multiple Routes per Day

Each of the codes provides some kind of procedure for scheduling a vehicle on more than one route in a day. This situation occurs when the number of vehicles is limited and the routes are short, so that the vehicle has to return to the depot to reload and embark on one or more other routes on the same day.

4.3.4. Maximum Time or Distance per Route

In practice, there may be some limitation on a route's distance or time. For example, a delivery vehicle may not exceed 8 h on any given route because of freshness requirements or perishability of the products it delivers. Of the codes surveyed, only DSS and RouteAssist have the capability for constraining a particular route by distance or time. In other codes, the constraints are the normal DOT regulations governing total work and drive time for a vehicle, irrespective of routes.

4.4 VEHICLES

4.4.1 Start and End Times for Vehicle

Generally, company vehicles scheduled by the dispatcher will have differing start times for leaving the depot and differing end times for returning to the depot. Thus, it is desirable for codes to specify each vehicle's start and end times separately. In practice, it is often not possible for all vehicles to leave the depot simultaneously. Fleet Router and Router are the only two codes that require all vehicles to start and end at the same time. The other seven codes allow for different start and end times.

4.4.2 Work- and Drive-Time Constraints

The intercity movement of goods often requires vehicles to be on the road for more than one day at a time. DOT rules and regulations govern the amount of work- and drive-time limits for vehicle operators. Work-time limits refer to the amount of time a vehicle can be on the road before a layover is required. Drive-time limits refer to the amount of drive time for an operator before a layover is required. Most codes allow for the entry of work- and drive-time limits as constraints. When either the work-time or drive-time limits are exceeded, the system will schedule a layover of a specified length. When both limits are entered, multiple-day trips can be scheduled in accordance with DOT regulations or similar company operational policies. Some codes also allow for the inclusion of a lunch break that further constrains the code's scheduling of individual stops on a route. Of the codes surveyed, only Fleet Router, DSS, and Roadnet have no provision for handling multiple-day trips.

4.4.3 Vehicle/Driver Operating Costs

Most codes allow vehicle costs to be entered as a mileage, hourly, or overtime charge. In addition, some codes allow driver costs to be entered as hourly, overtime, mileage, and layover charges. After the system has completed its vehicle routing and scheduling of stops, a printout may be obtained of the fixed and variable costs of each route. Micro Veh Plan and RouteAssist appear to be the most complete codes in this respect. These two codes even allow the user to explore the

possibility of serving particular stops via common carrier rather than private fleet for economic reasons. Of the codes surveyed, only DSS and Fleet Router have no capability to handle either vehicle or driver costs.

4.4.4 Vehicle Capacity Constraints

Every vehicle-routing program must allow for entry of vehicle capacities. The capacity is generally entered as a weight (CWT) or volume (CUFT). Other units may be used (e.g., pallets, cartons, boxes, etc.), as long as the unit is consistent with the demand units specified at the stops. Most codes assume that the truck is a single-compartment vehicle having only one load constraint. Truckstops allows for two load constraints, whereas DSS allows for seven different constraints, each corresponding to a separate truck compartment. The ability of a program to use separate compartments is useful when tracking goods that require special handling or treatment, for example, refrigerated vs nonrefrigerated.

4.5 INTERVENTION CAPABILITIES

The algorithms in the systems under review are heuristics, that is, they employ certain rules or procedures for constructing or improving vehicle routes. Because they are heuristics, they generally will not supply the optimum solution to a vehicle-routing problem. After review of the program's output, the dispatcher may decide that a vehicle route may be improved if customers or vehicles can be exchanged. The results of routing may provide a good initial solution to the routing problem; however, the solution may not correspond to what the company feels its operational and selected truck/stop combinations should be. The dispatcher is also aware of any additional constraints that the scheduling algorithms ignore. Another item that should not be ignored is the experience and knowledge of the dispatcher, who has developed a "feel" for the routes (i.e., which vehicles may best serve a given route). Thus, the capability for manual intervention to allow the scheduler to examine the routes and move about customers is extremely important.

DSS provides no intervention capabilities. On the other hand, Roadnet allows for multiple swaps of customers both within and between routes. The other codes allow the dispatcher to move one customer at a time in modifying the routes.

4.6 GRAPHICS

One of the impressive features of microcomputers is their ability to produce high-quality graphics. It is extremely useful to have a visual portrayal of the vehicle routes that includes assigned customer locations and, perhaps, highlights locations of unassigned customers. This aids in the dispatcher's ability to survey the entire sequence of routes and gain a perspective and understanding of problem areas that might be overlooked in a printout listing.

Of the four demonstration diskettes, Fleet Router's graphics capability is the best; the user can zoom in on a particular area and manually move the vehicle from one route to another. Truckstops has limited capability. The current vehicle's route and all customer locations can be portrayed; however, exchanges of customers or vehicles cannot be made. Micro Veh Plan offers graphics capability as an extra-cost option, and DSS has no graphics capabilities. Of the expensive codes, only Roadnet and RouteAssist have some graphics capabilities.

5. CONCLUSIONS

Although only 4 of the 13 codes described in this review were actually tested, it was apparent that there were significant advantages in using microcomputer-based vehicle-routing and scheduling systems. These systems allow the person most familiar with vehicle-routing operations, namely the dispatcher or scheduler, to perform two basic and closely related route-management functions: (1) to calculate which delivery or pickup stops go on which vehicles and (2) to calculate the order, sequence, or schedule in which each vehicle should make assigned delivery or pickup stops. These two functions can account for significant amounts of time and money for any company that operates a vehicle fleet. Experience has shown that good vehicle-routing software can reduce distribution expense and improve efficiency of operations significantly. Some vendors estimate that a savings of 10-30% is routine.

