TCC

NUREG/CR-0925
SAND 78-8178

DEVELOPMENT OF A TRANSPORT NETWORK FOR THE NRC PHYSICAL PROTECTION PROJECT

G. M. Anderson
H. J. Payne

ORINCON Corporation

POOR ORIGINAL

Prepared for
U. S. Nuclear Regulatory Commission

779 287

7908240142

Available from
National Technical Information Service
Springfield, Virginia 22161

NUREG/CR-0925
SAND 78-8178
RS

DEVELOPMENT OF A TRANSPORT NETWORK MODEL FOR THE NRC PHYSICAL PROTECTION PROJECTS

Prepared by
G. M. Anderson
H. J. Payne

ORINCON Corporation
for
Sandia Laboratories
Livermore, CA 94550

Manuscript Completed: August 1977
Date Published: August 1979

Prepared for
Division of Safeguards, Fuel Cycle and Environmental Research
Office of Nuclear Regulatory Research
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555
NRC FIN No. A1173

779 289

TABLE OF CONTENTS

779 290

TABLE OF CONTENTS (concluded)

Section Page

5.0 RECOMMENDATIONS

779 291

Abstract

The assessment of the requirements for a transportation system to transport special nuclear materials, due to the complexities deriving from schedule size and flexibility, convoy components and maintenance requirements, requires a well-formulated model and an associated computer package not presently available. Here, we detail the problem of sizing the transportation system, present several approaches to modeling this system, and provide recommendations for development of a computerized model.

779 292

1.0 INTRODUCTION

A vital part of the system for safeguarding special nuclear material used in the nuclear fuel cycle is the transportation system for this material. In order to analyze the requirements for this transportation system, both in terms of size and security, a realistic computerized model of the system is required. This model must include all the major features of this transportation network, including the shipment schedule for the nuclear material, different transportation modes (truck, aircraft and trains), requirements for security escort vehicles, different maintenance requirements for trucks and escort vehicles, personnel assignment policies, and provisions for convoying trucks and escort vehicles. It must provide for both fleet sizing and system simulation. The fleet sizing problem is complicated by the large amount of flexibility in the shipping schedule and the varied maintenance requirements of the different transport unit elements, including personnel. Unfortunately, the maintenance requirements appear to preclude the application of previously developed fleet sizing algorithms based on integer linear programming.

This report presents a discussion of the problems that must be addressed in developing a computerized model of this transportation system, reviews previously developed methods for fleet sizing, and provides a recommended approach for the development of this computerized model.

An important aspect of our recommended approach is the decomposition of this problem, in part to increase computational efficiency. The bases for decomposition used are time (schedule over a limited time period), transportation mode (separately schedule trucks, aircraft and trains), transport unit elements (sequentially schedule truck trailers, truck tractors, escort vehicles and personnel), and, if needed, geography. Each step of the sequential scheduling process establishes a service requirement that must be covered by the next step. For example, the schedule of trucks assigned to cover the required shipments, in turn, defines a set of services to be covered by the assignment of drivers. A basic assignment mechanism for covering the required services has been identified which involves linking together services that can be sequentially handled by one transport unit element to form itineraries. This linking process includes a new approach for enforcing maintenance requirements.

This report is organized as follows. A complete statement of the problem is given in Section 2. This includes a complete description of the components of the transportation system for nuclear fuel cycle material, the impact of each of these components on the overall system, and performance criteria to measure the effectiveness of the transportation system. Section 3 discusses various approaches to the development of the computerized model. These include possible representations of the required services and methods for linking two sequential services which can be handled by one transport unit element, a review of integer linear programming methods, and a discussion of our recommended approach. In Section 4 we present mathematical descriptions of the integer linear programming approaches and our recommended procedures. Recommendations and a step-by-step plan for the development and testing of this model are given in Section 5, followed by a list of references in Section 6. An annotated bibliography of relevant material that has been reviewed is presented in Appendix A.

779 294

2.0 PROBLEM STATEMENT

Computerized models of the transportation system for nuclear fuel cycle material can be divided into three types based on their intended use: sizing, simulation, and dispatching. The primary purpose of this effort is to develop a model that can be used to size the required transportation system and to study the effects on system size of changes in system parameters and assumptions. Of secondary importance are simulation models which are required to investigate the effects of major system perturbations, such as vehicle breakdowns, on the ability of the transportation system to perform its function. The development of dispatching algorithms will eventually be required for scheduling of the actual fleet when it evolves in the future. This dispatching problem, however, is a tertiary consideration in this investigation.

The development of a computerized transportation system model for the transport of nuclear fuel cycle materials requires consideration of two major factors: 1) the physical description of the components of the transportation system and 2) performance measures and design criteria for the model. Each of these major factors is discussed in detail in this section.

2.1 The Transportation System

The transportation system consists of the following elements:

(1) the network, i.e., the locations of the shippers and receivers,

(2) the nuclear material shipping schedule, including allowable ranges of delivery dates,

(3) the transport units which are comprised of the vehicles and their crews, including those devoted to the security function,

(4) the maintenance requirements for the transport unit components, both vehicles and crews,

(5) the mode choice (i.e., truck, aircraft or train), and

(6) the procedures for assigning transport units to shipments.

2.1.1 The Network

The transportation network is defined by the physical locations of the reactors, fuel reprocessing plants, fuel element fabrication plants and spent fuel/nuclear waste storage facilities, and by the characteristics of the nuclear fuel cycle itself. This nuclear fuel cycle is depicted in Figure 2.1.

The user of the nuclear fuel elements is the reactor, which must be periodically refueled. The current refueling policy is to yearly replace one-third of the fuel elements for pressurized water reactors (PWR) and one-fourth for boiling water reactors (BWR).(1) The old fuel elements which are removed from the reactor core are highly radioactive and must be stored at the reactor for a minimum cooling period, which is on the order of five months.(1)

Following this cooling period, the spent fuel can either be shipped to a long-term storage facility or to a reprocessing plant where usable fuel is separated from the waste material. This waste material is then shipped to a storage facility.

Usable fuel (U-235 and Pu) is shipped from the enrichment facilities and reprocessing plants to the fabrication plants where fresh fuel elements are made. These fresh fuel elements are then shipped to the reactors, thereby completing the fuel cycle.

779 296

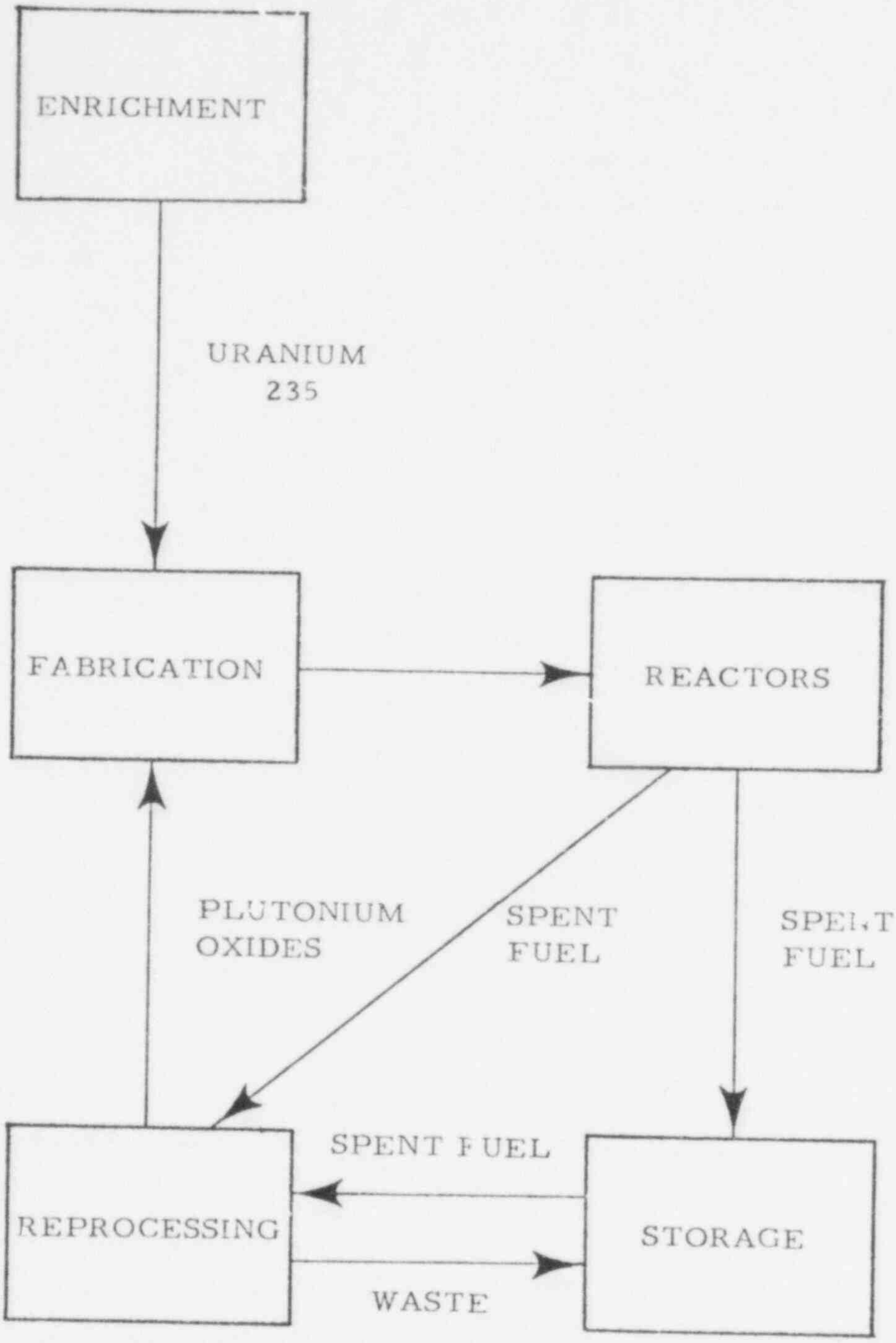


Figure 2.1 The Nuclear Fuel Cycle

779 297

Due to the high radioactivity of the spent fuel elements that must be shipped from the reactors to the reprocessors and to storage, heavy shielding is required. This greatly limits the number of spent fuel elements that can be shipped on one vehicle. For example, only two spent fuel elements from a pressurized water reactor (PWR) can be shipped on a conventional truck.(1) In contrast, less shielding is required for the shipment of fresh fuel and fresh fuel elements because of their lower radioactivity. This allows about fourteen fresh fuel elements for a PWR to be shipped on the same type of truck. Therefore, the portion of the nuclear fuel cycle that most affects the required size of the transportation fleet is the shipment of the spent fuel. The transportation requirements for the other parts of the cycle are about an order of magnitude less.

The security requirements may represent a lesser problem for the shipment of spent fuel than for the shipment of the fresh fuel (U-235 and Pu) and the fresh fuel elements. The reasons for this are that the high radioactivity of the spent fuel should reduce the likelihood of any hijacking attempts and the heavy required shielding provides a degree of inherent protection against sabotage. In contrast, the fresh fuel (U-235 and Pu) shipped to the fabrication plants and the fresh fuel elements shipped to the reactors could be used in the manufacture of nuclear weapons. This, therefore, may require a higher level of security for these parts of the nuclear fuel cycle transportation system.

An important parameter established by the network is the shipping time between two locations. This shipping time is a function of the mode (i.e., truck, rail, or aircraft) of the shipment, as well as the distance between these locations. The transportation system model must take these factors into account.

2.1.2 The Shipment Schedule

The factor which drives the shipment schedule is the periodic requirement to refuel each of the reactors. The current refueling policy for PWR's is to yearly replace one-third of the fuel rods. For BWR's, one-fourth of the fuel rods are replaced yearly.

The dominant feature of the shipping schedule is the flexibility in possible shipping dates. The only hard time constraint on the shipments of the spent fuel rods is that they cannot be shipped prior to the expiration of the minimum required cooling period. The fresh fuel rods must be shipped so as to arrive at the reactor prior to the scheduled refueling time. Even here there is a relatively long period, perhaps on the order of a month, during which the fresh fuel rods can be delivered. There is probably a similar degree of flexibility in the shipment of fuel from the reprocessing and enrichment plants to the fabricators. This shipment schedule flexibility should allow the actual schedule to be smoothed out so that peaks and valleys in the shipping load can be avoided. This smoothing process should tend to minimize the required number of transport units. In Reference (2), it was shown that a shipment flexibility of seven days using only trucks provides sufficient smoothness in the shipping load so that larger shipment flexibilities do not, in general, reduce the required number of vehicles. Greater flexibilities do, however, increase the computational burden in finding an optimal assignment of transport units to the shipments because of the increased number of assignment possibilities.

2.1.3 Transport Units

The basic transport unit elements are:

(1) the carriers, which include trucks, airplanes, and trains; the truck trailers and tractors should be considered separately for assignment purposes,

(2) the escort vehicles, and

(3) the personnel, which includes truck drivers, train crews, aircraft crews and guards.

The feature of the transport units which will have the greatest impact on the transportation model is the capacity of each type of carrier. The model must be capable of handling carriers of different capacities. Some examples of potential truck carriers with their capacities are(3)

(1) Conventional trucks (22,000 kg payload)

(2) Armored trucks (12,000 kg payload)

(3) Safe secure trailers (7700 kg payload)

(4) Integrated container truck (4500 kg payload).

These capacities of the assumed carrier will determine the number of carriers required per shipment, which will then, in turn, determine the escort vehicle and personnel requirements.

2.1.4 Maintenance Requirements

The procedures for the assignment of transport units to shipments must account for th periodic maintenance requirements of these units. Each type of transport unit is expected to have its own unique maintenance requirements. Generally, the requirements for a given transport unit type can be specified by some combination of a maximum allowable time and a maximum allowable distance travelled since maintenance was last performed. In addition, the length of time required to perform the maintenance must be specified, along with the locations of the maintenance bases and whether a unit can use the nearest maintenance base or must return to its home base for maintenance.

In the TRUCKING I model,[(2)] maintenance had to be scheduled before a maximum time interval since the last maintenance was exceeded. Specific values of 24, 27, and 30 days for this maximum time interval were considered, while the time to perform maintenance was varied from 5 to 7 days. This model considered the procedure of allowing a truck to receive maintenance at the nearest base, as well as requiring the truck to return to home base for maintenance. In this study the number of maintenance bases was varied from one to three.

The transportation scheduling algorithm of Reference (4) requires that during each month a truck must spend 152 hours out of 696 in maintenance. Thus the maximum allowable period between maintenance is 544 hours and the time to perform each maintenance is 152 hours. Four home bases were assumed and each truck was required to return to its home base for maintenance.

Deficiencies of both of these truck scheduling models are that they do not consider the separate maintenance requirements for the tractors and trailers, nor the distinct maintenance requirements for the escort vehicles and personnel.

Maintenance requirements for other possible modes of transportation must also be considered. For aircraft, the standard policy is to provide periodic maintenance based on the elapsed number of flying hours, and to perform more extensive maintenance at longer intervals of elapsed flying hours. Although maintenance requirements for trains may be less than for trucks and aircraft, train maintenance at periodic intervals must also be considered.

Probably the most stringent "maintenance" requirements will be those for the personnel, i.e., guards and drivers, of the transportation system. These requirements are defined by such quantities as the maximum allowable time since the last break at home base, maximum driving time without a break, holiday and weekend work rules, vacation policies, and any job classification rules that preclude persons in one job category from performing a task in another job category.

2.1.5 Mode Choice

Possible transportation modes for the shipment of nuclear material include trucks, aircraft and trains. The use of aircraft will probably be restricted to shipments between locations with suitable nearby airfield facilities. Similarly, shipments by train will probably require railheads at both the origin and destination points. These railheads may either be located on-site or in the vicinity of the site. When aircraft or trains are used, trucks must also be assigned to transport the material between the airport or railhead and the facility.

The choice of the mode to be used for a given shipment will depend on a number of factors. The availability of nearby airfields at both the origin and destination is required for shipment by aircraft and, similarly, railheads for trains. The nature of the material to be shipped (e.g., spent fuel, enriched U-235, fresh fuel elements) and the corresponding shipment security requirements may also affect the mode choice. For example, if trains are available, they may be used mainly for high volume shipments such as spent fuel and waste material. The availability of the various modes will also affect the mode choice, as may the distance between the origin and destination points.

Procedures for the assignment of transportation modes to shipments may significantly affect the fleet size. For example, one such procedure might be to maximize the use of a fixed fleet of aircraft. Trucks must then be assigned to transport the material to and from the airfields and to cover the remaining shipments. In such a case the term minimum fleet size might be interpreted as the minimum number of trucks. Another assignment procedure might be to make the mode choice based on some cost-effectiveness measure, subject to any mode choice constraints. An example of such a measure might be total shipment cost in dollars.

2.1.6 Transport Unit Assignment Procedures

In addition to providing fleet sizing information, a major output of this study will be procedures for the assignment of transport units to shipments. These assignment procedures will probably be driven, to a large extent, by the maintenance requirements for the different types of transport units. It can probably be expected that the maintenance requirements for one of the types of transport units will have a major effect on the assignment procedures of all the other transport unit elements.

To illustrate the effect of the maintenance requirements on the assignment procedures, consider the following example. Assume that the crews that drive the tractors must have a break (i.e., maintenance) at home base every two weeks and that the tractors require maintenance at home base every four weeks. Further assume that the crews must return to home base in the tractors, i.e., they are not allowed to take alternate transportation to and from the home base. In this case the crew maintenance requirements basically drive the assignment procedures for the other transport units since a given crew/tractor combination can be on the road at most two weeks at a time before it must return to the home base.

Next assume that the tractor crews can be changed while the tractor is away from the home base through the use of alternate means to transport the crews to and from home base. Now the maintenance requirements for the tractors, which must return to home base after four weeks on the road, drive the assignment procedures for the other transport unit elements.

It is expected that convoying of trucks and escort vehicles will be used to reduce the required number of escort vehicles. The convoying rules will probably affect the assignment procedures of all the transport unit elements.

2.2 Performance Measures

The first priority of the transportation system for shipment of nuclear fuel cycle material must be to meet all the shipping requirements and to satisfy all constraints introduced by security requirements. Subject to these firm requirements, the transportation system must be designed based on criteria such as minimum fleet size or minimum operating cost while remaining sufficiently flexible to accommodate vehicle breakdowns and other perturbations to the system.

2.2.1 Design Criteria

A common criterion for transportation system design is minimum fleet size. This is the basic goal of Trucking I(2) in which the number of vehicles in the fleet is increased until the minimum number is found that can accomodate the shipping requirements. This criterion has also been used in a number of other studies(5-9) in which the minimum fleet size is found directly using a variety of methods. All of these studies assumed given shipment schedules and of these only Trucking I included provisions for vehicle maintenance. None of them included provisions for convoying, assignment of escort vehicles, or assignment of personnel.