There is a definite trade-off between the (1) investment of time and money required to set up a computerized vehicle-routing system and (2) the degree of accuracy and responsiveness to real-time situations. Is it worth the cost? If savings of 10-30% is routine, as vendors claim, then the system would probably pay for itself within a year.

What kind of system should a company procure? This depends on several factors, primarily the size of fleet operations and the need for real-time scheduling information. The most expensive packages have geocoded systems that offer a great degree of accuracy in node-to-node travel times and an extensive capability for manual intervention in changing route schedules using interactive graphics tools. These systems are able to handle real-time situations in scheduling last-minute route changes or developing route schedules continually during the day to correspond to customer requests for service, as in the case of a limousine service. Also, the more expensive packages generally include extensive customization of program files and data bases, program installation, training, and customer support. The less expensive packages' main usefulness is in the planning of routes that are not expected to change much. Some have capability for manual intervention, but not to the degree that the expensive real-time systems do. Most of these packages will handle the real-world constraints of backhauling, time windows, vehicle/stop restrictions, and work- and drive-time limits. Instead of geocoding, they generally attempt to arrive at accurate travel times through the use of speed zones, barriers, and zip codes. For smaller companies having a limited number of routes, the less expensive packages would be perfectly adequate. The company seeking to purchase a computerized vehicle-routing and scheduling program has to determine the trade-offs between price and route schedule accuracy, system responsiveness, customized installation, and vendor support.

Also to be considered in selecting a computerized system is the probability that the number of vehicle-routing packages will continue to increase. Our survey found 13 packages that have been developed within the last 2 years. Survival of the packages will depend on a variety of factors such as price, ease of use, generality, geographic data base interface, and vendor support and training.

6. COMPARISON OF DEMONSTRATION DISKETTE PACKAGES

Of the 13 packages that have been discussed in this review, only 4 have demonstration diskettes available. Demonstration diskettes give the user a valuable insight into the system's capabilities, usually enough to evaluate the program's usefulness and applicability to the kind of routing problem to be solved. Generally, the size of the routing problem is limited to a certain number of stops, vehicles, and terminals. For example, the Truckstops demonstration diskette was limited to approximately 45 stops, 8 vehicles, and no barriers, compared with the complete system's 2000 stops, 200 vehicles, and up to 15 barriers. Table 3 lists summary characteristics of each demonstration package, following the same order as Sect. 4. A more detailed description of these characteristics for each package follows.

6.1 FLEET ROUTER

Fleet Router, by Dastek Corporation, Houston, Texas, is an inexpensive vehicle-routing package that would probably serve well as an entry program for a small-to-medium-size firm interested in automating its dispatching operations. The program can handle up to 200 customers and 50 vehicles. Distribution operations having more than these values must be split up into separate problems, solved to yield separate routes and vehicle usages, and then integrated to form a solution to the total problem. Of the four packages tested, Fleet Router is easily the most user friendly; it has a very readable manual, and all data entry and subsequent routing procedures are entirely menu-driven. There are seven menus: case management, main, file selection, file maintenance, order management, and solve/display. One of the appealing features of Fleet Router is that the user may set up different routing problems as separate cases. Thus, different combinations of vehicle stop, time window, and other routing constraints may be examined as individual cases. All customer, vehicle, product, barrier, and speed-zone data are stored under a unique case-file name. Each case file, in turn, is accessed through the case management menu through a series of prompts and different screens.

6.1.1 Distance Calculations

Fleet Router calculates distances in straight-line fashion only, except in cases in which the presence of a barrier precludes a vehicle from proceeding in a straight line between two customer locations. A scale factor, which is part of the control parameter file, may be specified that converts the calculated distance into an estimated distance. There is no provision for entering an actual distance matrix into the system; only the calculated distances are used in the actual construction of vehicle routes. According to the company literature, exact road distances are not a prerequisite for the efficient routing of vehicles. For most cases, approximate intercustomer distances will yield the same vehicle assignment and scheduling decisions as would be the case if exact road distances and times were available.

6.1.2 Speed Zones

Fleet Router allows the user much flexibility in partitioning the geographic dispatching area into speed zones. Speed zones may be concentric (i.e., a smaller zone embedded within a larger zone) and/or contiguous (i.e., side-by-side). Up to 15 speed zones are allowed. Speed zones are

Table 3. Summary characteristics of demonstration packages

Characteristics	Fleet Router (Dastek Co.)	Truckstops (MicroAnalytics)	DSS (Systems Research Corp.)	Micro Veh Plan (United Mgr.)
I. Travel times				
1. Travel-time calculation	Straight-line only; x-y coordinate capability only	Straight-line or rectilinear; coordinates entered as x-y or latitude/longitude	Straight-line or rectilinear; coordinates entered as x-y or latitude/longitude	Straight-line or rectilinear; coordinates entered as x-y or latitude/longitude
2. Interface to external data base	No capability to interface with user-created or external data base; user inputs x-y coordinates into program directly	Distance file and digitizer interface possible at extra costs; user has option of mixing distance file and calculated straight-line distances	No interface capability to user-created or external "true" distance matrix data bases; zip code data base available as option	Interface capability to external lat/long data base; system may also link to digitizer to automatically maintain stop distance coordinates (extra-cost feature); actual distances may also be entered for each network link
3. Speed zones	15 total, identified by map coordinates	6 possible: 4 short-range, 1 medium-range, and 1 long-range	Total of 10 possible	Three travel standards possible; standard includes a fixed time per stop plus a variable time per mile
4. Natural barriers	Total of 15 barriers, each having a maximum of 5 line segments	No limit on barriers; each barrier defined as straight line between two points and having a maximum of 5 transit unloading/loading times	Total of 10 barriers possible, specified by zone locations	None possible
II. Customer (stop) data				
1. Number of stops allowed	200 maximum; if more, additional area must be partitioned as separate case	2000	425	550 with 512K memory; 950 with 640K memory
2. Time constraints	No capability	2 time windows per stop—earliest and latest times for delivery/pickup at each stop	1 time window per stop; includes until, between, or after constraints for arrival/departure times for each stop	2 time windows per stop
3. Delivery times	Load/unload times individually specified for each stop; default values are 2 min for load, 3 min for unload	Specified for each stop as fixed stop time plus variable load/unload rate; if not specified, defaults to general parameter settings	Dock rates individually specified for each stop; defaults to user-specified parameter setting	Specified for each stop as a fixed stop time plus variable unload rate; can accept up to 7 different unit types (cartons, pallets, cases, etc.)
4. Vehicle/stop restrictions	None available	Can specify restrictions on type of truck allowed to serve stop or specific position on a truck (head, tail)	Can specify up to 7 restrictions for vehicle/stop matching	Can specify a particular truck type to serve individual stops; up to 10 different truck stops are permitted
5. Multiple depots	No capability	No capability	Can specify more than one depot; system will select "best" depot for given route	No capability; multiple depots are offered as enhancement at extra cost

Table 3 (continued)

Characteristics	Fleet Router (Dastek Co.)	Truckstops (MicroAnalytics)	DSS (Systems Research Corp.)	Micro Veh Plan (United Mgr.)
III. Routes				
1. Backhauling	No capability	Single or multiple backhauling capability; pickups can be made en route or after all deliveries made; follow nonbackhaul stop in the route schedule	Single or multiple backhauling capability; pickups can be made en route or after all deliveries made	Single or multiple backhauling capability; pickups can be made en route or after all deliveries made
2. Pickup and delivery	No capability	No capability	No capability	Can handle general pickup and delivery problem
3. Multiple routes per day	Yes	Yes	Yes	Yes
4. Maximum time or distance per route	No capability	No capability	Can specify maximum time or distance for a given route	Can specify maximum time for all routes stemming from a given terminal
IV. Vehicles				
1. No. of vehicles allowed	50	200	100	Unlimited
2. Vehicle/driver time constraints	Shift-time limit for each vehicle; all vehicles constrained to start and end at same time	Earliest start time/latest finish time per vehicle; work- and driving-time limit per vehicle operator; layover-time constraint	No work- and drive-time constraints for vehicles	Maximum drive- and work-time limits; DOT weekly limits and layover requirements may be specified
3. Vehicle/driver operating costs	No capability to enter cost information	Hourly, mileage, and overtime costs may be entered	No capability to enter cost information	Vehicle mileage and fixed cost can be entered; driver mileage, hourly, layover, and overtime costs may be entered vs common carrier
V. Intervention capability	Routes can be interactively modified in graphics mode, one stop at a time	Routes may be manually constructed; also includes optimization routines for single and multiple trucks	No intervention capability	Stop sequence may be changed within route; program then calculates new schedule and costs and checks for constraint violations
VI. Graphics	Extensive graphics, with zooming capability	Limited graphics capability	None	None

identified on a speed-zone screen by entering map coordinates of the upper left and lower right corners of the rectangular area of the speed zone, along with the corresponding zone speed. Generally, the user will require at least three speed zones: city, suburban, and country. The city speed zone would be the average speed the company's vehicles are expected to achieve in a congested city area. Similarly, the suburban speed zone would be the average speed the vehicles are expected to achieve in a less congested suburban area, and the country speed would cover average speeds for all areas outside the city and suburban zones. A default country speed of 50 mph applies to the entire geographic area unless otherwise specified by the zone speed.

6.1.3 Natural Barriers

Fleet Router provides considerable flexibility in modeling barriers. Generally, in and around the dispatch area there are likely to be numerous man-made and natural barriers preventing vehicles from driving between customer sites in a straight line. These must be accounted for so that an accurate estimate of travel time between customer sites can be made. The barrier, which may include lakes, shorelines, parks, rivers, etc., is modeled by specifying up to five straight-line segments, each with an (x1,y1) coordinate starting point and an (x2,y2) coordinate ending point. Thus, even oddly shaped barriers, such as a shoreline, may be reasonably approximated through the use of multiple-line segments. A total of 15 barriers, each having a maximum of 5 line segments, is allowed.

6.1.4 Distance Calculation Method

As stated previously, distances calculated by Fleet Router are straight-line distances only. A shortcoming is that no provision is made for rectilinear distance calculation as one might expect at the block-face level.

6.1.5 Network-Based Travel Times

Fleet Router does not allow actual distances to be entered for each network link (e.g., node i to node j). All travel times are calculated given the straight-line distance between customer locations and the average speed entered for that zone.

6.1.6 Time Windows

Fleet Router does not have the capability to enter specific time windows for pickup or delivery at a customer location. Also, the system cannot enter constraints for earliest and latest times for delivery or pickup.

6.1.7 Delivery Times

Fleet Router allows specification of a fixed load and unload time for each customer order. There is no provision for a variable rate (load or unload time per unit of goods).

6.1.8 Backhauling

Fleet Router does not have backhauling capability. All stops are intended for either pickup or delivery; no combination of the two is allowed for individual routes. This significantly restricts the

application of this software because of the greater efficiency in combining pickup and delivery operations on the same route to maximize vehicle utility.