Other design criteria have been used as bases for scheduling a fixed transportation fleet to cover a shipping schedule. These include minimizing estimated fleet operating costs in dollars,(4) maximizing the profit for the fleet,(10) and minimization of deadheading for a fleet of trucks.(11) Again, complicating factors such as assignment of personnel, convoying and maintenance (except for Reference 4) were not considered.

A distinguishing feature of the transportation system for nuclear fuel cycle material is the relatively large amount of flexibility in shipment and delivery dates. This flexibility results in a large number of possible ways to schedule transport units to cover the shipments. Some set of criteria are, therefore, needed to construct a "good" set of itineraries for the transport units.

An itinerary for one transport unit element can be built by connecting shipments which can be sequentially handled by that element, while providing for required maintenance. The ways by which two shipments can be so connected are:

(1) direct connection - the transport unit delivers a shipment to a location and immediately picks up another shipment,

(2) connection with an idle period - the transport unit delivers a shipment to a location and waits at that location for another shipment from there to become available,

(3) connection with a deadhead - the transport unit delivers a shipment to location A and then deadheads to location B to pick up a shipment there, and

(4) connection with a deadhead and idle - this is the same as 3) except that an idle period is also included at either location.

These ways for connecting two shipments are listed in terms of probable decreasing desirability. By associating penalties with each type of connection, it would be possible to associate an overall penalty with each itinerary. A possible means for constructing a "good" schedule might be to attempt to minimize the sum of the penalties associated with each of these itineraries.

The personnel assignment portion of the scheduling algorithm will have its own unique criteria. The principal driving factors here will be the personnel "maintenance" requirements discussed in Section 2.1.4. It can also be expected that some assignments will be undersirable from a crew's viewpoint. Provisions may be required to ensure that one crew is not burdened with an excessive number of trips of this type.

2.2.2 Computer Model Requirements

The purpose of the computerized model of the nuclear fuel cycle transportation system will be to provide a flexible tool to investigate the sizing and scheduling requirements for this system.

Specifically, this model should provide the capability to investigate the effects on fleet and crew roster size and scheduling procedures of such factors as

(1) various mixes of different transportation modes (i.e., truck, aircraft, and rail),

(2) various vehicle and personnel maintenance requirements,

(3) different planning horizons,

(4) various amounts of flexibility in the shipping schedule,

(5) different truck convoying rules, which include the rules for assigning escort vehicles and guards to the convoys,

(6) various vehicle carrying capacities,

(7) various criteria for the sequential connection of shipments to be handled by one transport unit element, and

(8) limiting of the hours per day that a vehicle can travel, including the possibilities of no arrivals, departures or travel on weekends, holidays or nights.

In addition the model must provide for the capability to investigate the effects on the system of vehicle breakdowns and the procedures for handling these breakdowns.

Wherever possible, the computerized model should provide graphical outputs that represent the sensitivity of the fleet size and schedule optimization criterion to each of the above listed items.

3.0 APPROACHES TO MODEL DEVELOPMENT

The development of a computerized model for sizing and simulation of the nuclear fuel cycle transportation system will necessarily depent upon consideration of (1) the size of the shipping schedule, (2) the presence of distinct transport unit types (trains, aircraft, trailers, tractors, escort vehicles, drivers and guards) and their interrelationships, and (3) maintenance requirements differentiated by type of transport unit.

The basic problem in developing this computerized model is how to assign the transport unit elements (trailers, tractors, aircraft, railroad cars, escort vehicles and personnel) to cover the shipping schedule for the nuclear fuel cycle material. To illustrate the magnitude of the problem, consider a system involving 500 shipments in a year. This is a level which might be achieved if plutonium were recycled.(1) To each of these shipments a truck trailer must be assigned. Then tractor assignments are required for each trailer. Depending on the convoying and escort requirements about two escort vehicles may be required per truck, and finally, personnel must be assigned to each tractor and escort vehicles, say one crew (2 persons) to each tractor and escort vehicle. Thus the total number of individual assignment tasks in this case is about 3500. A rough estimate can be made of the required fleet size for this problem by assuming that there are about 250 working days in a year and that the time per shipment averages 3 days (this includes allowances for deadheading and maintenance). The resulting fleet is about 7 tractors and trailers, 14 escort vehicles and 21 crews. Each transport unit element would average about 73 shipment assignments per year.

This example did not include shipments of spent fuel from the reactors to the reprocessors. Including this portion of the nuclear fuel cycle increases the required number of individual truck shipments in the year from approximately 500 to 5000 or so, an order of magnitude increase. This increases the number of individual assignments to about 35,000, while the estimated size requirements increase by factors of 10 for each transport unit type as well; i.e., to 70 tractors, 140 escort vehicles and 210 crews.

In this section, we consider the applicability to this problem of previously developed minimum fleet sizing methods which are based upon integer linear programming (ILP) formulations. The principal variables in these formulations are those related to the linking of two sequential services (e.g., shipments). Certain aspects of the nuclear fuel cycle transportation system, specifically, the presence of deadheading and the interdependence of the several transport unit types, require extensions to the ILP formulations, but they can be handled without disturbing their basic nature. However, we have been unable to find a representation of maintenance requirements in the form of linear constraints phrased in terms of the service linking variables.

Because of these difficulties with the maintenance requirements, alternative fleet sizing methods appear to be necessary for this problem. Key aspects of the methods developed here are:

(1) the central roles of the recursive procedure for linking pairs of services,

(2) the concept of itinerary construction based upon the recursive linking of pairs of services,

(3) the natural or required decomposition of the problem into manageable parts, each of which is also a sizing (or simulation) problem,

(4) the division of methods into fixed fleet and nonfixed-fleet approaches.

After a presentation of preliminaries devoted to services (e.g., shipments), this section is directed toward an examination of previously developed methods for sizing and then to alternative methods which can solve the problem at hand.

The presentation of mathematical details are reserved entirely for Section 4.

3.1 Representation of Required Services

The shipping schedule defines requirements for the carrying vehicles, e.g., trains, aircraft or trucks. In the methods developed in this section, there is utility in generalizing this concept to one of a set of required services that must be covered. For example, the movements of trucks define a set of required services for truck drivers. Thus here we adopt the more general terminology of services rather than shipments.

3.1.1 Services with Fixed Times

A service with fixed departure and arrival times is defined by

1) the origin

2) the destination

3) the quantity of the service (e.g., amount of material to be shipped)

4) the departure time

5) the arrival time

Several such services are illustrated in Figure 3.1.

3.1.2 Services with Flexible Times

An important characteristic of the shipment schedule for special nuclear materials is the flexibility in the departure and arrival times. One simple means for representing this flexibility is the use of a discrete set of pairs of departure and arrival times. This is illustrated in Figure 3.2. This representation is typical of those used in the integer linear programming approaches discussed subsequently.

A second simple means for representing flexibility is to allow a continuous range of departure times (and corresponding arrival times) over an interval. Finally, flexibility might be represented by a set of such intervals, as illustrated in Figure 3.3. This latter representation is required to allow for such schedule details as presence of holidays and restrictions on loading and unloading times.

3.1.3 Periodic Sets of Services

For certain purposes, we shall be concerned with periodic sets of services. Consider a set of services with period T, as illustrated in Figure 3.4. To define a periodic set of services, it is of course only necessary to list services associated with a single designated interval of duration equal to T. For this purpose, the departure time for a service will be taken in the designated interval. If the associated arrival time then happens to fall beyond the end of this designated

779 311

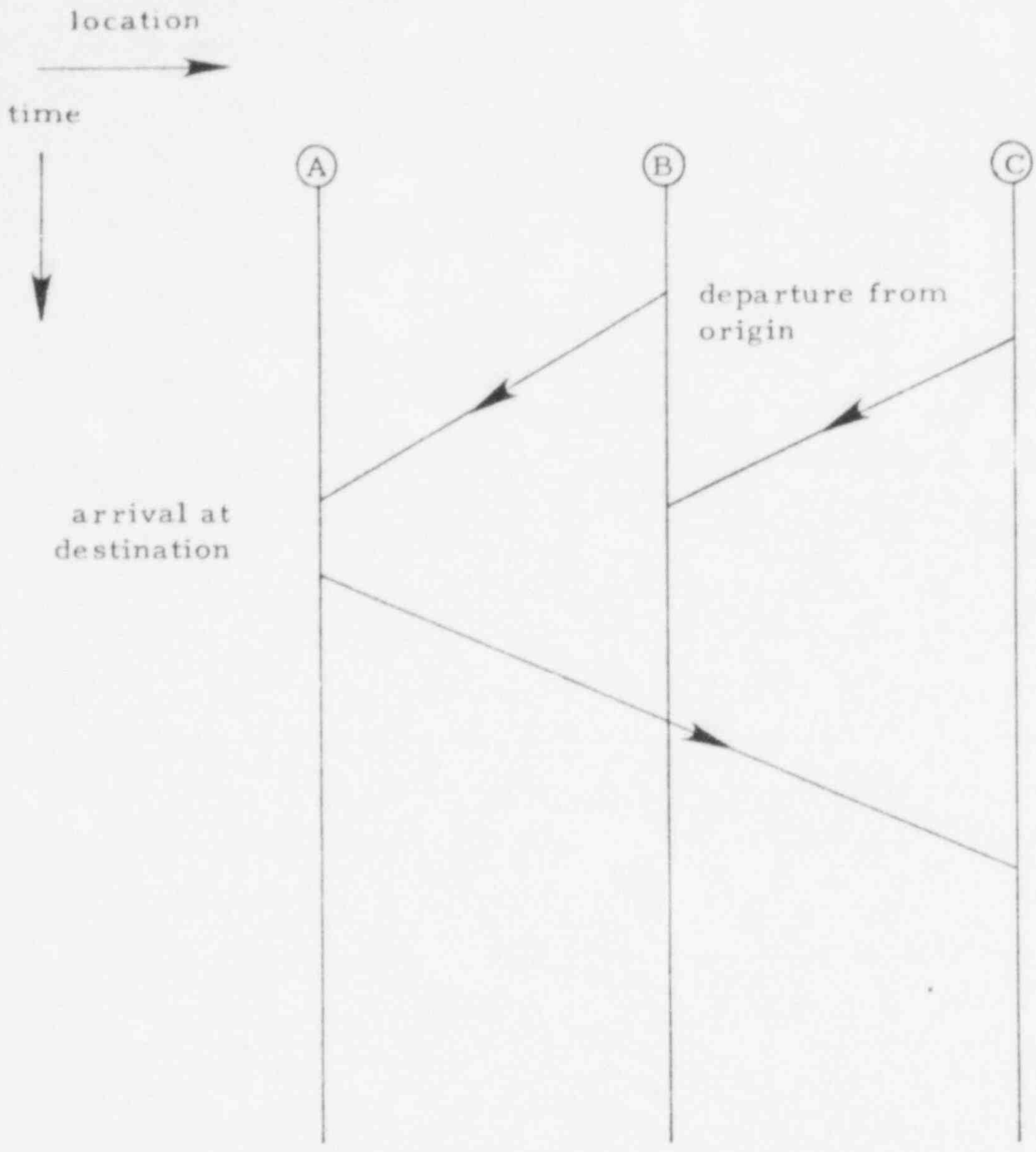


Figure 3.1 Services with fixed departure and arrival times.

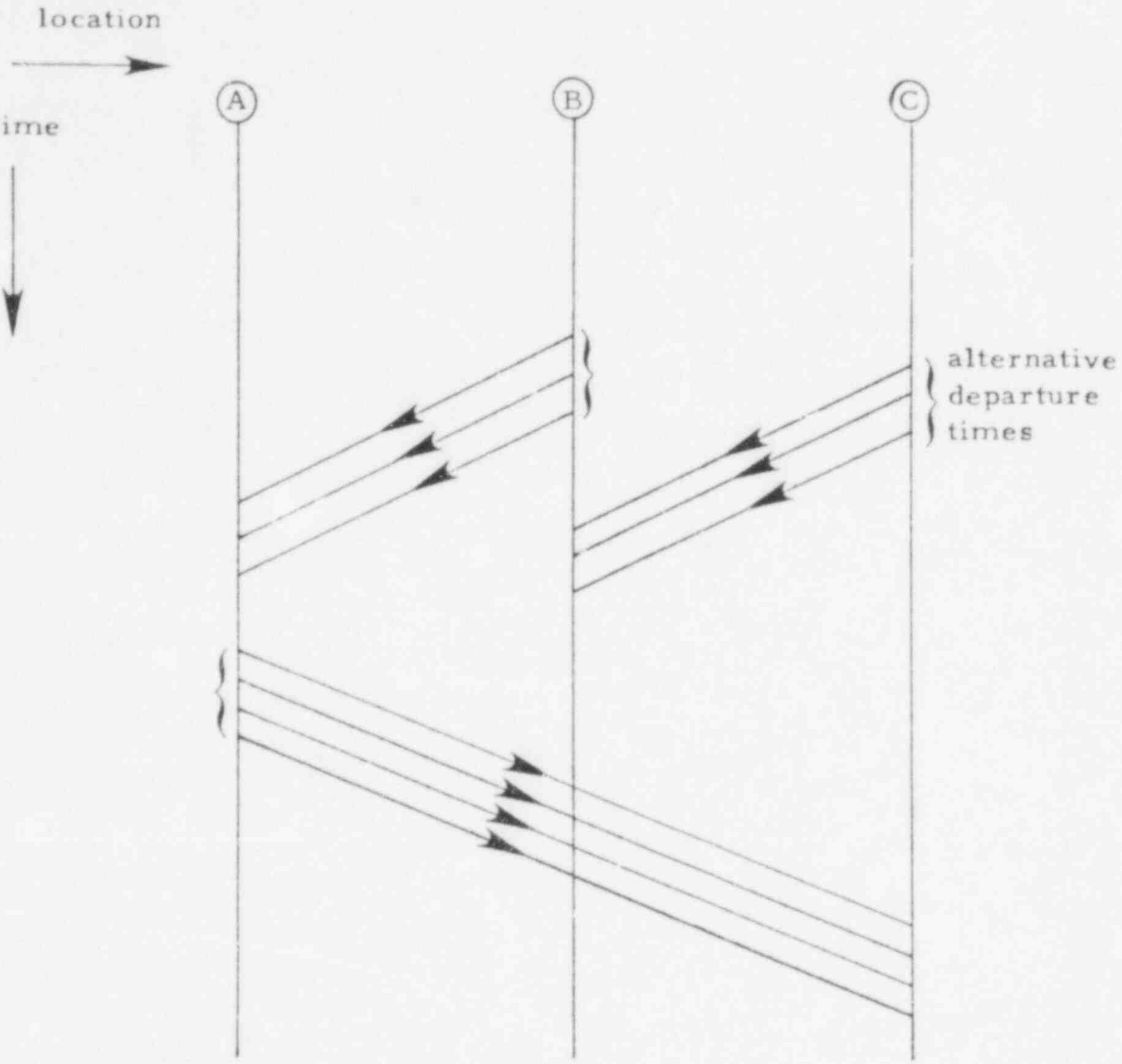


Figure 3.2 Services with discrete alternatives for departure and arrival times.

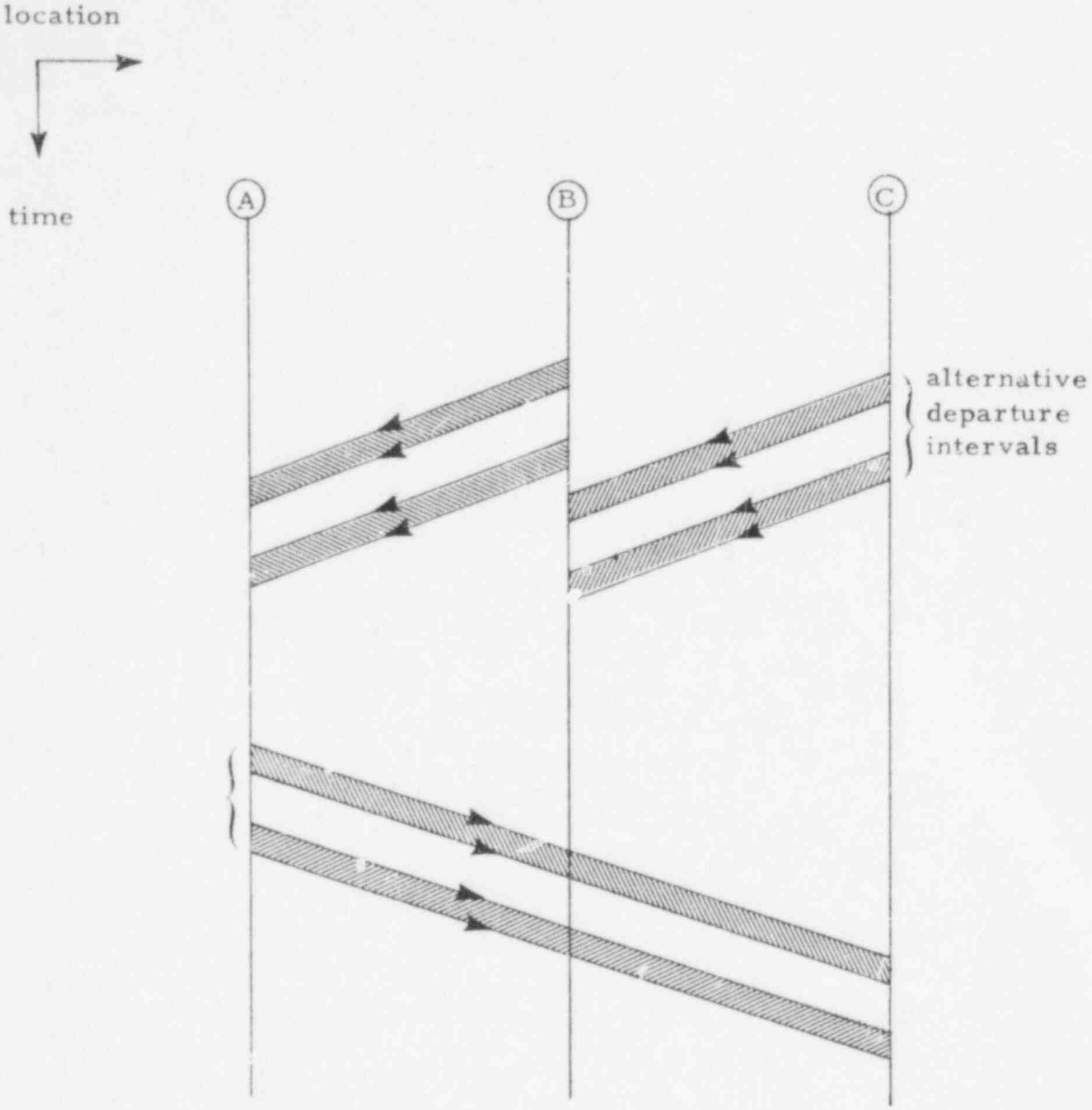


Figure 3.3 Services with alternatives for departure and arrival times in several intervals.

779 314

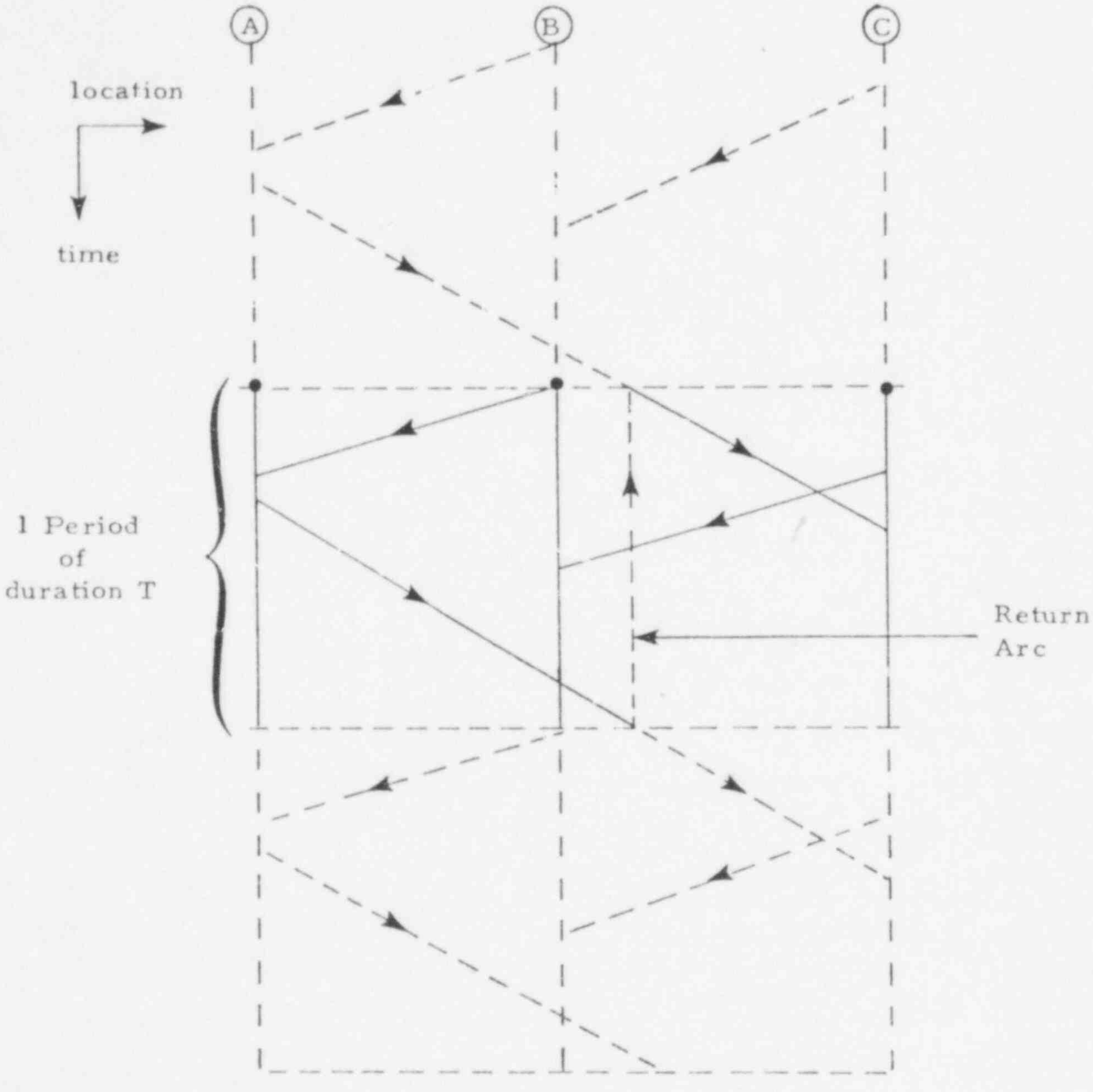


Figure 3.4 A periodic set of services.

7/9 315

interval, as illustrated in Figure 3.4, an equivalent representation with an arrival time within the interval is obtained by considering the service to be in two pieces. The first piece is obtained from the original service by terminating it at the end of the period. The second piece is obtained from a second service identical to this service but arriving one period earlier than actual arrival time. It is generated by cutting this new service off at the beginning of the period. These two pieces can then be joined by a return arc, as illustrated in Figure 3.4.

It should also be noted that services can cover several periods. For example, with a period of two days, a seven-day service will cover four or five periods. An extension of the ideas presented above leads to the identification of several pieces and associated return arcs within one period.

3.2 Linking of Services

The itinerary for a transport unit will consist of a sequence of journey legs which include services covered, periods of idling, deadhead trips, and stays in maintenance and at home base. The elementary step in constructing an itinerary is the linking of two services to be sequentially covered.

Several possibilities for linking two services (with fixed departure and arrival times) are illustrated in Figure 3.5. These possibilities include

(1) direct linking, i.e., the prior service has destination and arrival time coincident with the origin and departure time for the second service,

(2) linking with idling only, i.e., the first service has destination coincident with the origin of the second service, but an arrival time earlier than the second service's departure time,

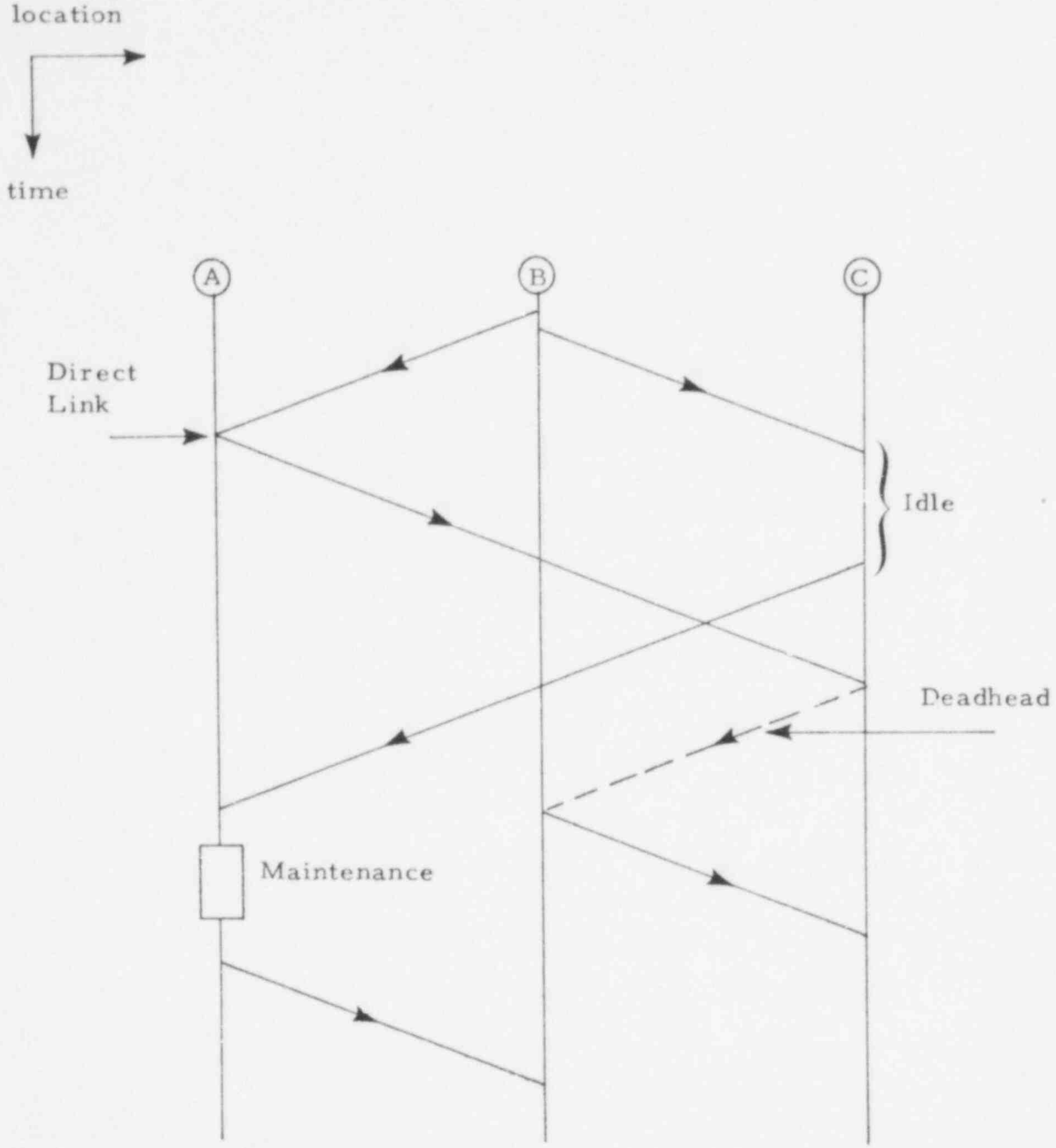


Figure 3.5 Examples of linking services.

779 317

(3) linking with deadheading only

(4) linking with deadheading and idling

(5) linking with an intermediate stop at maintenance (with various further distinctions pertaining to deadheading and idling).

In constructing itineraries, a candidate pair of services must be tested for two types of feasibility conditions:

(1) maintenance, i.e., is the accumulated "duty" less than the maximum allowed before maintenance (for vehicles, rest for people)? Linking of two services may require an intermediate stop in maintenance to meet this feasibility condition.

(2) temporal sequences, i.e., is the time of arrival at the origin of the second service later than the departure time for the second service? When the destination of the first service does not coincide with the origin of the second service, the deadheading time must also be considered.

Two services which can be linked can be represented for many purposes as a single equivalent link, as illustrated in Figure 3.6. Specifically, this combined service is defined as follows:

(1) the origin is the origin of first service

(2) the destination is the destination of the second service

(3) the quantity is the minimum of the quantities of the first and second services

(4) the departure time is the departure time of the first service

(5) the arrival time is the arrival time of the second service

(If the quantities of the first and second services differ, that service with the greater quantity is split into two parts (services) before linking, with one part (service) having the quantity equal to that of the other service).

This representation of linked services as one service gives rise to

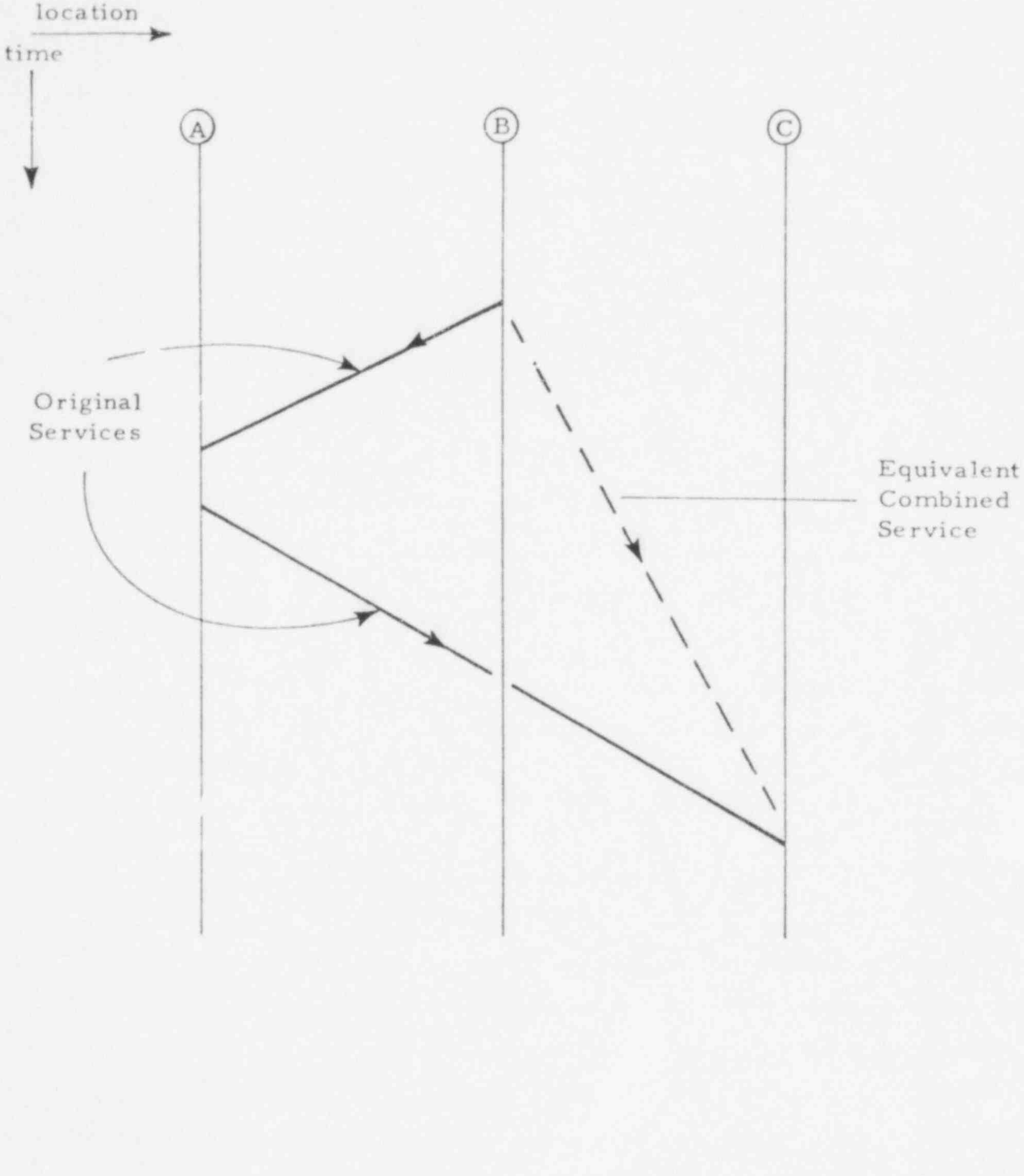


Figure 3.6 Equivalent service representation of two linked services.

779 310

the possibility for simple, recursive itinerary construction schemes.

Now consider the linking of two flexible services (i.e., services with alternative pairs of departure and arrival times). For example, consider two services with discrete alternatives, as illustrated in Figure 3.7. In principle, one must consider linking each alternative for the first service with each alternative for the second service. In general, one will find more than one pair of alternatives to be feasible. Each of these could then be included in the equivalent representation of the pair of services, but only certain of these pairs will actually be retained.

Reasonable rules for retaining feasible linkings are as follows:

(1) do not include a maintenance stop, unless it is necessary

(2) discard any resultant service which covers a strictly larger time interval than some other resultant service with the same arrival or departure time (this eliminates unnecessary idling between the services).

Based on these rules, the resultant retained combined service for the flexible services illustrated in Figure 3.7 are those indicated by a heavy dashed line. The one indicated by a light dashed line is eliminated by these rules.

Linking of services taken from a periodic set of services can be easily reduced to linking of services as described above and the resultant service can be placed in the desired form. Details are provided in Section 4.3. Of special note, however, is the possibility of a service being linked to itself to form a closed loop. This is illustrated in Figure 3.8. Provision for "self-linking" requires some further special assumptions. Details are also provided in Section 4.3.

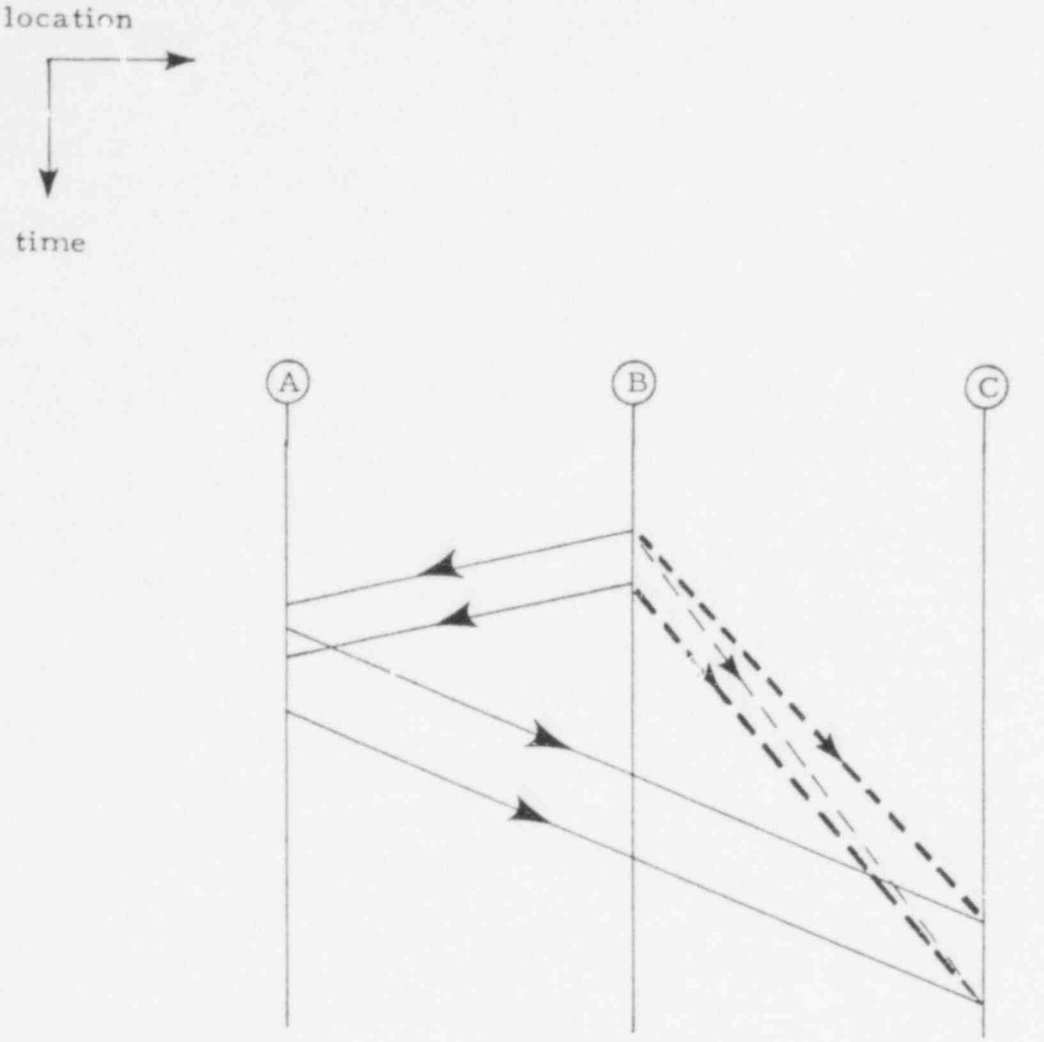


Figure 3.7 Linking of two services with alternate pairs of departure and arrival times.