6.1.9 Vehicle Constraints

Fleet Router assumes all vehicles start and end at the same time. This is clearly a somewhat dubious assumption because, in the real world, vehicles are leaving the depot at different times and will probably return at different times. Shift-time limits, which define the maximum length of shift time in minutes that a vehicle can be on the road, can be entered for each vehicle. Shift-time limits apply only for a given day; no overnight trips are allowed. Another shortcoming is that Fleet Router does not allow computation of the operating costs of the vehicles assigned to the computed routes. There is no capability for entering mileage or variable hourly or overtime costs for each vehicle.

6.1.10 Vehicle Operating Costs

A definite shortcoming of Fleet Router is that it has no capability for entering vehicle- or driver-operating costs. Thus, no economic comparisons can be made of different stop sequences within or between routes.

6.1.11 Intervention Capability

Upon completion of routing a stop sequence, the dispatcher may call up the graphics menu to see an overview of the scheduled routes. At this time he may decide to exchange customers between routes or trucks between routes. This is done through the use of a cursor or light pen, first focusing on the customer or vehicle to be exchanged and then moving it to another route. Fleet Router then calculates the revised route schedule and checks for vehicle-constraint violations.

6.1.12 Graphics

Of the four packages tested, Fleet Router has the most extensive graphics capability, which is surprising because its price is half that of Truckstops or Micro Veh Plan. The route displays are clear, in color, and include any barriers the user may have created. Statistics on ordered volume per stop, truck capacity, route distance, and time are displayed next to the routes. In addition to the manual intervention capabilities mentioned in Subsection 6.1.11, Fleet Router has zooming capability that allows a particular route location to be examined in detail.

6.2 TRUCKSTOPS

Truckstops, from MicroAnalytics, Arlington, Virginia, is an inexpensive, full-featured, analytic, vehicle-routing system that is very user friendly and highly automated. The system allows route construction within minutes, even while coping with most of the constraints identified previously: backhauling, special vehicle/stop restrictions, time windows, speed zones, and barriers. The system can handle up to a maximum of 2000 stops, 200 vehicles, and 200 stops per vehicle. Larger problems must be partitioned into subproblems and solved separately. The screens used for data entry and updating are easy to understand and make extensive use of a simple command menu located at the bottom of each screen. The manual is well written, complete, and clearly describes each screen's function and the fields used for entering truck, stop, and parameter data. Among the

manuals of the four demonstration packages, the Truckstops manual is by far the most understandable, descriptive, and complete.

Truckstops consists of two operating programs, an editor and a route-analysis program. The editor allows entry and manipulation of data in three basic areas: stop data, truck data, and general problem or parameter data. Each of these data inputs is accessible through a separate file using a menu-driven set of commands. The edit program considerably streamlines the time-consuming and repetitive data entry process by making use of Wordstar-like commands and special PC function keys. For data likely to be repeated in each stop or truck record, the user may set up a template that contains these data in the appropriate fields. Each record then added will automatically contain the template default values. Once data have been entered for a given routing problem, little or no additional information need be reentered for individual Truckstops runs. In normal use, Truckstops requires a selection of stops to be scheduled and an update of the volume per stop. Quick record selection and modification capabilities allow the user to easily change fields of any record.

The other Truckstops operating program, a route-analysis program called Truckload, performs the following functions:

1. Route scheduling and optimization. Route schedules may be generated for the vehicle fleet, given the input data on stops, vehicles, etc., generated by the program editor.
2. Route simulation. Existing or prospective routes may be simulated. This is useful in trying to set general parameter settings such as scale factors, speed zones, and time per stop.
3. Post-solution analysis. Output for a given vehicle route may be modified and reoptimized to perform "what if" studies.
4. Solution saving and retrieval. Route results can be saved for later modification and reloading. Different "what if" cases for a route can be saved for analysis and comparison.

6.2.1 Distance Calculation

Truckstops allows use of latitude/longitude or x-y coordinates for stop locations. Distance calculations can be specified as straight-line or rectilinear. Additional accuracy may be obtained through the use of a "true distance" file, which retrieves actual distances from a road network the user sets up. Distances are entered in a "from node i to node j" fashion. Also available as an extra-cost enhancement is a location coordinate interface, which contains latitude/longitude coordinates of up to 177,000 U.S. cities and towns. Use of distance-file interfaces considerably slows the operation of Truckstops because the program must perform a binary search of the distance file for each record until a match is found for the stop's address key.

6.2.2 Speed Zones

Truckstops has considerable flexibility for developing precise estimates of travel time through the use of speed zones. The user may specify as many as six speed zones (four short-range, one medium-range, and one long-range). The user specifies the distances from a stop and the speeds that apply to the different zones. For example, if the lower limit of the middle-range zone is 25 miles from a stop, then for any distance to this stop that is less than 25 miles, Truckstops will use the short-range speed zone information to calculate travel times.

6.2.3 Barriers

Truckstops contains a barrier routine that allows the user to specify up to 15 barriers as straight lines represented by 2 sets of x-y coordinates. A total of five transit points may be specified for each barrier. The barrier routine calculates a shortest path through the transit points when one or more barriers lie between two points. Using multiple barriers and transit points slows down the route schedule computation considerably because the system must first check for the existence of a barrier and then search the barrier for the transit point to allow calculation of a shortest distance. Before using barriers, not only in Truckstops but also in other programs, the user must examine carefully the importance of barriers to distance and time estimates. Personal communication with the vendor indicated that, in benchmark tests using fairly dense networks of barriers (more than 33% of distances affected by barriers), roughly two-thirds of the barrier-based distances differed by <5% from distances obtained without barriers.

6.2.4 Time Windows

Truckstops allows entry of two time windows per stop. The program will schedule stops onto routes so that time window constraints will be met. This may mean that some waiting time has to be scheduled to meet the early arrival time constraint of a stop.

6.2.5 Delivery Times

Truckstops calculates delivery time at a given stop by using a fixed stop time and adding to it a variable unloading time that is specific to that stop. Two unloading rates per stop may be specified, corresponding to two different quantity measurements (e.g., weight or cube) or two different cargo types or compartments. Truckstops, along with DSS, is one of the few packages surveyed that can handle multiple-vehicle-compartment capacities and specify separate unloading rates for each compartment.

6.2.6 Vehicle/Stop Restrictions

Of the demonstration packages tested, Truckstops has the most extensive treatment of vehicle/stop restrictions. For example, a stop can be flagged with a code to indicate that the stop must be serviced uniquely by the vehicle having a matching code. A stop can also be designated as a head or tail load, indicating that it is to be the first or last stop to be serviced by the truck, respectively. These special vehicle/stop restrictions introduce a certain amount of additional computational burden.

6.2.7 Backhauling

Truckstops allows for both single and multiple backhauling. The program schedules backhauls to follow all nonbackhaul stops in the route schedule and assumes that the full capacity of the vehicle is available for the backhaul stop. Truckstops does not handle the general pickup and delivery problem.

6.2.8 Vehicle Drive-Time Constraints

Truckstops allows driving- and work-time limits to be entered for each vehicle. The scheduling routine keeps track of the total work and drive times accumulated during a route schedule. When

cumulative totals meet or exceed DOT or company-directed limits, the program schedules a layover. Earliest start and latest finish times can also be specified for each vehicle.

6.2.9 Vehicle/Driver Operating Costs

Truckstops allows mileage, hourly, and overtime costs to be entered for each vehicle. No provision is made for driver costing. A useful feature is the ability to show the incremental cost of keeping a particular stop within a route. This information appears as one of the Truckstops route schedule outputs.

6.2.10 Intervention Capability

One of the more useful features of Truckstops is its ability to perform additional calculations, once a solution has been found, to attempt to find a better result. This allows the user to make modifications and then use the program's capabilities to reoptimize. The optimization routines work by performing an orderly search to rearrange the routes and schedules to reduce total cost. A branch-exchange heuristic is used in this search process, similar to the Lin-Kernigan 3-OPT procedure.⁸

The optimization is performed in two ways. First, the program can evaluate changes in the schedules for individual vehicles (single-truck optimization). Second, the program can check for cost-saving moves of stops between vehicles (multitruck optimization).

Generally, the single-truck optimization should be run before the global optimization routine is run. The single-truck optimization, when it makes a cost-reducing change, normally opens up additional time on the route and thus increases the ability of the global routine to find cost-reducing moves during its calculations.

Truckstops is the only demonstration program to have these optimization routines as a separate command that can be invoked after the routing program has produced an initial solution. In benchmark tests, the Truckstops optimization routine was found to produce a solution about 10% less costly than the initial solution. Other packages, when they use branch-exchange procedures to optimize routes, generally embed the optimization procedures within the main routing and scheduling program; thus, they cannot be invoked separately by the user.

6.2.11 Graphics

Truckstops has limited graphics capability. Basically, the user can call up a monochrome display of the stop sequence for the truck being scheduled or a global display of all stops plus the truck being scheduled. The display is not too informative, and there are no interactive procedures for moving a given stop from one route to another. A substantially more sophisticated graphics package is available as an added-cost enhancement. With this enhanced system, the user can modify routes and evaluate "what if" scenarios interactively while viewing the routes as they change.

6.3 MICRO VEH PLAN

Micro Veh Plan, from United Manager Consultants, Fairfax, Virginia, is a versatile truck-fleet-routing and scheduling model typically used in over-the-road or local delivery for private fleet or dedicated-carrier operations. The system will handle up to 950 stops in the 640K-memory version and 1900 stops in the 1024K-memory version. The system is menu driven, using Dbase-II screens

for entering and modifying data for routes, trucks, and control parameters. The program will handle most of the constraints identified previously: backhauling, time windows, and work- and drive-time limits.

The system may be used strategically to plan fleet mix and delivery days and operationally to schedule trucks for day-to-day pickup and delivery requirements. As a strategic planning tool, the system affords quick answers to "what if" questions such as (1) evaluation of the incremental cost of adding a new stop—how much more will it cost to route to a new store location? (2) truck-fleet evaluation—what types of trucks fit the network characteristics best, and how many are required? (3) length of driver workday—should overtime or overnight work periods be used to increase fleet utilization? and (4) drive and unload standards analysis—how will traffic congestion affect routing?

As an operations tool, Micro Veh Plan can be linked to the company's order-processing system, so that daily order information can be entered into the route program automatically. Route schedules are then developed during the day that may be modified by the dispatcher to include backhauls or late customer orders. Thus, the system has a great deal of manual intervention capability to modify and reschedule routes.

Micro Veh Plan is not as user friendly as the other demonstration diskettes tested. The data entry and modification procedure is somewhat cumbersome because it is not streamlined for making global changes. For example, if the data in one field of a truck record are repeated throughout all truck records, each record must be retrieved and data entered individually for that particular field; there is no capability to develop a template for recurring data. One annoying feature of the system is that the user must obtain a hard-copy printout to view all records in a particular file; no capability exists for viewing the file records on the screen. Also, the manual is not very complete in its description of the various screens and fields.

The system consists of three modules: (1) data-maintenance utilities, (2) Micro-Dispatch, and (3) Dispatcher. The data-maintenance utilities are contained in a main menu, which controls all system operations such as maintenance of control, customer, travel standards, time window, terminal, and other data. There are a total of 15 different screens that can be accessed from this main menu. The Micro-Dispatch is the optimization module of the system. It takes customer demand as input to the module, processes the stops into least-cost routes, and prints the dispatch reports. Dispatcher is a module designed to assist the dispatcher in modifying routes and seeing the route cost and schedule impact of these changes. Having a total of 15 different screens for data entry and scheduling vehicles is troublesome for the first-time user; however, the procedure is quickly learned.