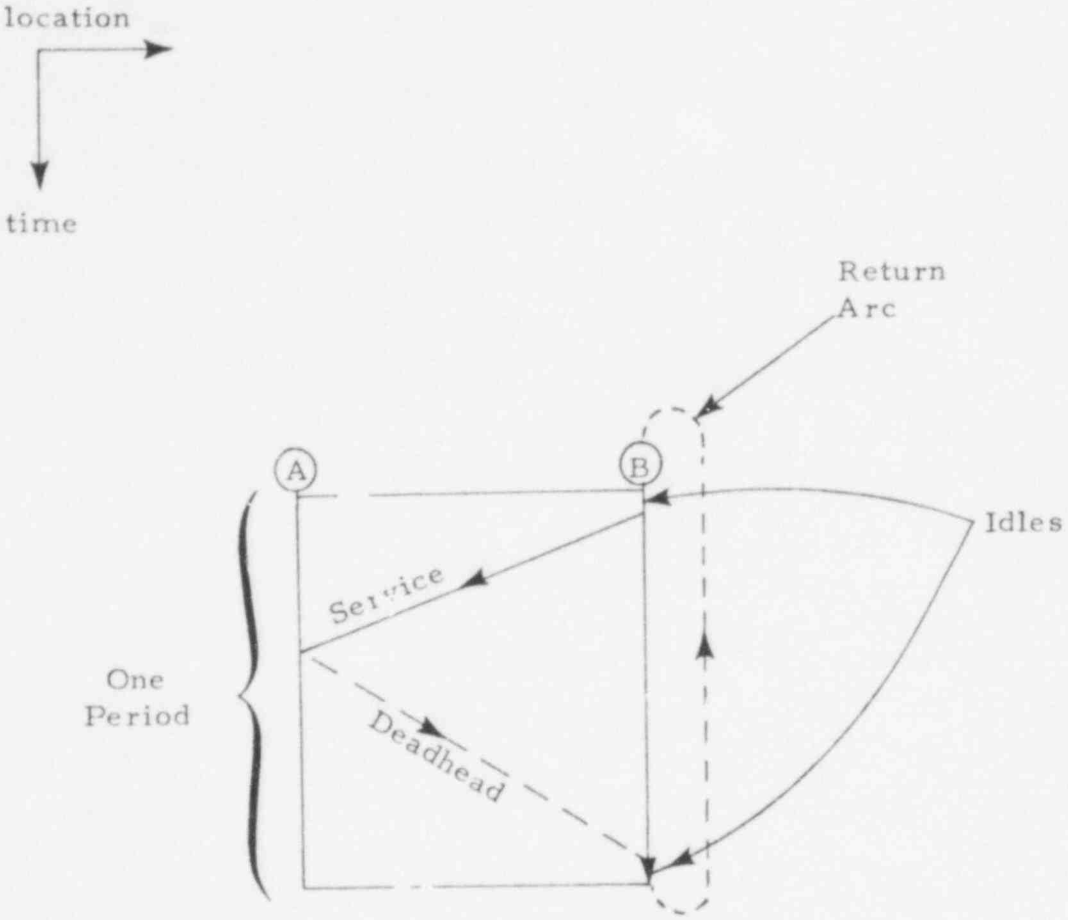


Figure 3.8 Self-linking in a periodic service set to form a closed loop.

For purposes of measuring the value of linkings and for providing measures of the transportation system as a whole, it is useful to associate a set of elementary measures with each service. These measures include

(1) Total time
(2) Total miles
(3) Active duty time
(4) Active duty miles
(5) Deadhead time
(6) Deadhead miles
(7) Idle time
(8) Flexibility (range of alternative departure times).

3.3 Integer Linear Programming (ILP) Formulations

One rational measure for the cost of a transportation system which involves a single type of transport unit is the size of the required fleet. This "minimum fleet size" problem has received considerable attention in the Operations Research literature.(2, 5, 7) Here we examine the applicability of the methods which have been previously developed to the problem of sizing the nuclear fuel cycle transportation system.

In several of the methods developed for the minimum fleet problem, a key role is played by variables pertaining to the pairwise linking of sequential services. If no linkings were made, the fleet size required would equal the number of required services, i.e., one transport unit for each service. Each linking of services eliminates the need for one transport unit element. Hence the minimum fleet size problem can be phrased in terms of a problem of maximizing the number of pairwise linkings.

The effectiveness of these methods derives from the fact that the feasibility of each linking is assumed to be independent of all others, and all constraints can be expressed in linear form.

The simplest of these methods pertains to a fixed schedule of required services. Feasible pairwise linkings are first defined. The problem is then to maximize the number of such pairwise linkings. This problem can be formulated as a maximum flow problem on a bipartite graph with each unit of flow corresponding to a selected linking. The out-of-kilter flow (OKF) algorithm is particularly well-suited to this problem.(13)

Introduction of flexibility requires a new formulation for which the OKF algorithm no longer applies. Levin(7) discusses several ILP formulations which account for flexibility through the use of "bundle

779 324

constraints", where each service is represented by a set (bundle) of discrete alternate service times. The independence of feasible linkings (for services with specific choices of service times) is still assumed. Problems with several hundred constraints (where the number of constraints corresponds to the number of service alternatives) are computationally feasible.

In the presentations of these ILP methods, no consideration is given to deadheading. Extensions to include deadheading are straightforward, however, since the possibility of deadhead trips can be incorporated in the prior identification of feasible linkings.

Hence, if the problem at hand could be described as the minimization of the number of units of a single type to cover a flexible schedule represented by discrete alternative services with deadheading allowed, previously developed methods would appear to be applicable.

Two further issues remain however: (1) the composite nature of the transportation system, i.e., the presence of several transport unit types and their interrelationships, and (2) maintenance considerations.

The composite nature of the transportation system leads to a necessity to resolve the fundamental multicriteria nature of the problem (e.g., minimize number of truck, number of escorts, and number of personnel), and to mathematically formulate the interdependencies among transport unit types. These interdependencies can be phrased as linear inequality constraints. Furthermore, if the sizing problem is phrased in terms of a linear combination of numbers of each type, or if a priority assignment technique is adopted, the ILP structure can be maintained. Details are given in Section 4. However, the number of the interdependence constraints appears to make computational feasibility a serious question, even where modest-sized shipment schedules (e.g., 500 shipments per year) are involved.

However, the issue of maintenance appears to preclude the use of ILP techniques. In many fleet sizing problems the maintenance issue can be ignored when it is accomplished on a regular basis independent of itinerary construction. For example, urban buses operate on a daily schedule with routine maintenance performed at either end of the day or by removing the bus from the fleet for one or more days for maintenance. Thus maintenance is accomplished completely outside of the scheduling period.

Unfortunately, the nuclear fuel cycle transportation system does not seem to allow this type of regular maintenance. It appears that provisions for maintenance must be included directly in the itinerary construction process of linking sequential services. We have thus far been unable to formulate these maintenance requirements in the form of linear constraints which are required for the ILP methods. This indicates the need for alternate approaches to the fleet sizing problem for the nuclear fuel cycle transportation system.

779 326

3.4 Recommended Approach

It is apparent from the discussion of the previous section that the sizing problem for the nuclear fuel cycle transportation system cannot be solved by application of previously developed integer linear programming methods. Before addressing alternative approaches, we will review the requirements for a method which can successfully solve the sizing problem. The method must address, at a minimum,

- schedule details, including spatial diversity of origins and destinations, and flexibility in service times
- the role of deadhead trips
- maintenance requirements differentiated by transport unit type.

We have concluded that these three items dictate that itineraries, i.e., sequences of journey legs, including services, deadheads, idle periods and stays at maintenance or home base, must be explicitly represented. This is in contrast to the ILP methods discussed in Section 3.3 where only pairwise connections of journey legs received explicit representation.

Optimal techniques exist, in principle, which are based upon variables related to itineraries. These techniques require that all feasible itineraries be explicitly or implicitly generated. Due to the presence of maintenance considerations, the only technique known to us for generation of feasible itineraries is implicit enumeration.(14) That fact and the enormous number of feasible itineraries, even in modest sized problems, indicates that optimal techniques will have to give way to suboptimal techniques. The approaches we develop here are suboptimal in that a limited collection of feasible itineraries are generated for examination. In fact, a key to the success of these approaches is

779 327

the development of effective techniques for generating a "good" set of itineraries.

We envision two generic approaches for solving the sizing problem:

(1) "fixed-fleet" approaches, in which a sequence of specified transportation systems (e.g., a "fixed-fleet" of trucks) are examined for feasibility with the minimize sized, feasible transportation system as the goal.

(2) "non-fixed-fleet" approaches, which represent an extension of the approach used in the ILP methods presented in Section 3.3, in which feasible itineraries are generated from the shipping schedule without prior specification of the size of the transportation system. The required size is then deduced from the itineraries so constructed (e.g., by counting them to get the number of transport units required).

In developing these approaches, additional problem requirements which must be addressed are:

- multiple transport unit types, with implications for the presence of multiple criteria and for a need to represent interdependencies of transport unit types,
- mode choice, i.e., choice of shipment by truck, train or aircraft,
- shipment quantities; i.e., the fact that shipments generally require a number of trailers (or carrying containers), and
- provision for convoying, i.e., the simultaneous movement of several trailers in order to improve security or reduce guard requirements.

In principle, sizing is most accurately approached by establishing all future requirements. Clearly, these requirements will vary (generally increase) with time. This approach is impractical. A more reasonable approach is to identify an interval of time for which requirements are to be deduced, i.e., a planning interval. Specifically, a shipping schedule is identified for that interval, and feasible itineraries are constructed to cover that schedule. A problem which arises in this approach is the handling of planning interval boundaries.

In the fixed-fleet approach, this boundary problem can be handled by using a warm-up interval in which itineraries are constructed from fixed initial locations for transport units. Positions at the end of the warm-up interval become initial positions for the "real" itinerary construction. The purpose here is to provide a realistic initial condition which reflects prior commitments of transport unit elements to prior shipping requirements.

In the non-fixed-fleet approach, this boundary problem can be handled by taking the shipping schedule to be periodic, with the period being the planning interval. It is emphasized that we are <u>not</u> assuming that the shipping schedule is actually periodic. This is merely a technical device to handle the boundary problems.

This distinction in means for handling the boundary problem for the fixed-fleet and non-fixed-fleet approaches leads to a distinction in methods for itinerary construction, as is discussed in the next section.

3.5 Itinerary Construction

The fundamental procedure in the recommended approach is itinerary construction. Two forms of this procedure are described here:

(1) Open itinerary construction, appropriate for the fixed-fleet approach

(2) Closed itinerary construction, appropriate for the non-fixed fleet approach where a periodic schedule representation is used.

In using the term "fleet" here, it should be recognized that we are using it in a general sense to refer to the collection of all transport unit elements of a given type, e.g., the collection of trucks, or the roster of crews. To avoid cumbersome language, we shall refer to the elements as trucks.

3.5.1 Open Itinerary Construction

In the fixed-fleet approach, the fleet size and the initial conditions (at home base, en route to a pickup, etc.) of all elements are specified. These initial conditions define partial itineraries. The objective is to attach services to these partial itineraries to produce full itineraries covering the specified set of services. This is achieved by

(1) regarding the partial itineraries as the tail ends of services, and

(2) recursively linking all services until the number of remaining composite services is equal to the fleet size.

779 330

Feasibility of the specified fleet is connected with the number of remaining composite services. If this number exceeds the fleet size, the specified fleet is too small to handle the shipping schedule.

The result of the process is illustrated in Figure 3.9, where two trucks are indicated (service flexibility is not shown in order to simplify the illustration). Truck 1 is initially located at A; truck 2 is en route to C. Three "shipment" services and two "partial itinerary" services are involved. The process itself is based upon the recursive linking of pairs of services as described in Section 3.2.

The procedure is as follows:

Step 1: Determine all feasible linkings of services. If there are none, stop; else go to Step 2

Step 2: Compute a value for each feasible linking; go to Step 3

Step 3: Determine that linking of highest value; go to Step 4

Step 4: Merge the linked services into an equivalent service; go to Step 1.

Steps 1 and 4 were described in Section 3.2. The remaining critical step is that of assigning a value to a feasible linking. This issue is deferred to Section 3.5.3.

3.5.2 Closed Itinerary Construction

In the non-fixed fleet approach, we will obviate specification of initial conditions by adopting a framework of a periodic set of services. The objective of itinerary construction is now to construct closed loops so that, in effect, the implied initial conditions are defined by a corresponding set of terminal conditions. Specifically, as illustrated in Figure 3.10, the association is defined by the presence of the "return arc". In the illustration, it can be seen that two trucks are

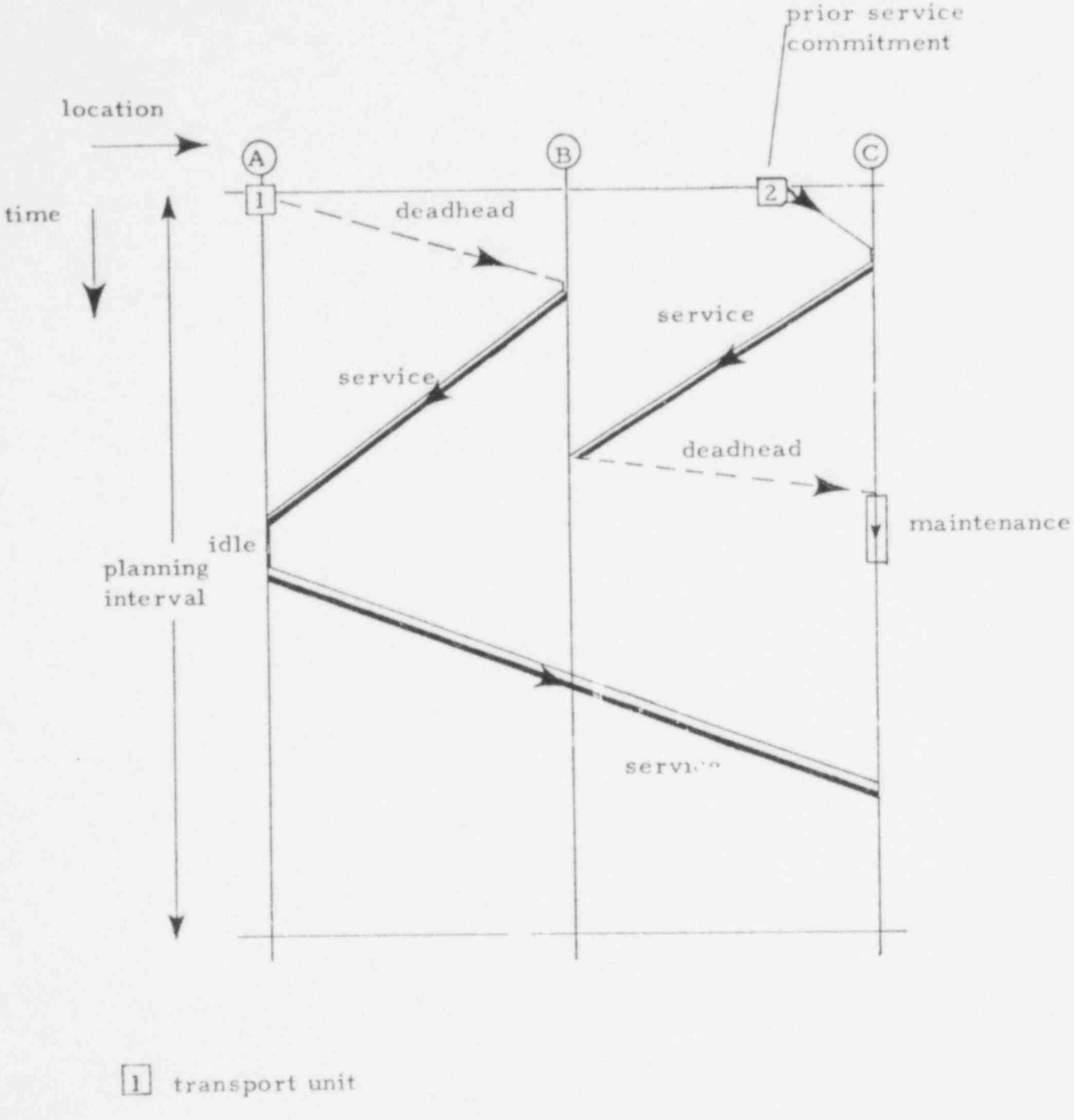


Figure 3.9 Fixed-Fleet Itinerary Construction

779 332

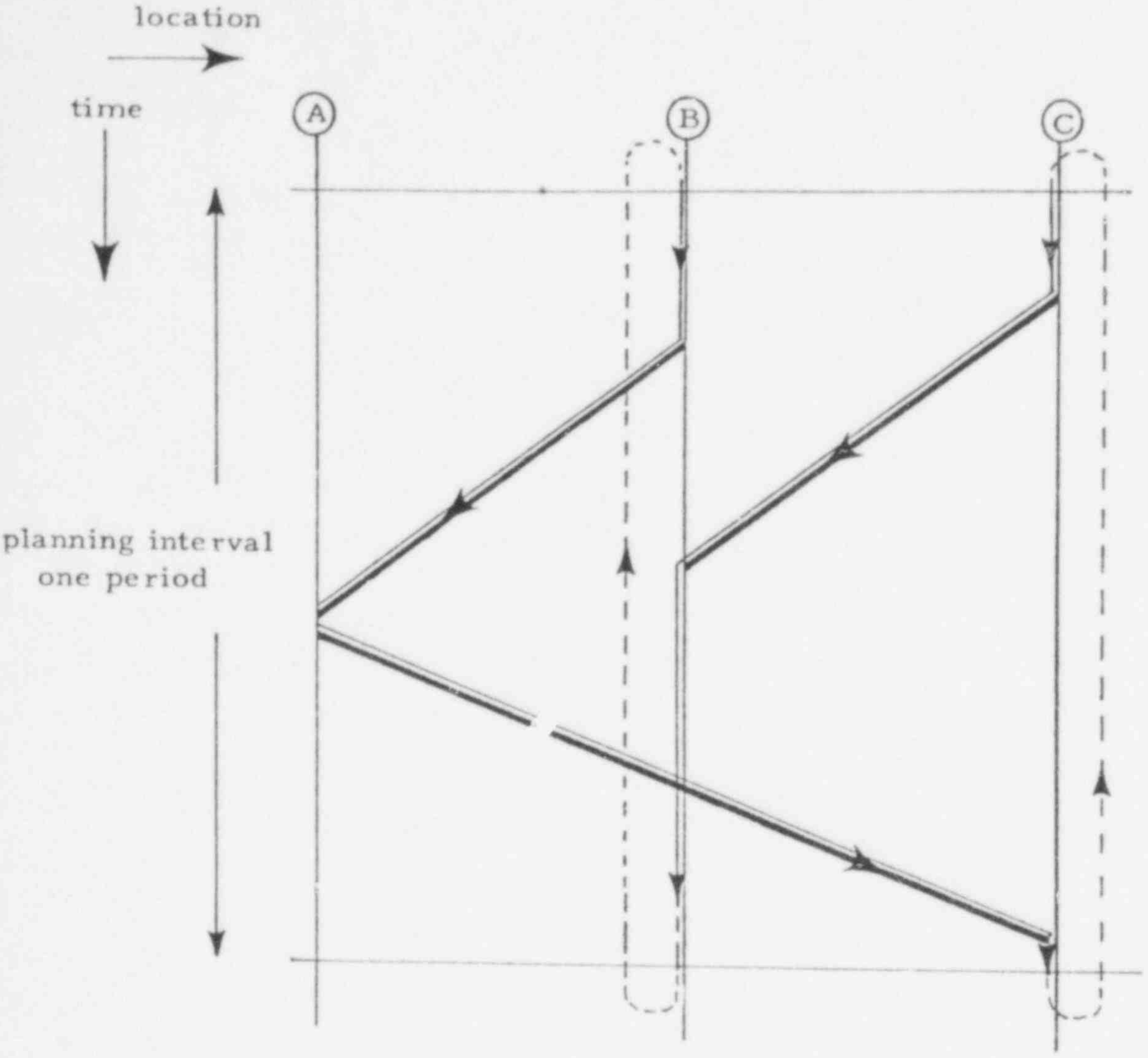


Figure 3.10 Closed Itinerary Construction (one two-period chain)

779 333

required to cover the services if the itineraries indicated there are adopted. This is reflected by the presence of two return arcs.