6.3.1 Distance Calculations

Micro Veh Plan accepts customer locations in x-y coordinates and calculates straight-line distances only. The mileage estimation uses a formula of the type: $\text{actual miles} = a + b \times (\text{measured miles})$, where a is a constant and b is a variable. The mileage formula is initially set up for the average company's road network but can be fine-tuned using regression analysis to reflect more accurately the actual road network. Together with grid scale factors, this formula yields distances that are within 5% of actual distances, according to marketing literature. An interface to a data base of 178,000 U.S. city latitude/longitude coordinates is available at extra cost.

6.3.2 Speed Zones

Micro Veh Plan does not use actual speed zones but so-called travel standards in estimating travel times. The user may input three different travel standards, corresponding to three different formulas of the type: $\text{travel time} = A + B \times (\text{calculated distance})$, where A is the fixed time per stop (min) and B is the variable time per mile (min). Generally, a standard will be set up for inner-city, suburb, and intercity driving conditions.

The use of travel standards vs speed zones requires regression analysis to develop a travel formula suitable for a particular company's network. Thus, they are somewhat more cumbersome to use than speed zones, which are in units of miles per hour, and more easily understood than units in time per mile and time per stop.

6.3.3 Network-Based Travel Times

Micro Veh Plan allows the entry of actual distances into a file accessed from the main menu. Distances are entered in a "from location i to location j" fashion. Micro Veh Plan is the only demonstration system tested that offers this capability as a standard feature.

6.3.4 Time Windows

Micro Veh Plan allows two time windows per stop per day. Up to 20 different delivery window ranges may be specified, referenced as window type 1, window type 2, and so on. For example, window type 1 may be 8:00 a.m. to 5:00 p.m., whereas window type 2 may be 8:00 to 10:30 a.m. and 2:00 to 5:30 p.m. The window types are defined using the delivery-time-window maintenance screen, and the window-type numbers are then entered in the customer-file maintenance screen. Thus, two screens must be accessed to change window information. This exemplifies how Micro Veh Plan's multiplicity of screens makes modification of data more troublesome than it needs to be.

6.3.5 Delivery Times

As in other codes, Micro Veh Plan allows specification of a fixed time per stop plus a variable time per unit in minutes. Seven different unit types may be specified, examples of which are number of cases, totes, cartons, pieces, pallets, drums, etc., or if these units are not required to specify demand, just weight and volume. Along with these seven different unit types, there are three different travel standards used to specify different delivery rates. Two screens must be accessed to enter both delivery standards and different delivery rates, another example of a case for which a single screen would probably do just as well.

6.3.6 Vehicle/Stop Restrictions

Micro Veh Plan allows the specification of up to ten different truck types that may service individual stops. The user may specify which of these truck types are permitted to serve a given stop by entering a "y" or an "n" for truck type permitted on the customer-maintenance screen. The truck types are defined on the truck-maintenance screen.

6.3.7 Multiple-Depot Capability

The basic Micro Veh Plan system does not allow multiple depots for different routes. A vehicle and route must be preassigned to a given depot. However, as an enhancement, Micro Veh Plan has

multiple-depot capability that allows the user to specify depot service or will decide on the best depot for a given service area.

6.3.8 Backhauling

Like most of the other codes, Micro Veh Plan can schedule single or multiple backhauls on the return route to the depot after all deliveries have been made. Where Micro Veh Plan differs is in its ability to also schedule pickups en route, depending on vehicle capacity and cost. The pickups are scheduled by entering a positive quantity on the customer-data-maintenance screen, along with a reasonable estimate of pickup time.

6.3.9 Pickup and Delivery

Micro Veh Plan is the only code tested that is able to handle the pickup and delivery problem, in which goods picked up at one stop are delivered to another stop, not necessarily the depot. The user specifies in the truck-maintenance screen whether all deliveries must be made before picking up an order (the backhaul problem solved by most codes) or whether pickups may be made between deliveries (the pickup and delivery problem).

6.3.10 Maximum Time or Distance per Route

Micro Veh Plan only has capability to constrain a route by time. A maximum duration in hours may be specified for all routes stemming from a depot; individual route-time constraints cannot be specified.

6.3.11 Work- and Drive-Time Constraints

Micro Veh Plan is the most comprehensive of the four demonstration packages in its treatment of work- and drive-time constraints. All DOT regulations affecting layovers are considered, which include (1) maximum drive time (h) between layovers, (2) maximum on-duty time between layovers (drive + delivery + delay time), (3) layover time (h)—the duration of DOT-type layovers, and (4) DOT weekly limit (d)—the maximum accumulated on-duty time over the DOT weekly period.

In addition to DOT drive- and work-time constraints, lunch break, coffee break, and pretrip and posttrip preparation times may be scheduled for each vehicle leaving a given terminal. These constraints are entered on the terminal-maintenance screen. Also, refuel-time constraints may be specified, with minimum and maximum miles before refueling and a refuel time (min) entered for a given vehicle.

6.3.12 Vehicle/Driver Operating Costs

Micro Veh Plan is the most complete of the four codes tested in its treatment of operating costs. Whereas most codes allow for some entry of vehicle costs on a per-mile or hourly basis, Micro Veh Plan allows not only for such vehicle costing but also detailed driver cost information. The system separates tractor and trailer costs and includes fields for weekly equipment fixed cost and variable costs (taxes, insurance, etc.). Driver's cost data that can be entered include (1) hourly cost for drive time, (2) hourly cost for nondrive time, (3) weekly fringe fixed cost, (4) overtime hourly cost, and (5) layover cost. All of these cost data can be associated with one truck type. Because as many as

ten different truck types are allowed, one can appreciate the system's flexibility in dealing with cost constraints.