The requirement of closed loops is connected to the idea of forcing the initial condition for each truck to coincide with some terminal condition.

The procedure in this instance involves

(1) representation of the set of services in periodic form (see Section 3. 2), and

(2) recursive linking of services as appropriate to a periodic set of services (see Section 3. 2), including allowance for self-linking.

Self-linking provides the essential closure of itineraries. It will be recalled that the periodic representation for services involves an enumeration of the number of return arcs. The required fleet size is simply the sum of the number of return arcs in the set of closed itineraries which cover the services.

The procedure here is identical to that for open itinerary construction, except that return arcs and self-linking are now allowed.

3. 5. 3 Criteria for Itinerary Construction

Itinerary construction as we have outlined it depends upon the valuation of feasible linkings. We envision this valuation to be based upon the recursively defined elementary measures previously delineated at the end of Section 3. 2.

A reasonable candidate for a "cost" of a linking can be defined in terms of the following three quantities:

added idle time = idle time in combined service
- [sum of idle times in constituent services]

added deadhead time = deadhead time in combined service
- [sum of deadhead times in consituent services]

loss of flexibility = flexibility in combined service
- 1/2[sum of flexibilities in constituent services]

This candidate is

k_1 [added idle time]

+ k_2 [added deadhead time]

+ k_3 [loss of flexibility]

Careful formulation of the "linking value function" is expected to be necessary to produce good itineraries.

779 335

3.6 Problem Decomposition

Adopting, as we have, the construction of itineraries as the basis for our approaches to the sizing problem. it appears to be necessary, and it is certainly convenient, to decompose the problem The approaches we have developed (and to be described subsequently), distinguished as the fixed-fleet and the non-fixed-fleet approaches, involve the assignment or scheduling of a single transport unit type to a specified planning interval. In order to make use of these elementary scheduling approaches, it is necessary to identify a decomposition into a set of problems, each of which can be addressed by the elementary scheduling approaches, and which collectively address all aspects of the sizing problem. We envision the possibility of decomposition according to any one of the following aspects:

(1) Mode. Possible transportation modes include trucks, aircraft and trains. There is a necessity for a decision mechanism to determine the mode for each shipment which includes consideration of cost, safety and security. Once a decision is made, the set of shipments can be partitioned into separate sets of requirements for each of the modes. Note that shipments to be handled by trains and aircraft will likely require associated shipments by trucks (e.g., to the railhead).

(2) Transport Unit Type. Each shipment must be carried in one or more carrier units such as truck trailers.

779 336

Then a tractor is required to haul each trailer, escort vehicles must be assigned to the tractor-trailer combinations, and crews must be assigned to the trucks and escort vehicles. This assignment process suggests a natural decomposition by transport unit type in which assignments of trailers, tractors, escort vehicles, and personnel are made sequentially. An advantage of this decomposition is that constraints, such as the requirement that a moving tractor requires a driver, now appear as relatively simple interface problems.

(3) Time. Here the transport units assignments are made over a time interval which is shorter than the total available shipment schedule. This time interval could be as short as one or two days and as long as several months.

(4) Geography. Rather than considering the shipment requirements over the whole United States, the country can be divided into regions and the assignment problems for each region can be treated separately.(12)

The recommended decomposition is a combination of partitioning by mode, transport unit, time, and possibly geography, if needed. First a planning horizon must be set for the scheduling process. The investigation of the effect of this planning horizon on the schedule will be an important part of the study. Within this planning horizon the shipping schedule will be decomposed by modes. Aircraft and trains will probably first be scheduled, thereby imposing a service requirement for trucks. The transport units associated with truck shipments will then be sequentially assigned. For example, truck trailers may first be assigned to cover the transportation of the air shipments to

779 337

and from the airfields, followed by trailer assignments to cover the remainder of the shipping schedule. The next step might be to assign tractors to cover the requirements of the trailers. This is followed sequentially by the escort vehicle assignments to the trucks, and finally the crew assignments to the trucks and escort vehicles. This general process is illustrated in Figure 3.11. Note that each step of the assignment process defines a service requirement for the next step. Since all the assignment processes are similar, it is expected that the same basic assignment algorithm can be used for each step.

It is important to note that other decompositions of the assignment process are possible and may be desirable. As another example, assume that the work rules for the truck crews require that they have a break at home base every two weeks and that they must always remain with the assigned truck tractors between the breaks. Thus each crew must drive the tractor back to home base toward the end of the two week period. The tractor/crew combination could then be considered to be a single unit during the two week period between breaks. A possible scheduling procedure based on these rules might appear as shown in Figure 3.12. Other possible decompositions of the scheduling process should be apparent.

To illustrate the reduction in the magnitude of the assignment problems when decomposition is used, again consider the numerical examples used earlier. Assuming a one-month planning horizon, the average number of truck shipments that must be considered are about 40 without spent fuel and 400 with spent fuel.(1) These two figures represent the average number of trailer assignments that must be made to cover the shipments. This is actually the most difficult of the assignment processes due to the flexibility in the shipping schedule. Once

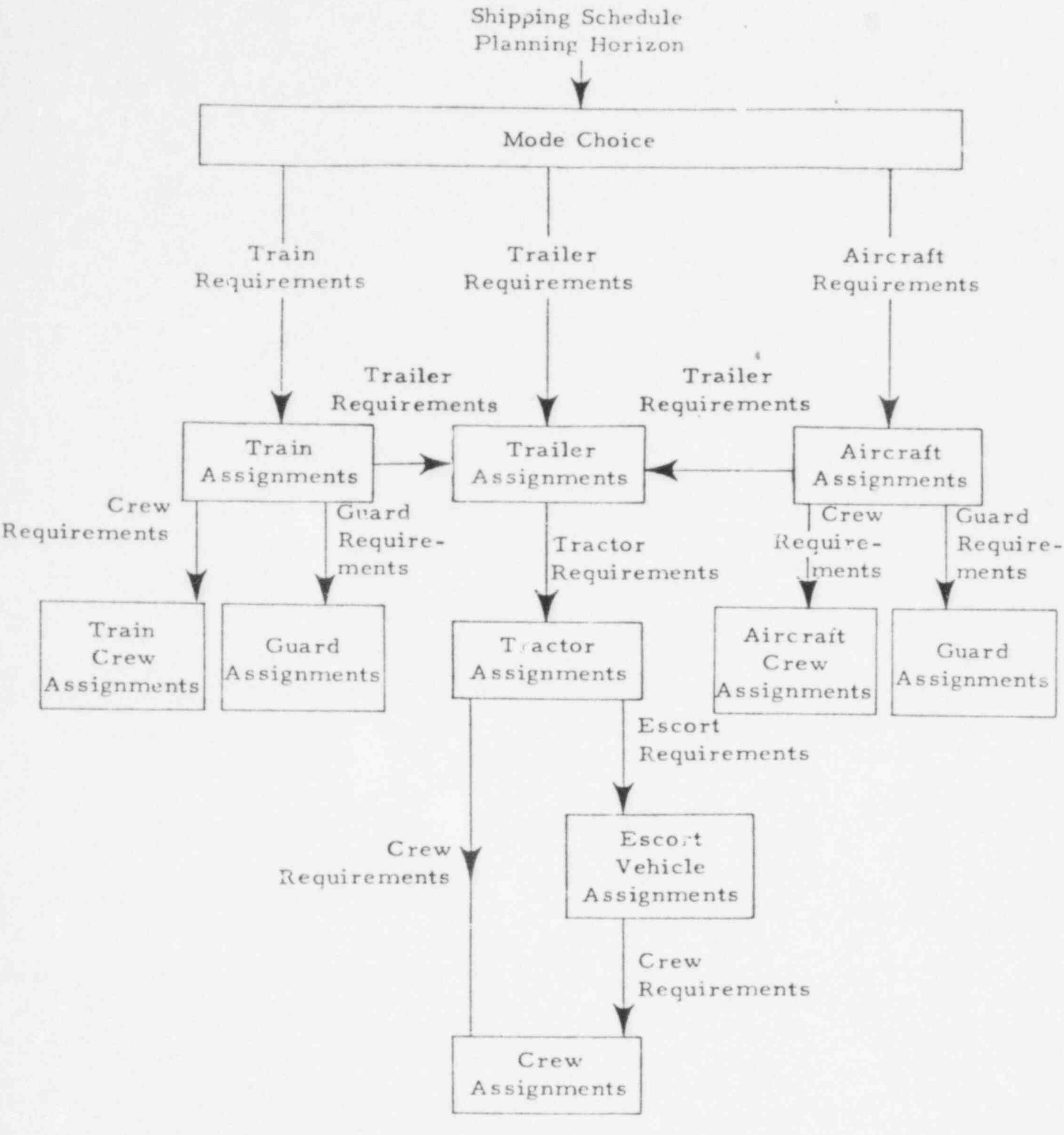


Figure 3.11 Example of possible decomposition of the scheduling process

779 337

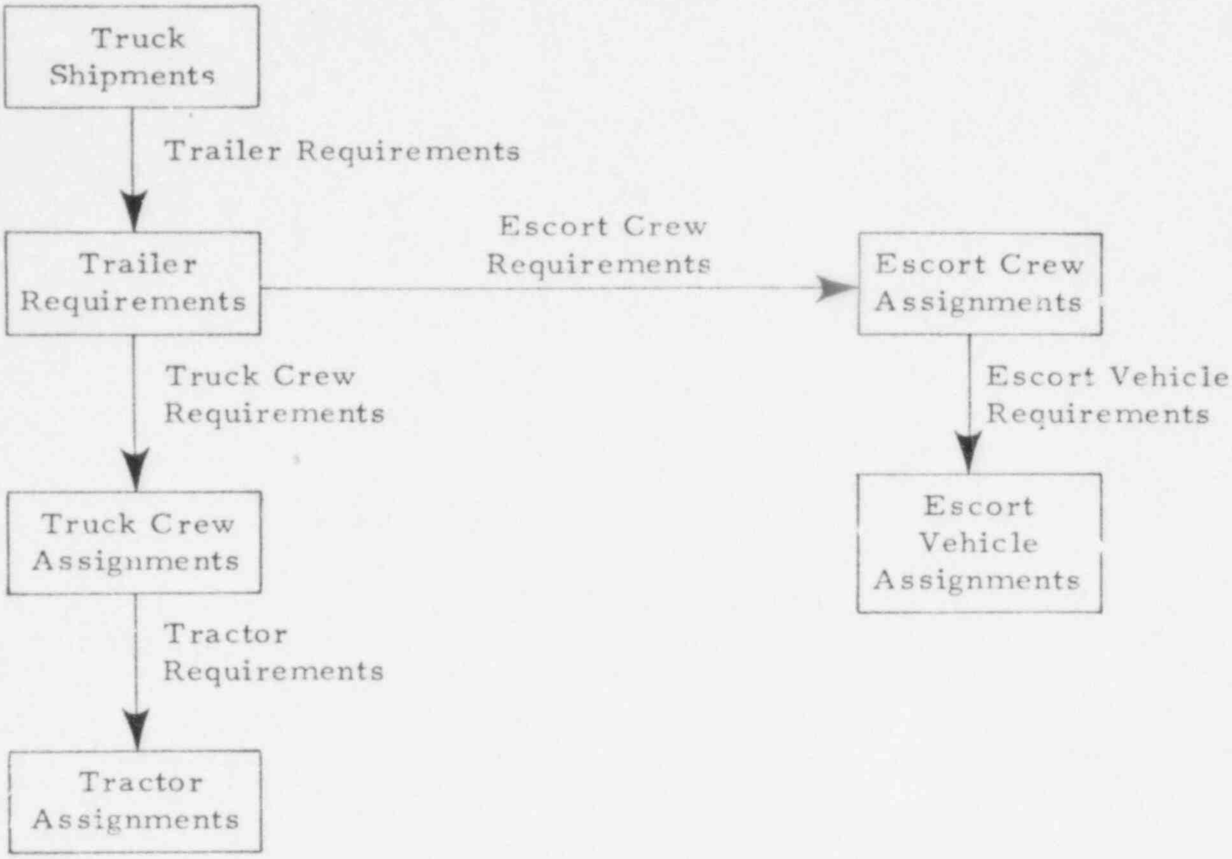


Figure 3.12 Example of possible decompositon of scheduling process for trucks.

the trailers are assigned, they represent essentially a fixed schedule service requirement to the tractors and the escort vehicles. The crew assignments are made based on the fixed tractor and escort vehicle itineraries. With this decomposition, the assignment of the crews to the tractors and escort vehicles represents the largest number of assignments that must be considered at one time. These numbers are approximately 130 and 1300 respectively, for shipments with and without spent fuel.(1) This is a considerable reduction over the total number of assignments that must be simultaneously accomplished without any decomposition. This assignment process is further simplified since the crews are assigned based on a fixed schedule service requirement.

3.7 Approaches to the Elementary Scheduling Problem

The decomposition of the sizing problem has reduced the technical issues to that of identifying a method for solving the elementary scheduling problem, i.e., the problem of scheduling for a single transport unit type for shipments in a specified planning interval. We have identified two approaches to this elementary problem, distinguished as the fixed-fleet and non-fixed-fleet approaches.

3.7.1 The Fixed-Fleet Approach

The fixed-fleet approach involves use of the open-itinerary construction procedure outlined in Section 3.5.1. In the simplest version of this approach, shipments are considered in order of earliest possible departure time, one at a time. Thus, trucks are assigned to shipments in this order. This is the essence of Trucking I.(2)

The fixed-fleet approach we envision involves the direct application of the open-itinerary construction procedure, with the planning interval (the decomposition by time) being a parameter of the method. In particular, one parametric choice reduces the approach to Trucking I, while another extreme involves consideration of the entire interval for which itineraries are to be constructed.

This approach requires statement of initial conditions in the form of the number of units and their current commitments. A "warmup" interval will be necessary to remove the dependence of results upon an arbitrary choice of these initial conditions which might tend to bias the results.

Application of the open-itinerary construction technique terminates when no further reduction in the size of service set is possible. The specified number of transport units is feasible if all shipments have been assigned, i. e., attached to initial itineraries. If this does not occur, it is necessary to test feasibility of a larger number of units. As observed in Reference (2), it is not sufficient to merely provide for these extra shipments by adding more units at some point in time in the middle of the planning interval, as this ignores the service that these additional units may have performed in the earlier segment of the time interval, and therefore may lead to an overestimate of the required number of units.

It can be seen that ascertaining the required number of units, say n , involves the determination that n-1 units cannot handle the shipments, but n units can. Thus, it is desirable to have mechanisms for:

(1) bounding the required number of units from above and below,

(2) reducing this interval iteratively.

When the number of units is likely to be relatively small, say ten, relatively simple procedures, e.g.,

(1) take interval to be $(1, \infty)$

(2) start with one unit and increase until feasible

will perhaps suffice. But, when the number is on the order of twenty or more, more efficient techniques should be identified.

This fixed-fleet approach can easily be modified to provide a simulation algorithm for the study of the ability of the transportation system to respond to major perturbations such as vehicle breakdowns. With such a simulation tool, the fleet size will be kept fixed and the initial conditions may be specified so that no warm-up period may be required.

Important inputs to such a simulation algorithm are the models for breakdowns and the policies for responding to them. One possible response is to completely restart the scheduling process when a breakdown occurs. Another is to attempt to keep the same basic schedule and to handle the breakdown by a relatively small perturbation to the schedule.

3.7.2 The Non-Fixed-Fleet Approach

The non-fixed-fleet approach derives from application of the closed-itinerary construction method described in Section 3.5.2. In this approach, no warm-up is required, nor are iterations on the number of units. These features are advantages that drive consideration of this alternative approach.

In this approach, the entire planning interval of interest is considered in the "elementary" problem. It is necessary that the process of constructing closed itineraries terminate with all itineraries closed in order that a representation of initial and terminal conditions for the transport units be complete. A critical element of the detailed procedure is to assure that this occurs.*

If the return arcs are broken (or ignored) on all the closed itineraries, the resultant picture is identical to that for the fixed-fleet approach. It is easily seen that the total fleet requirement coincides with the total number of return arcs.

3.8 Shipment Quantities and Convoys

Many shipments in the nuclear fuel cycle will require several convoying units, e.g., trailers. In our discussion of itinerary construction (Section 3.5), we have indicated how the quantities of shipments would be taken into account.

Beyond merely accounting for shipment quantities, it may be desirable to emphasize the creation of convoys in which several trucks move together under a common escort, the purpose being to improve security, or to reduce overall costs for security.

The itinerary construction methods we have described are not directly suited to convoy construction, except in a limited way. If convoys were to remain intact for the entire duration of the planning interval, emphasis (in the value function, Section 3.5.3) on linking shipments with quantities of the desired amount would tend to produce convoys. The more likely situation, however, is that convoys will not remain intact for more than one or two shipments.

---

*Technically, this will not be a problem, as closure can be obtained by use of an idle period of sufficient duration.

779 344

To handle convoys, a major revision in the itinerary construction procedure (recursive linking of services) appears to be necessary. It will be necessary to provide for the merger of two or more services to form the desired service (convoy). The difficulty does not appear to be conceptual, but technical details will have to be worked out.

779 345

4.0 MATHEMATICAL FORMULATIONS

In this section we give some preliminary mathematical formulations of some aspects of the computer model of the nuclear fuel cycle transportation system. Specifically, the following items are covered: mathematical representation of services, elementary measures on the services, linking of sequential services, the details of the integer linear programming (ILP) techniques, and the generation of itineraries.

4.1 Representation of Required Services

The representation of required services adopted here includes provisions for flexibility in service times within several intervals (see Figure 3.3), assumption of a periodic schedule which includes return arcs (see Figure 3.4), maintenance, and for quantities of required services. This is the most general situation we expect to represent.

A set of required services is in the form of a list, the i^{th} element of which has the form

$$[a_i, b_i, c_i, \{(s_i^p, t_i^p, n_i^p, u_i^p,), \; p = 1, \ldots, P_i\}, v_i, m_i, w_i]$$

where

a_i	origin
b_i	destination
c_i	quantity of service

779 340

s_i^p	earliest departure time in p^{th} interval
t_i^p	earliest arrival time in p^{th} interval
n_i^p	number of return arcs corresponding to (s_i^p, t_i^p)
u_i^p	width (flexibility) of p^{th} interval
P_i	number of alternative time intervals
v_i	accumulated duty from beginning of this service
m_i	logical variable for inclusion of a maintenance stop within this service
w_i	accumulated duty to the end of this service

The service time alternatives are defined by a choice of a departure interval $p \in [1, \ldots, P_i]$ and then a departure time τ within the interval $[0, u_i^p]$. For these choices, the departure time is $s_i^p + \tau$ and the arrival time is $t_i^p + \tau$.

If the services are considered to be periodic, the actual arrival time, relative to the departure time, must be adjusted to $t_i^p + \tau + n_k^p T$, where T is the period.

The accumulated duty variables are related to maintenance requirements, i.e., maintenance (or rest) is required after a specified accumulated duty, and the amount (duration) of maintenance required may depend upon the accumulated duty. The presence of two accumulated duty variables will be explained subsequently.

779 347

4.2 Elementary Measures

To prepare for the evaluation of linkings of services and of itineraries, we introduce some further notation pertaining to certain standard, elementary measures on services. A set of such measures would be associated with each discrete alternative interval for each service, in the form

$$[f_{i\ell}^{p}, \ \ell = 1, \ldots, L_1], \ p = 1, \ldots, P_i$$

$$[g_{i\ell}, \ \ell = 1, \ldots, L_2]$$

L_1	number of elementary measures (taken to be seven at present) distinguished by the discrete service time alternative parameter
f_{i1}^{p}	total service time = $t_i^p - s_i^p + Tn_i^p$
f_{i2}^{p}	total service miles (= distance from a_i to b_i for original services)
f_{i3}^{p}	active service time (= total service time for original services)
f_{i4}^{p}	active service miles (= total service miles for original services)
f_{i5}^{p}	deadhead time (zero for original services)
f_{i6}^{p}	deadhead miles (zero for original services)

779 343

f_{i7}^{p} idle time (zero for original services)

and L_2 number of elementary measures pertaining to the entire service (at present one)

g_{i1} flexibility (range of departure times) = $s_i^{pi} + u_i^{pi} - s_i^{1}$

We have indicated how these measures would be defined for the original set of services. Measures for equivalent services formed by linking of two services are defined in the next section.

4.3 Linking of Services

Here we provide details pertaining to the linking of services. To do this, we must first consider constraints on accumulated duty (i.e., maintenance and rest requirements) and temporal feasibility. If this linking is found to be feasible, the resultant equivalent service can then be identified. Also considered here are the linking of services in a periodic set of services and the special considerations for "self-linking".

4.3.1 Maintenance Considerations

Maintenance requirements are defined by (1) an upper bound on the accumulated duty allowed between maintenance intervals, and (2) the required duration of the stay in maintenance. In considering the feasibility of linking two services, we first attempt a linking without introducing a stay in maintenance. If that violates the bound on accumulated duty, a linking with a maintenance stop between the two services is considered.

Consider a sequence of services, as illustrated in Figure 4.1, which are linked together to form composite service i. This sequence contains a stay at maintenance. In considering the possible linking

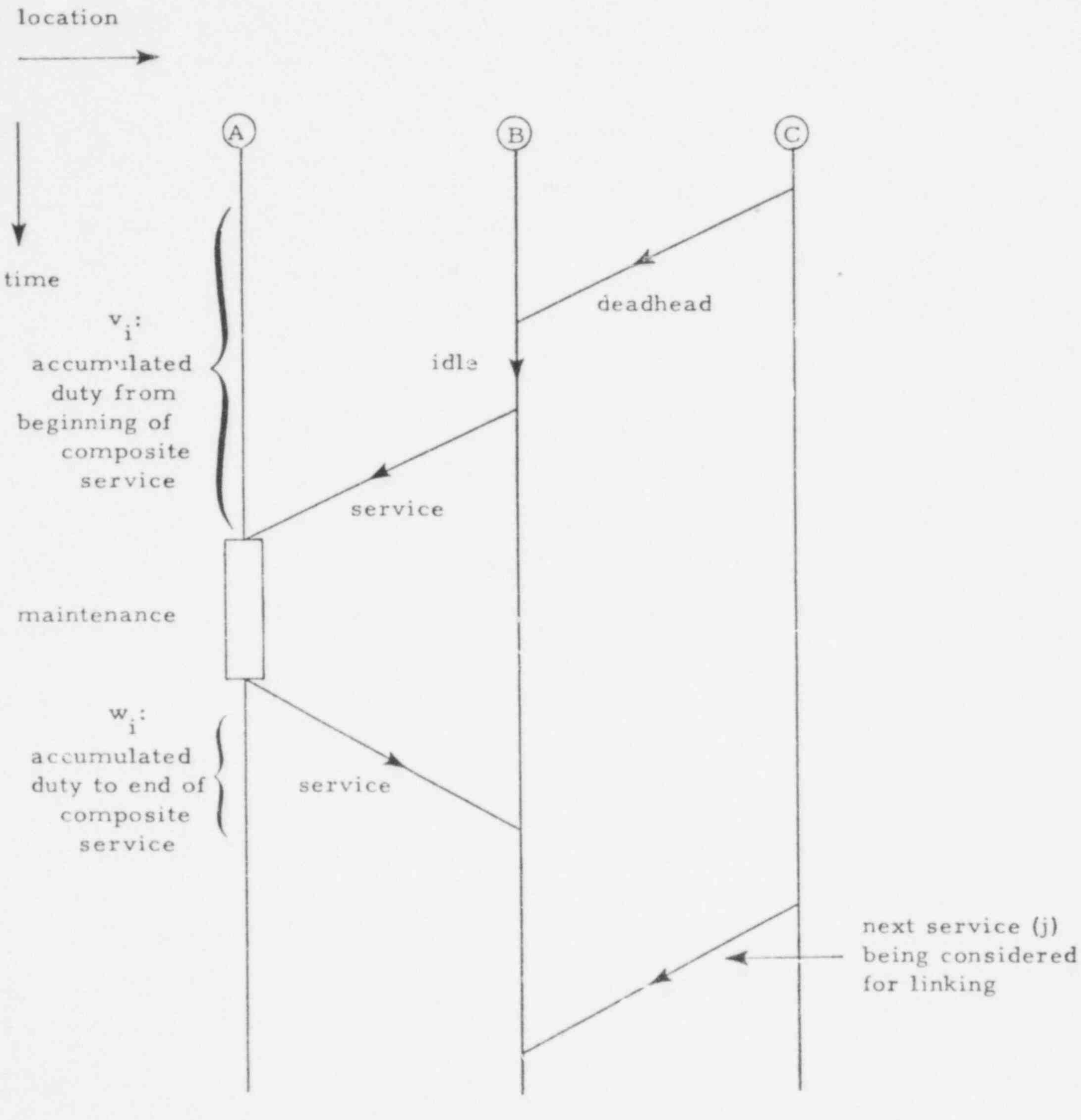


Figure 4.1 Accumulated duty for a service.

of this composite service (i) with another (possibly composite) service (j), it is necessary to distinguish between the accumulated duty from the beginning of service i, v_i, and the accumulated duty to the end of the service, w_i. This distinction is necessary only if there is one (or more) stays at maintenance contained in the sequence. To specify this condition, we define the logical variable m_i by

$$m_i = \left[\begin{array}{ll} 1 & \text{if the service contains a stay at maintenance} \\ 0 & \text{otherwise} \end{array}\right.$$

If $m_i = 0$, we have, by definition, $w_i = v_i$.

In considering the feasibility of linking services i and j, there are four possible combinations of m_k and m_j which can occur. To investigate these cases, the following variables are required:

ξ = travel time from b_i to a_j

η = "internal accumulated duty" in travel from b_i to a_j (e.g., $\eta = \xi$)

$\beta_i (\beta_j)$ = accumulated duty in travel from $b_i (b_j)$ to maintenance base (e.g., equal to travel time)

$\alpha_i (\alpha_j)$ = accumulated duty in travel from maintenance base to $a_i (a_j)$ (e.g., equal to travel time)

We shall make the general assumption that accumulated duty is additive by journey leg. Then, for example, if neither service (i or j) includes a stop at maintenance ($m_i = m_j = 0$), the accumulated duty for the new combined service (k) is

$$v_k = v_i + \eta + w_j$$

If we also account for necessary travel to and from maintenance at either end of the service, we find the constraint to be

$$v_k + \alpha_i + \beta_j \leq D$$

where D is the bound on accumulated use.

Maintenance feasibility conditions, and the resultant accumulated duty variables are given in Table 4.1 as functions of m_i and m_j assuming no maintenance stop between services i and j.

If the bound on accumulated use is violated, an intermediate stop at maintenance must be provided for the linking of services i and j to be feasible. This requires a redefinition of the travel time from b_i to a_j to include the maintenance stop, i.e.,

ξ = travel time from b_i to maintenance
+ required time in maintenance
+ travel time from maintenance to a_j

Table 4.2 summarizes the resultant accumulated duty variables in linking services i and j with an intermediate maintenance stop as functions of m_i and m_j. Note that all these linkings are feasible from a maintenance viewpoint.

Table 4.1 Accumulated use assuming no intermediate maintenance stop

$m_i = 0, \ m_j = 0$:

$v_k = v_i + v_j + \eta$

feasible if $\alpha_i + \beta_j + v_k \leq D$

$m_k = 0$

$w_k = v_k$

$m_i = 0, \ m_j = 1$:

$v_k = v_i + v_j + \eta$

feasible if $\alpha_i + v_k \leq D$

$m_k = 1$

$w_k = w_j$

$m_i = 1, \ m_j = 0$:

$v_k = v_i$

$m_k = 1$

$w_k = w_i + \eta + v_j$

feasible if $w_k + \beta_j \leq D$

$m_i = 1, \ m_j = 1$:

$v_k = v_i$

$m_k = 1$

$w_k = w_j$

feasible if $w_i + \eta + v_j \leq D$

779 353

Table 4.2 Accumulated duty assuming an intermediate stop for maintenance

$m_i = 0,\ m_j = 0$:

$$v_k = v_i + \beta_i$$

$$m_k = 1$$

$$w_k = \alpha_j + v_j$$

$m_i = 0,\ m_j = 1$:

$$v_k = v_i + \beta_i$$

$$m_k = 1$$

$$w_k = w_j$$

$m_i = 1,\ m_j = 0$:

$$v_k = v_i$$

$$m_k = 1$$

$$w_k = v_j + \alpha_j$$

$m_i = 1,\ m_j = 1$:

$$v_k = v_i$$

$$m_k = 1$$

$$w_k = w_j$$

4.3.2 Temporal Feasibility

The temporal feasibility condition for linking services i and j is based on checking whether or not the departure time for the second service (j) can be delayed to a time equal to or later than the arrival time at a_j following the first service (i). This arrival time must account for any required intermediate maintenance stops and deadheading.

To mathematically address this temporal feasibility question, define for service i* for fixed p and τ, $\tau \in [0, u_i^p]$

$$s_i = s_i^p + \tau$$

$$t_i = t_i^p + \tau$$

$$u_i = u_i^p$$

$$\tau \in [0, u_i^p]$$

and for service j for fixed q and θ, $\theta \in [0, u_j^q]$,

$$s_j = s_j^q + \theta \quad ,$$

$$t_j = t_j^q + \theta$$

$$u_j = u_j^q$$

---

[*] We take the nonperiodic time representation for this discussion so that the n_i^p are zero. Discussion of periodic services is deferred to section 4.3.3.

779 355

The temporal feasibility condition for given values of p and τ, which define the departure time of service i, can be stated as

$$s_j^q + u_j^q \geq t_i + \tau \qquad (4.1)$$

for at least one value of q. Services i and j can be connected if this inequality is satisfied for at least one set of values of p and τ.

To assess temporal feasibility and to define the resultant composite service variables, all possible pairs of alternative arrival and departure times must be considered. We approach this issue in two steps.

The first case to be addressed is the linking of services with only discrete choices of arrival and departure times, i.e., $u_i = u_j = 0$. If alternative p of service i is connected to alternative q of service j and results in alternative r for the composite service k, the departure and arrival time that result for the composite service are defined by

$$(s_k^r, t_k^r), \qquad r = 1, \ldots P_k$$

where P_k is the number of possible alternatives for the combined service.

The feasibility and resultant departure and arrival times for the combined services are determined by the algorithm which is summarized in Table 4.3. The algorithm incorporates the rule for eliminating any unnecessary internal idling in the resultant composite service.

Temporal feasibility for the linking of services with alternative

Table 4.3 Algorithm for checking feasibility and determining departure and arrival times for the resultant composite service for the discrete alternatives case.

```
Step 1:  Set $p = 1$
         Set $r = 0$
         Set $q = 0$

Step 2:  Set $q = q + 1$
         If $q > P_j$, stop
         Else
             Set flag = false
             Go to Step 4
         End If

Step 3:  Set $p = p + 1$
         If $p > P_i$, stop
         Else go to Step 4
         End If

Step 4:  Compute $\gamma = s_j^q - (t_i^p + \xi)$
         If $\gamma \geq 0$, go to Step 5
         Else go to Step 2
         End If

Step 5:  If flag = false
             Set flag = true
             Set $r = r + 1$
             Set $t_k^r = t_j^q$
         End If
         Set $s_k^r = s_i^p$
         Go to Step 3
```

Note: The final value of q is the number of alternatives, i.e., equal to P_k; if $P_k = 0$, there is no feasible linking.

779 357

service times contained in an interval is described completely by the temporal constraint (4.1). If feasible, the resultant service has service times defined by

$$t_k = \max\left[t_i + (t_j - s_j) + \xi,\ t_j\right]$$

$$s_k = \min\left[t_k - \xi - (t_i - s_i) - (t_j - s_j),\ s_i + u_i\right]$$

$$u_k = \min\left[u_j - (t_k - t_j),\ s_i + u_i - s_k\right]$$

The previous algorithm, and these resultant service definitions, can then be combined to produce the desired algorithm for testing feasibility of and defining the resultant services alternatives pertaining to the linking of service i followed by service j. These resultant services are denoted by

$$(s_k{}^r,\ t_k{}^r,\ u_k{}^r),\ r = 1, \ldots, P_k$$

This algorithm is summarized in Table 4.4.

4.3.3 Linking of Services in a Periodic Set

Linking of services in a periodic set can be reduced to linking of services as previously described. This is accomplished in three steps:

1) transform all service times to aperiodic form
2) execute linking of services
3) transform resultant linked service to periodic notation.

Details of these steps are now provided.

Table 4.4 Algorithm for checking feasibility and determining resultant composite service variables for alternative interval service times.

```
Step 1:   Set $p = 1$
          Set $r = 0$
          Set $q = 0$

Step 2:   Set $q = q + 1$
          If $q > P$, stop
          Else
              Set flag = false
              Go to Step 4
          End If

Step 3:   Set $p = p + 1$
          If $p > P_i$, stop
          Else go to Step 4
          End If

Step 4:   If $s_j^q + u_j^q \geq t_i^p + \xi$ go to Step 5
          Else go to Step 2
          End If

Step 5:   If flag = false
              Set flag = true
              Set $r = r + 1$
              Set $t_k^r = \max [t_i^p + t_j^q - s_j^q + \xi, t_j^q]$
              Set $s_k^r = \min [t_k^r - \xi - (t_i^p - s_i^p) - (t_j - s_j), s_i^p + u_i^p]$
              Set $u_k^r = \min [u_j^q - (t_k^r - t_j^q), s_i^p + u_i^p - s_k^r]$
              Go to Step 3
```

Note: The final value of $r = P_r$; if $P_r = 0$, there is no feasible linking.

In transforming service times to aperiodic form, it is most convenient to arrange for the arrival times t_i^p for service i, and the departure times s_j^q for service j to fall in the standard interval, with other times being adjusted accordingly. Specifically, if t_i^p does not fall in the interval, adjust the <u>departure</u> time of i according to

$$s_i^p \leftarrow s_i^p - Tn_i^p, \qquad p = 1, \ldots , P_i$$

Similarly, if s_j^q does not fall in the desired interval, adjust the <u>arrival</u> time of j according to

$$t_j^q \leftarrow t_j^q + Tn_i^q, \qquad q = 1, \ldots , P_j$$

For the second step, we attempt a linking of services. If not feasible, service times for service j are increased by the amount T, and linking is again attempted.