A very useful cost feature of Micro Veh Plan is its ability to examine the possibility of serving a particular stop via common carrier vs private fleet. A for-hire rate can be entered for each stop that may be served by common carrier. After Micro Veh Plan has completed its route scheduling and cost comparison, the program will indicate on the dispatch report those stops that should be served by common carrier.

6.3.13 Intervention Capability

Micro Veh Plan has some degree of manual intervention capability. After the initial routes have been scheduled, the dispatcher may change the sequence of stops for a given route via the route-maintenance screen. Once the routes have been edited to reflect the dispatcher's desired stop sequence, the dispatcher program is run to resimulate the edited routes and print the resulting route schedule and costs. Because the edited routes may violate some user-defined constraints, such as truck capacity or customer service time, the program will also generate diagnostic messages to inform the dispatcher of any such constraint violations. The lack of graphics capability is the main shortcoming of the system's manual intervention procedures. To make routing changes, a hard copy of the route schedule must be generated and reviewed, the route maintenance screen accessed, and changes made using the editor; this is a total of four different steps taken to make a routing change. A much easier and more efficient method would be to display the route schedule on the screen and make changes interactively, as some codes can.

6.4 DSS

DSS, from Systems Research Corporation, Manhattan, Kansas, is the least expensive (\$750) of the four packages tested but has surprising capabilities for its price. Geared to smaller operations, the system is limited to 425 stops, 20 terminals, and 100 trucks. Input to DSS consists of stop, terminal, truck, control, speed-zone, and method-of-distance-calculation data. There are three main system components: (1) the entry program, (2) the prepare/modify program, and (3) the DSS routing program.

Briefly, the entry program manipulates and edits the data in the DSS master file, which contains all the data necessary to solve a given routing problem. The input to the entry program is in a conversational mode, unlike the screen-entry approach used in the other three demonstration packages. Commands are available to add, change, delete, or list data. The prepare/modify program creates a "select" file that defines a desired routing problem or changes an existing file. The select file retrieves the specified stations, trucks, and terminals from the master file for a given routing problem. The DSS routing program then performs the route analysis and produces the route schedule. Thus, one can set up different routing scenarios involving different combinations of the same routing data.

The routing program is easy to use and provides quick data entry and modification once the user is familiar with some of the commands. Global changes for records containing recurring data are easily made. DSS's main shortcomings are the lack of graphics capability, limited manual intervention to interactively modify routes once scheduled, and a manual that is somewhat difficult to read and comprehend.

6.4.1 Distance Calculation

DSS accepts location data in latitude/longitude coordinates and calculates distance in either straight-line or rectilinear fashion. A zip code interface program is available to extract latitude/longitude information. There is no capability to enter a true distance file.

6.4.2 Speed Zones

DSS has the capability to specify speeds within ten different zones. If no speed-zone information is entered, the system defaults to an average speed defined in the control data file.

6.4.3 Barriers

DSS specifies barriers by the zones they traverse, rather than by x-y coordinates. This method is less accurate than using line segments to specify the barriers, as other codes do.

6.4.4 Time Windows

DSS allows one time window per stop. In addition, the system allows earliest time of arrival at a stop and latest time of departure from a stop. Only one of the three constraints may be specified at any time for a stop.

6.4.5 Delivery Times

DSS allows for entry of a fixed-stop time plus a variable dock-rate time to calculate total delivery time. This is similar to the other codes; however, DSS has the capability to specify dock rate for seven different truck compartments, any of which may be used for pickup or delivery.

A variable rate in pounds per minute, cartons per minute, or any other units is specified for each compartment. DSS then totals the delivery time by multiplying these individual dock rates by the demand quantities by compartment at each stop.

6.4.6 Vehicle/Stop Restrictions

Up to seven different restrictions may be placed on each stop. In selecting a truck to service a route, the truck's restrictions are compared with those of each station on the route. If the truck and any station have these one or more restrictions in common, then the truck is not assigned to the route.

6.4.7 Multiple-Depot Capability

One of the best features of DSS is its ability to select the best terminal to service a given route. The user can specify any number of potential origins for the network. The model will then optimally determine the routes and simultaneously assign them to the best terminal. This feature is very useful if several plants or warehouses can ship the same product. DSS is the only demonstration package on which this capability is standard.

6.4.8 Backhauling

DSS provides for single or multiple backhauling only for the return trip to the terminal. Pickup quantities by compartment are entered for each stop. No capability exists for pickup and delivery operations.

6.4.9 Maximum Time or Distance per Route

DSS is the only demonstration package that allows specification during route construction of a maximum time or distance that a route may assume.

6.4.10 Vehicle Work- and Drive-Time Constraints

DSS does not allow for specification of start/end times for vehicles and for work- and drive-time constraints. Departure- and arrival-time constraints may be made for a given terminal, but these would then apply to all trucks assigned to this terminal; individual vehicle constraints are not possible.

6.4.11 Vehicle-Capacity Constraints

DSS has the most capability of all the demonstration packages in handling different vehicle capacities. A total of seven different compartment capacities can be specified for each vehicle; only Truckstops assumes more than one load constraint per vehicle. Different units may be specified for compartments corresponding to a product (e.g., CUFT and CWT), or these compartments may correspond to different product capacities for each vehicle.