In either case, for the third step, the resultant service alternatives are transformed to periodic form by first defining

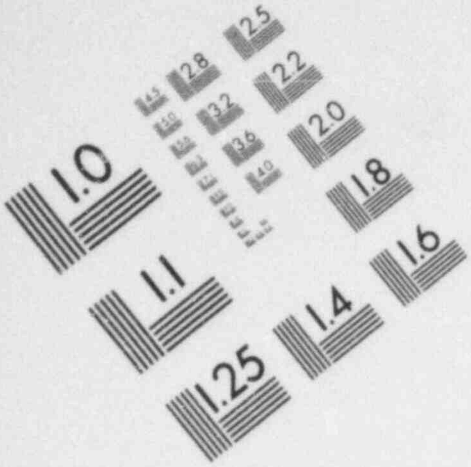
$$z_k^r = [s_k^r / T]$$

where [x] is the greatest positive or negative integer which is not greater than x, and

$$y_k^r = [t_k^r / T]$$

In periodic form the resultant departure time, arrival time, and number of return arcs are found from

779 360



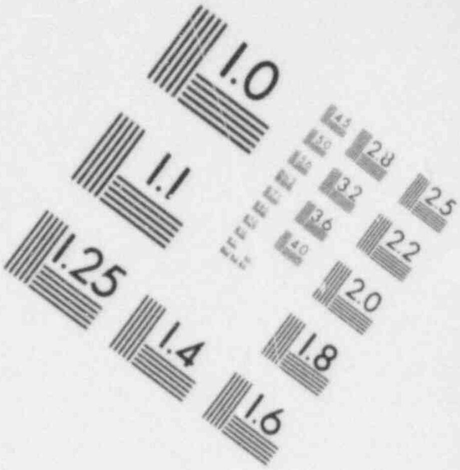
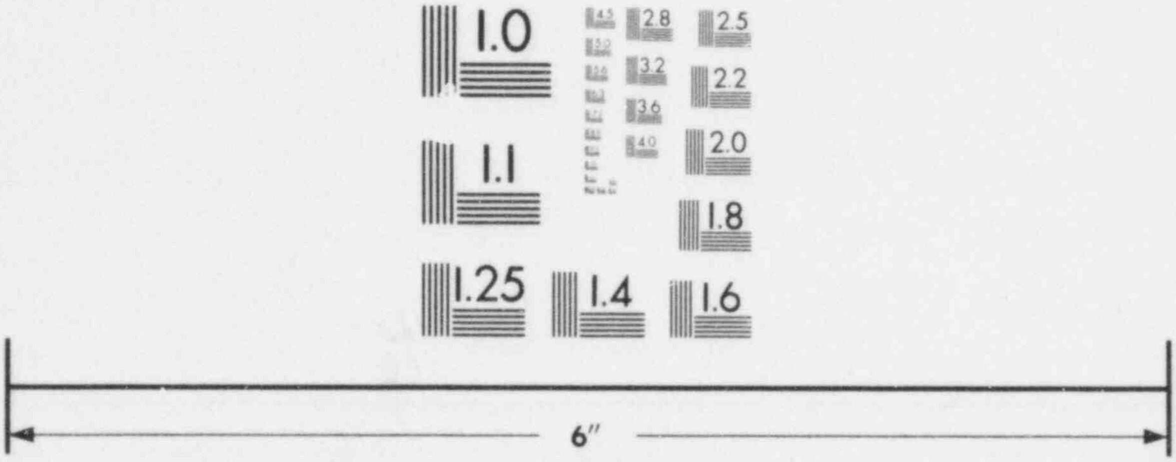
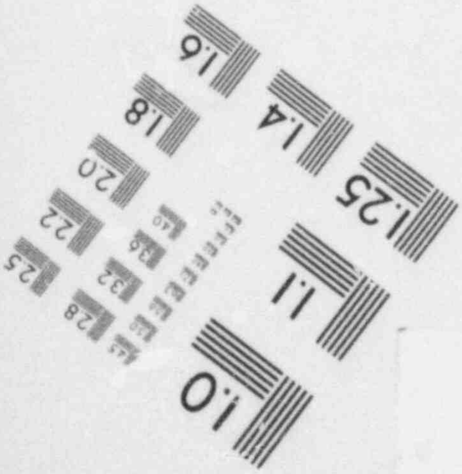
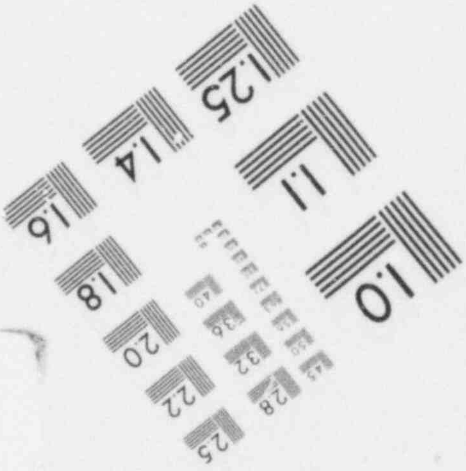
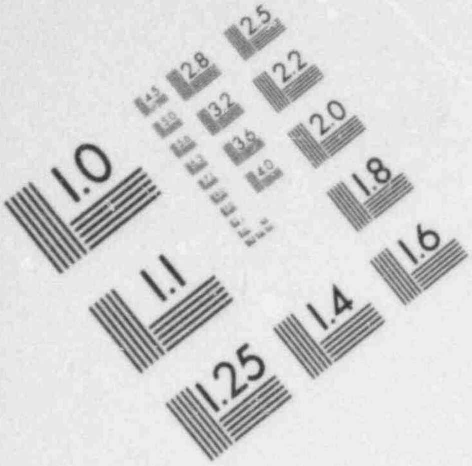


IMAGE EVALUATION TEST TARGET (MT-3)









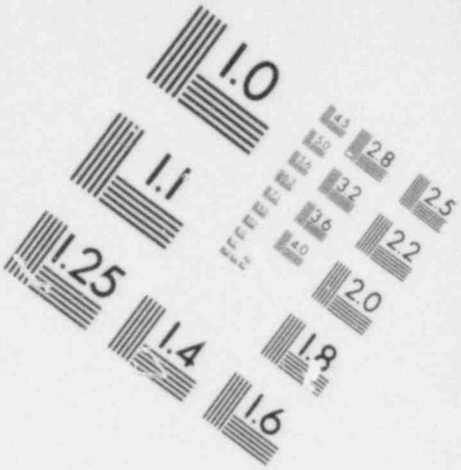
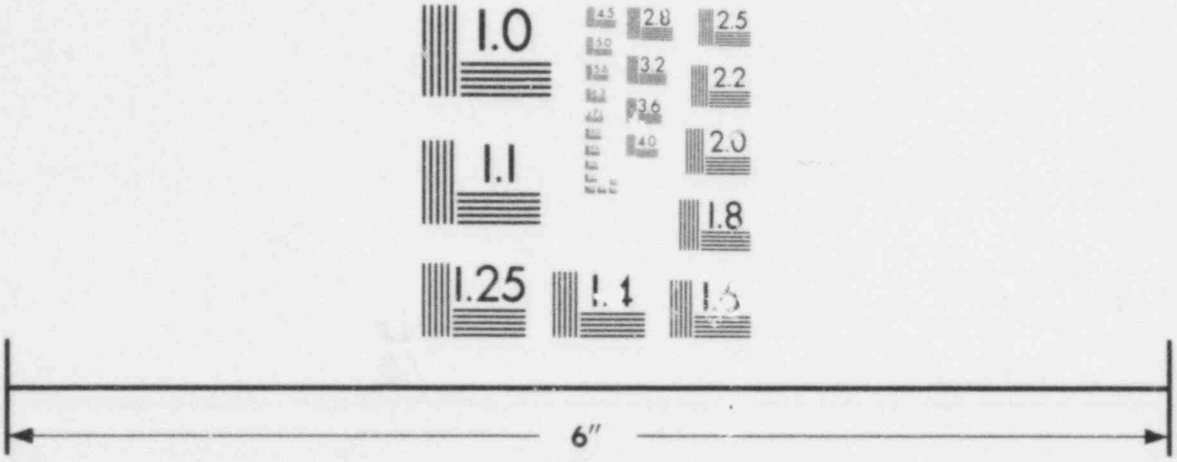
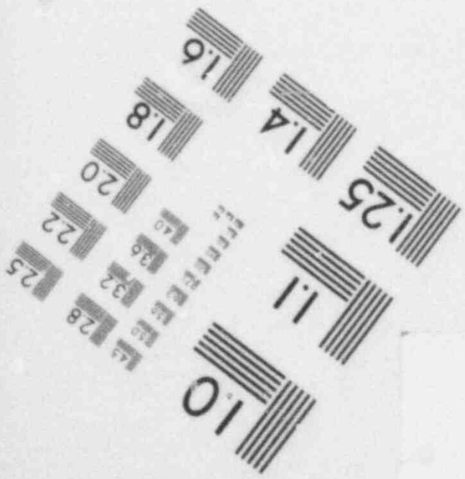
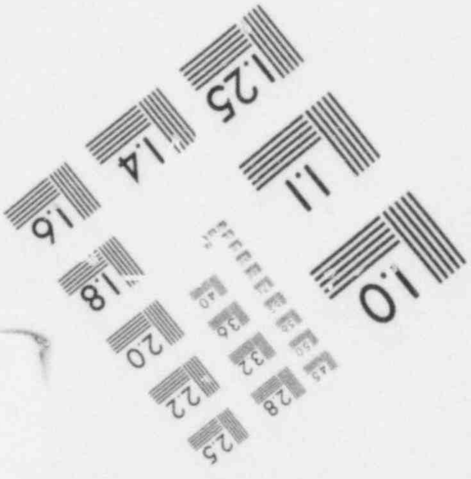
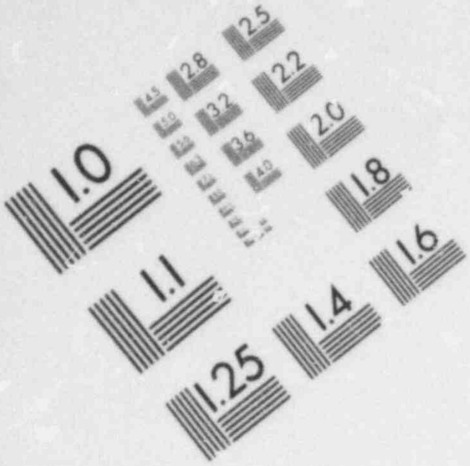


IMAGE EVALUATION TEST TARGET (MT-3)







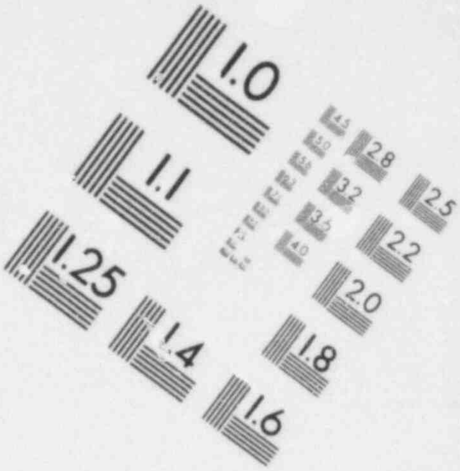
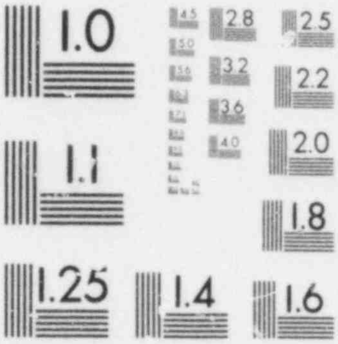
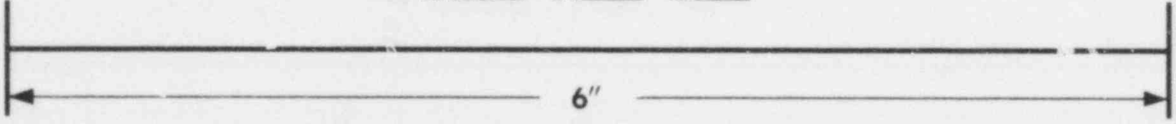
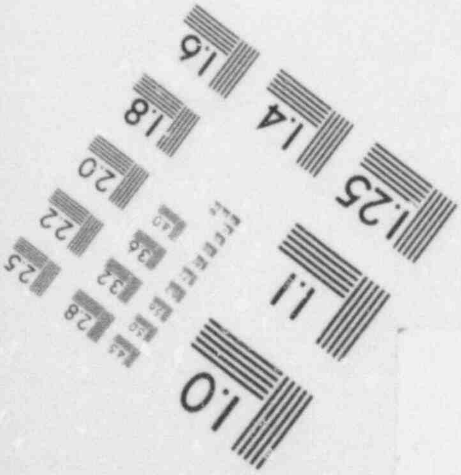
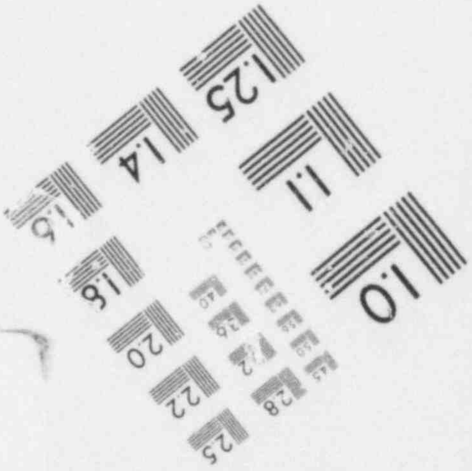


IMAGE EVALUATION TEST TARGET (MT-3)









$$s_k^r \leftarrow s_k^r - T z_k^r$$

$$t_k^r \leftarrow t_k^r - T y_k^r$$

$$n_k^r \leftarrow y_k^r - z_k^r$$

4.3.4 Measures for the Resultant Service

Measures for the linked services i and j and the resultant service k are distinguished by the discrete alternative parameters p, q and r respectively. The measures for alternative r of the resultant service are defined as follows: (see Section 4.2 for the basic definition of these measures)

$$f^r_{k1} = t_k^r - s_k^r + Tn_k^r$$

$f^r_{k2} = f^p_{i2} + f^q_{j2}$ + distance from b_i to a_j, including deadheading if necessary

$$f^r_{k3} = f^p_{i3} + f^q_{j3}$$

$$f^r_{k4} = f^p_{i4} + f^q_{j4}$$

$f^r_{k5} = f^p_{i5} + f^q_{j5}$ + deadhead time introduced to link service i to j

$f^r_{k6} = f^p_{i6} + f^q_{j6}$ + deadhead miles introduced to link service i to j

$$f_{k7}^{r} = f_{i7}^{p} + f_{j7}^{q} + \text{idle time introduced to link service } i \text{ to } j$$

$$g_{k1} = s_k^{Pk} + u_k^{Pk} - s_k^{1}$$

These computations of elementary measures can be easily incorporated into the temporal feasibility algorithms.

4.3.5 Self-linking

Self-linking is a special case of linking which can arise with services in a periodic set. The resultant service is a closed loop which involves connecting the destination of the service to its origin by means of a return arc.

Maintenance considerations can be handled as previously described. Temporal feasibility and definition of the resultant service, however, requires special treatment.

The previous algorithm can be adapted for this by noting that the periodic nature of the resultant service implies that the service time alternatives for service i and service j (actually, a copy of service i) must be the same, i.e., $p = q$ and $\tau = \theta$. Details of this adaptation are in preparation.

The elementary measures for the resultant service are also defined a bit differently. Specifically, we have

$$f_{k1}^{r} = Tn_k^{r}$$

$$f_{k2}^{r} = f_{i2}^{p} + \text{distance from } b_i \text{ to } a_i$$

$$f_{k3}^{r} = f_{i3}^{p}$$

780 002

$$f^{r}_{k4} = f^{p}_{i4}$$

$$f^{r}_{k5} = f^{p}_{i5} + \text{deadheading miles from } b_i \text{ to } a_i$$

$$f^{r}_{k6} = f^{p}_{i6} + \text{deadheading time from } b_i \text{ to } a_i$$

$$f^{r}_{k7} = f^{p}_{i7} + \text{idle time introduced to connect } b_i \text{ to } a_i$$

4.4 Integer Linear Programming (ILP) Formulations

Here we provide a series of integer linear programming formulations for generally increasingly complex forms of the minimum fleet problem.

4.4.1 Fixed-Schedule Problems

Let services be labelled generically by i and j. Define

$$x_{ij} = \begin{cases} 1 & \text{if service } i \text{ is directly followed by (linked to) service } j \\ 0 & \text{otherwise} \end{cases}$$

$N =$ total number of services

$A(i) = \{ j \mid \text{service } j \text{ can follow service } i \}$

$B(j) = \{ i \mid \text{service } i \text{ can preceed service } j \}$

The minimum fleet problem can then be formulated as the following ILP:

$$\max \sum_{i=1}^{N} \sum_{j \in A(i)} x_{ij}$$

subject to

$$\sum_{j \in A(i)} x_{ij} \leq 1$$

$$\sum_{i \in B(j)} x_{ij} \leq 1$$

These constraints quantify the requirement that service i can be linked to (followed by) at most one service j; and service j can be linked to (preceeded by) at most one service i. In words, the fleet size is minimized when the number of connections of services is maximized. This problem is efficiently solved by application of the out-of-kilter flow (OKF) algorithm.$^{(13)}$

4.4.2 Flexible Schedule Problems

Consider services with discrete alternatives for service times, represented as follows:

$$K_\ell = \{ i \mid \text{service } i \text{ is an alternative in the service "bundle" } \ell \}$$

A specific choice is specified by the variables

$$u_i = \begin{cases} 1 & \text{if service alternative } i \text{ is selected} \\ 0 & \text{otherwise} \end{cases}$$

Other definitions are as in Section 4.4.1.

Certain constraints now enter. First, only one alternative is selected in each bundle:

$$\sum_{i \in K_\ell} u_i = 1$$

Secondly, a service alternative can be involved in a linking only if it is selected. Hence

$$u_i \geq \sum_{j \in A(i)} x_{ij}$$

$$u_j \geq \sum_{i \in B(j)} x_{ij}$$

This first inequality will hold with equality for all services except for the last one in a chain when $x_{ij} = 0$, $j \in A(i)$, since no service can follow i. Similarly, the second inequality will hold with equality for all services except when j is the first service in a chain.

4.4.3 Deadheading

Deadheading can be handled in either of two ways. The simpler way is to extend A(i) and B(j) as follows:

$A(i) = \{j \mid$ service j can follow service i, with perhaps a deadhead trip$\}$

$B(j) = \{i \mid$ service i can preceed service j, with perhaps a deadhead trip$\}$

These sets can be determined a priori, for example, by exercising the algorithm detailed for temporal feasibility in Section 4.3.

The second formulation involves explicit representation of the deadhead trips and leads to a considerably larger problem. For this purpose we define

R: the set of alternatives for the required services

$R_\ell = \{i \mid i$ is an alternative for required service $\ell\}$

O: the set of alternatives for the optional services (i.e., deadhead trips and idle periods)

$O_\ell = \{i \mid i \text{ is an alternative for optional service } \ell\}$

The total number of services now includes the optional services O as well as the required services R.

Sets A(i) and B(j) from Section 4.3.2 are now defined in terms of direct connections only, i.e., if required service i can be followed by required service j only with an intermediate deadhead, then $j \notin A(i)$. If k is such an intermediate deadhead, we now have $k \in A(i)$, $j \in A(k)$, $i \in B(k)$ and $k \in B(j)$.

The ILP criterion must be adjusted to account for the fact that extra services are introduced to provide linkings. Note that now

$$\sum_i u_i$$

is the total number of services. Then the number of units required is seen to be

$$z = \sum_i u_i - \sum_\ell \sum_{i \in R_\ell} \sum_{j \in A(i)} x_{ij} - \sum_\ell \sum_{i \in O_\ell} \sum_{j \in A(i)} x_{ij}$$

This ILP formulation now requires the minimization of z.

4.4.4 Multiple Transport Units and Interdependence

The presence of transport unit elements of different types leads to additional complexities in problem formulation in two areas: 1) the need to resolve an approach to a fundamentally multicriteria problem, and 2) formulation of constraints which define the interdependencies of the transport unit types.

The details of any specific formulation depend upon the specific nature of the interdependencies assumed. For example, if all transport unit elements are required to travel together, and are maintained in similar fashion, they effectively form a single unit and the complexities mentioned do not arise. As a second example, suppose crews always stay with their vehicles while out on the road, but reassignments are possible at home base. Then crews and vehicles must be separately represented, but the statement "crews always stay with their vehicles while out on the road" must be translated into constraints involving those variables which define the assignments of crews and vehicles.