6.4.12 Vehicle Operating Costs

A serious shortcoming of DSS is that no cost information can be specified for vehicles or drivers. Thus, no economic comparisons of different route schedules can be made to select the best routes; comparisons can be made only on the basis of total route distance.

6.4.13 Intervention Capability

Once routes have been constructed by the DSS routing program, there is little capability for modification of the routes other than modifying the input data and rerunning the program. The lack of interactive graphics makes changing of route schedules cumbersome.

7. DEMONSTRATION PACKAGE TEST RESULTS

Two vehicle-routing problems were selected from Christofides *Distribution Management*⁵ for testing the demonstration packages. Fleet Router was not used for testing because the demonstration diskette does not allow input of user-created data or modification of the existing sample problem that comes with the diskette. Thus, only three packages were available for testing: DSS, Micro Veh Plan, and Truckstops. Two problems, one for 21 cities and one for 30 cities and each containing demand quantities and vehicle capacities, were input to each of these three programs. Two cases were then prepared: (1) infinite vehicle capacity, in which case the problem becomes a single-vehicle traveling-salesman problem, and (2) limited vehicle capacity, in which case the problem becomes a multivehicle-routing and scheduling problem. No time windows or start/end time restrictions for vehicles or routes were imposed. The 30-city problem was the largest that could be run on all 3 programs because of the limited problem size that could be handled by the demonstration versions of the 3 packages.

As shown in Table 4, Truckstops produces the least-distance route in all 4 cases, except for the 30-city vehicle-routing problem (with capacity constraints for the vehicles imposed). However, DSS, with a total route distance of 531 miles, achieved this through the use of 4 vehicles, compared with a total distance of 564.3 miles and 3 vehicles used by Truckstops. (If DSS had capability to enter vehicle operating cost per mile, then clearly the Truckstops route solution would be the less expensive.) As mentioned previously, the Truckstops optimization procedure, run after the initial routes are constructed, produces a savings of about 10% from the initial solution. This can be seen in Table 4. The procedure used in this optimization was to run the single-truck optimization routine first to evaluate changes in the schedules for individual vehicles, followed by a global optimization routine to check for cost-saving moves of stops between vehicles. Based on the results of this testing, it would appear that Truckstops offers the best results as far as route optimization is concerned.

Table 4. Demonstration software performance comparisons

Problem	Truckstops	Micro Veh Plan	DSS
21-city TSP ^a	314.6 283.1 (after optimization)	295.61	281
21-VRP ^b problem with constraints	424.0 375.3 (after optimization)	411.08	388 (4 trucks for all 3 systems)
30-city TSP	418.2 387.5 (after optimization)	415.41	401
30-city VRP with constraints	631.9 (3 trucks) 564.3 (after optimization)	606.1 (3 trucks)	531 (4 trucks)

^aTSP refers to traveling-salesman problem with single-vehicle, no capacity constraints.

^bVRP refers to vehicle-routing problem with vehicle-capacity constraints.

Of the four demonstration packages tested, Truckstops and Micro Veh Plan offer the most features and capabilities and are clearly the two superior packages. The two other packages are limited by the lack of capability in estimating operating cost, providing for backhauling (in Fleet Router's case) and manual intervention (DSS), and in providing graphics (DSS). These two packages might be appropriate for a company having small distribution operations that do not require changes on a daily basis. The following compares Truckstops and Micro Veh Plan.

1. Distance calculation. The two packages appear equal in this respect. Truckstops has both straight-line and rectilinear capabilities, whereas Micro Veh Plan has only straight-line. However, Micro Veh Plan offers capability to enter a distance file matrix; this feature is an extra-cost option for Truckstops. Both packages offer interfaces to external data bases for extraction of coordinate information.
2. Speed zones. Truckstops uses speed zones, whereas Micro Veh Plan uses travel standards, which are more difficult to use.
3. Barriers. Truckstops has barrier capability, whereas Micro Veh Plan does not.
4. Time windows. Both systems allow two time windows per stop.
5. Delivery times. Both systems use a fixed-plus-variable unloading rate time to calculate total delivery time. Truckstops, however, has capability for specifying two separate truck compartment unloading rates; Micro Veh Plan has only one.
6. Vehicle/stop restrictions. Truckstops has more extensive restriction capability, including head or tail load specification for individual stops and specification of which trucks may serve particular stops. Micro Veh Plan only allows specification of trucks serving particular stops.
7. Backhauling. Both systems handle the single- and multiple-backhaul problem. However, Micro Veh Plan will allow for pickups en route and can handle the general pickup and delivery problem.
8. Work- and drive-time constraints. Micro Veh Plan has more capability in this area.
9. Vehicle/driver operating costs. Micro Veh Plan allows for both vehicle and driver costing, whereas Truckstops has limited vehicle costing only.
10. Intervention capability. Truckstops, with its optimization routines, has somewhat more capability in this area.
11. Graphics. Truckstops has limited graphics capability; Micro Veh Plan has none.
12. Solution quality. As Table 3 shows, Truckstops, using its optimization routine, consistently outperformed Micro Veh Plan in all four cases.
13. Run time. Both systems appear roughly equal. The run time of Micro Veh Plan may be slightly longer than for Truckstops.

In summary, Micro Veh Plan and Truckstops appear to be about equal in capabilities; one system's superiority in a particular characteristic is generally balanced out by the other's superiority in another area. However, the real difference between the systems is the greater ease of use and user friendliness of Truckstops vs Micro Veh Plan. The smaller number of screens (four vs ten) for

data entry and manipulation, the extensive global data modification capability, and a more understandable manual make Truckstops easier to use and more flexible in meeting the user's needs. The enhanced color graphics system and the location-coordinate data base (offered as options) make the Truckstops system especially useful in serving the distribution operations needs of most companies admirably.

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