The points we wish to make here are as follows:

(1) there exist methods for resolving the multicriteria nature of the problem

(2) interdependencies appear to allow representation as linear inequality constraints

(3) interdependencies lead to enormous growth in the number of constraints where deadheading and schedule flexibility are also involved.

We require the following notation to mathematically develop the formulation of this problem. Define the service sets as follows:

S_k: set of all possible services for transport unit type k

$S_k = R_k \cup O_k$

where

R_k: set of all possible alternatives for required services that must be covered by transport unit type k

O_k: set of all possible alternatives for optional (e.g., deadhead) services for transport unit type k

$R_{k\ell} = \{ i \in R_k \mid$ service i is an alternative in the required service bundle $\ell \}$

$O_{k\ell} = \{ i \in O_k \mid$ service i is an alternative in the optional service bundle $\ell \}$

$N_{k\ell}$: number of required services for transport unit type k

$M_{k\ell}$: number of optional services for transport unit type k

Define service alternative variables:

$$u_{ki} = \begin{cases} 1 & \text{if alternative service i is selected for transport unit type k} \\ 0 & \text{otherwise} \end{cases}$$

And linking variables:

$$x_{kij} = \begin{cases} 1 & \text{if alternative service i is linked to (followed by) alternative service j for transport unit type k} \\ 0 & \text{otherwise} \end{cases}$$

Feasibility of the linking of service alternatives is defined by

$A_k(i) = \{ j \mid$ service alternative j can follow service alternative i for transport unit type k $\}$

$B_k(j) = \{ i \mid$ service alternative i can preceed service alternative j for transport unit type k $\}$

Given values of the service alternative and linking variables, the number of units of type k is expressed as

$$z_k = \sum_i u_{ki} - \sum_{\ell} \sum_{i \in R_{k\ell}} \sum_{j \in A_k(i)} x_{kij} - \sum_{\ell} \sum_{i \in O_{k\ell}} \sum_{j \in A_k(i)} x_{kij}$$

Several approaches exist for handling the several measures for the distinct transport unit types. These approaches are

(1) to produce tradeoffs for Pareto optimal solutions(15)

(2) combine z_k's into a single measure, e.g.,

$$z = \sum c_k z_k$$

(3) employ a priority scheme, e.g., with the unit type indexing possibly reordered, solve in sequence

$$\min z_1 \equiv z_1^*$$

$$\min (z_2 \mid z_1 = z_1^*) \equiv z_2^*$$

$$\vdots$$

$$\min (z_n \mid z_1 = z_1^*, \ldots, z_{n-1} = z_{n-1}^*) \equiv z_n^*$$

where there are n transport unit types. We do not at this point make a choice between these methods, but rather proceed to a discussion of the constraints required.

Constraints required are first, a unique selection of an alternative for each required service:

$$\sum_{i \in R_{k\ell}} u_{ki} = 1, \ \forall k, \ell$$

at most one alternative for each optional service

$$\sum_{i \in O_{k\ell}} u_{ki} \leq 1, \ \forall k, \ell$$

and linking of only of selected alternative services.

$$u_{ki} \geq \sum_{j \in A_k(i)} x_{kij}, \ \forall k, i$$

$$u_{kj} \geq \sum_{i \in B_k(j)} x_{kij}, \ \forall k, j$$

These constraints represent a straightforward extension of constraints for a problem with a single unit type.

The remaining constraints define the interdependencies among the transport unit types. In order to illustrate these constraints, we will consider a specific example of truck scheduling, where the truck can be separated into a trailer and a tractor. We shall require that a tractor be assigned to any trailer movement.

For this purpose, let k = 1 correspond to the trailers, k = 2 correspond to the tractors. Further define

R_1: trailer movements required to move material

O_1: deadhead trips for trailers

R_2: tractor movements required to move material

O_2: deadhead trips for tractors

We assume that service alternatives for required services R_1 and R_2 are compatibly labelled so that $u_{1i} = 1$, $u_{2i} = 1$ means the trailer and tractor are together. Then we require that

$$u_{1i} = u_{2i} \quad i \in R_1 \, (R_2)$$

Further, those tractor deadhead trips which correspond to trailer deadhead trips will also be compatibly labelled. Then we also require

$$u_{2i} \geq u_{1i} \quad i \in O_1$$

Introduction of interdependencies apparently forces the more complex formulation when deadheads are involved in order that we be able to express the fact that the deadhead trips (of the trailer) require covering (by the tractor).

For problems with many service alternatives and possibilities for deadheads, it can be seen that the number of constraints and "basic variables" (variables which have value 1 in a feasible solution) is very large indeed.

4.4.5 Maintenance

Maintenance considerations require that some means be identified for assuring that a complete set of linkings does not include any sequence of services which violates bounds on accumulated duty. Clearly, one could adopt an ILP approach as outlined here, solve the

780 011

problem and then check maintenance constraints. But if these constraints are found to be violated, there arises the question as to what should be the next step.

It would be desirable to incorporate maintenance considerations directly in the problem formulation. However, we have been unsuccessful in finding a means for representing maintenance-related constraints in the form of linear inequalities in terms of the linking variables. Our conclusion is that maintenance considerations lead to a requirement for an alternative formulation, one in which maintenance-related constraints can be easily formulated and checked.

4.5 Itinerary Construction and Recovery

Here we present details of algorithms pertaining to the construction of itineraries. The first three involve the recursive linking of services to produce open or closed itineraries. The key to the approach is that a partial itinerary can be represented as a service for this purpose. A fourth algorithm is then required to recover the details of these itineraries.

4.5.1 Itinerary Construction

We provide here a sequence of three algorithms which pertain to the construction of both open and closed itineraries. The first of these algorithms (Algorithm I1) represents slight detailing of the procedure outlined in Section 3.5. This algorithm provides for the linking of services based on a linking value function that provides a measure of the desirability of each linking. As was discussed in Section 3.5.3, this linking value function might be based on added idle time, added deadhead time and loss of flexibility caused by the linking.

780 012

Algorithm I1 (Basic Itinerary Construction)

```
Step 1:   Define linkings to be considered (as new linkings
              to be considered)
          Go to Step 2

Step 2:   For each new linking
              Determine feasibility of the linking
              If feasible
                  Determine value of the linking
                  Save value in a sorted "linking value list"
              End If
          End For
          Go to Step 3

Step 3:   If no feasible linkings, stop
          Else
              Select linking of highest value
              Get combined service
              Save selection in "linking selection list"
              Go to Step 4
          End If

Step 4:   Adjust service list
          Adjust "linking value list"
          Define new linkings to be considered
          Go to Step 2.
```

Algorithm I2 (Itinerary Construction with a Restricted Linking Value List)

```
Step 1:  Define linkings to be considered
         If no linkings, stop
         Else Go to Step 2
         End If

Step 2:  For each linking
             Determine feasibility of the linking
             If feasible
                 Determine value of the linking
                 Save value in a restricted, sorted "linking
                     value list"
             End If
         End For
         If no feasible linkings, stop
         Else
             Compute bound for saving values
             Go to Step 4
         End If

Step 3:  If no feasible linkings
             Go to Step 1
         Else
             Go to Step 4
         End If
```

780 014

Algorithm I2 (continued)

```
Step 4:   Select linking of highest value
          Get and save combined service
          Save selection in "linking selection list"
          Go to Step 5

Step 5:   Adjust service list
          Adjust "linking value list"
          Define new linkings to be considered
          Go to Step 6

Step 6:   For each new listing
              Determine feasibility of the linking
              If feasible
                  Determine value of the linking
                  If value not less than bound
                      Save value in restricted, sorted "linking
                          value list"
                  End If
              End If
          End For
          Go to Step 3.
```

The set of linkings to be considered may be quite large. For example, if the service list contains 100 entries, there could be as many as 10^4 linkings to be considered. The resultant list of the linking value functions will require considerable storage. One way to reduce this requirement is to restrict the list of values retained to the top n, with n perhaps equal to one hundred.

Algorithm I2 incorporates this concept. The saving and sorting of linking values is now performed in two phases. In the first phase, embodied in Step 2, all linkings are examined, the top n are identified, and the n^{th} largest value is computed for use in the second phase. Step 6 embodies this second phase. Here only newly identified linkings are examined, and values are sorted into the service list, but only if they exceed the previously identified bound.

At some point, the list of values may become exhausted, but only because the values for all remaining possible linkings are less than the bound. The algorithm then returns to Step 1 and Step 2 is repeated on the remaining reduced set of services.

Algorithm I3 provides for a degree of optimization through a backtracking procedure in which linkings with less than highest value are selected. This algorithm is derived from Algorithm I2 by replacing in Step 1 of that algorithm the statement

"If no linkings, stop"

by the statement

"If no linkings, Go to Step 7"

and the addition of Step 7 and 8 as follows:

Step 7: If no combined services remain or if enough solutions have been found, stop

```
         Else
             Dismember last remaining combined service
             Adjust service list
             Recover linking values
             Suppress last selected linking
             Go to Step 8

Step 8:  If no more selections of feasible linkings at this
             stage are available
             Go to Step 7
         Else
             Go to Step 4
         End If.
```

Algorithm I3 is the version which will be implemented. Note that by limiting the number of solutions to be found to one, this algorithm reduces to Algorithm I2. Implementation requires the detailing of a number of procedures indicated, for example, "Define linkings to be considered." The procedure "Determine feasibility of the linking" was previously detailed in Section 4.3.

In implementing Algorithm I3, differences in open and closed itinerary construction will arise in several procedures, in particular:

(1) "Define (new) linkings to be considered." In closed itinerary construction, all pairs of services are candidates for linkings, including self-linkings. In open itinerary construction, services representing initial itineraries may only be predecessors in a linking, whereas services representing shipments may be either predecessors or successors.

(2) "Determine feasibility of the linking" and "Determine value of the linking". Closed itinerary construction requires provision for self-linking.

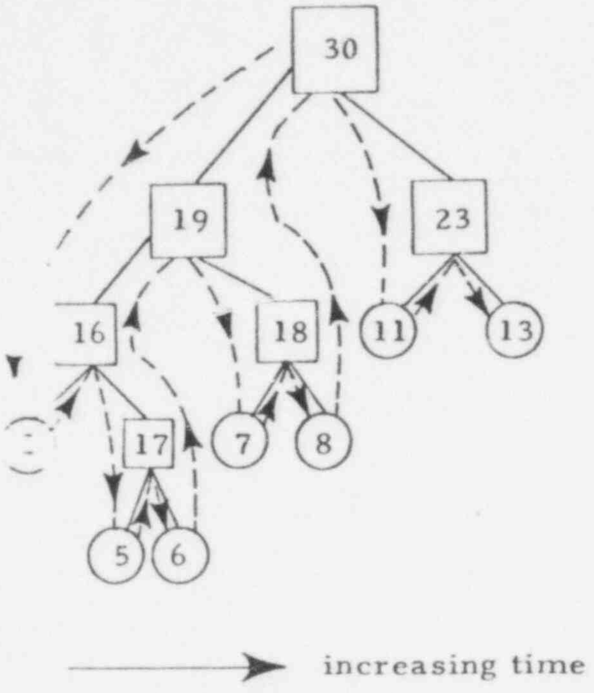
These differences will result in distinct implementations.

4.5.2 Recovery of Itineraries

The recovery of itineraries is basically a two part process. The first part is to represent an itinerary by a binary tree which represents all the linkings of services which were used to build the itinerary. This is illustrated in Figure 4.2. Here, for example, combined service 16 was formed by linking original service 1 and combined service 17, which, in turn, was formed by linking original services 5 and 6. This tree can be built with the time order of the original services increasing to the right, as shown. In this example, the itinerary handles, in order, original services 1, 5, 6, 7, 8, 11 and 13.

The next step in this recovery process is to use an "inorder" traversal algorithm(16) to recover the legs of the itinerary. The "inorder" traversal algorithm is illustrated by the dotted lines in Figure 4.2. Starting with combined service 30 at the top of the tree, the algorithm searches down and to the left until an original service is encountered, in this case number 1. It then searches up the tree to find that original service 1 is part of combined service 16. At this point the details of the linking of services 1 and 17 (5), e.g. a maintenance stop, a deadhead leg and/or idle time, are extracted. Then the search proceeds down until original service 5 is encountered. Proceeding up to combined service 17, the details of the linking of services 5 and 6 are extracted. At this point we have extracted the details of the linkings between original services 1 and 5, and 5 and 6. This process then continues, as indicated by the dotted line in Figure 4.2, until all the original services in the itinerary are considered.

Algorithm 14 describes this process for the recovery of the details of the itineraries.



Order of Consideration of Services Using Inorder Traversal

Figure 4.2 Example of Recovery of Itineraries

780 020

Algorithm I4 (Recovery of Itineraries)

```
Step 1:   Find last service in service list that has not
              been considered
          If none, stop
          Else
              Mark this service considered
              Go to Step 2
          End If

Step 2:   Build itinerary tree by expanding all services
              until all original services are identified
          Go to Step 3

Step 3:   Traverse the itinerary tree in "inorder" to
              recover the order of linking of services.
              As each node that is a combined service is
              reached, output all related journey legs.
          Go to Step 1.
```

5.0 RECOMMENDATIONS

The purpose of this section is to define the capabilities of the ultimate model, and to describe a software development sequence leading toward this ultimate model.

5.1 Ultimate Model Capabilities

The ultimate model to be developed will provide two distinct functions:

(1) vehicle fleet and crew roster sizing

(2) simulation of performance of fixed fleets and crew rosters, including occurrences of breakdowns.

In accomplishing these functions, the following items will be provided:

(1) shipping schedule of variable* size and covering an interval of variable duration

(2) a variable number of modes, to represent possibilities of shipments by aircraft, trains or trucks

(3) a variable number of convoy element types, to represent, for example in the truck mode, the trailers, tractors, escort vehicles and personnel

(4) variable problem decomposition structure

In addition to these fundamental structural elements of the model, provision for flexible specification of various rules will be made, specifically for

(1) the linking value function,

(2) convoy make-up rules, and

(3) performance measures.

---

*That is, the actual number will be a problem parameter subject only to dimension constraints.

Output options will include

(1) itineraries for all transport units

(2) various performance measures for individual and sets of itineraries (e.g., average percent idle time)

(3) fleet and crew roster sizes.

We intend to use structured programming techniques in developing and documenting the code. The higher level structure of the code, as presently envisioned, is presented in Figure 5.1. The characteristic features of this approach are top-down design and the structuring of code into small, logically coherent segments of code, embodied as distinct FORTRAN functions and subroutines.

Such modularization provides flexibility by isolating functions to one or a few subroutines so that alternative approaches can be easily implemented. For example, the choice between a fixed fleet or nonfixed fleet approach to sizing is manifested by a choice of the segment of code labelled as GENITN in Figure 5.1. One version of GENITN is further detailed in Figure 5.2. The remainder of the code is not impacted, except for certain input options whose details are specific to the choice of approach.

Another area where this modularization will be important is the selection and testing of various rules for ordering linking of services. We plan to isolate provisions for these rules in a single function.

5.2 Model Development

It is recommended that model development be carried forward in a sequence of versions, as described in Table 5.1. An overall model design will be identified which will provide for this sequential

780 025

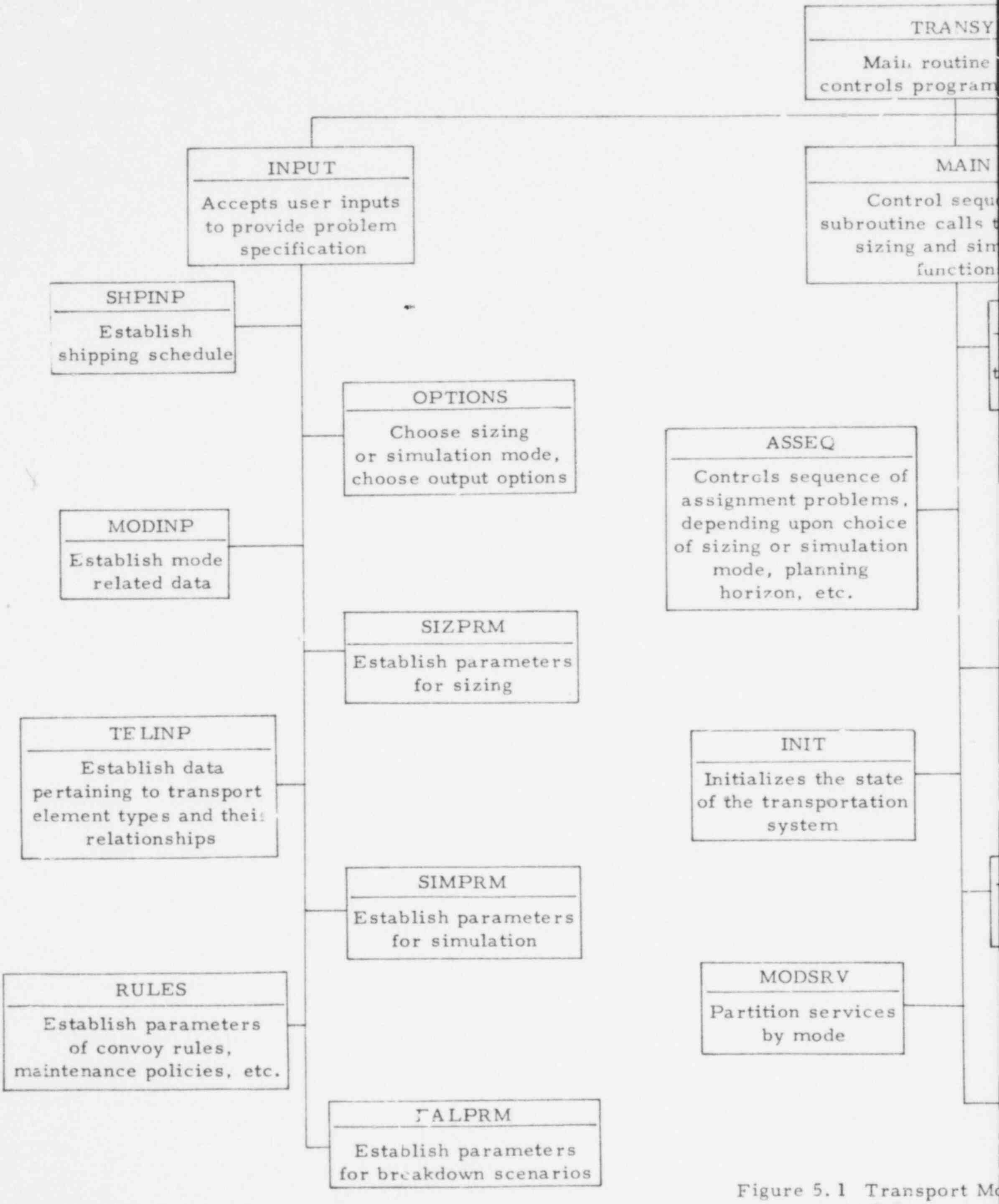
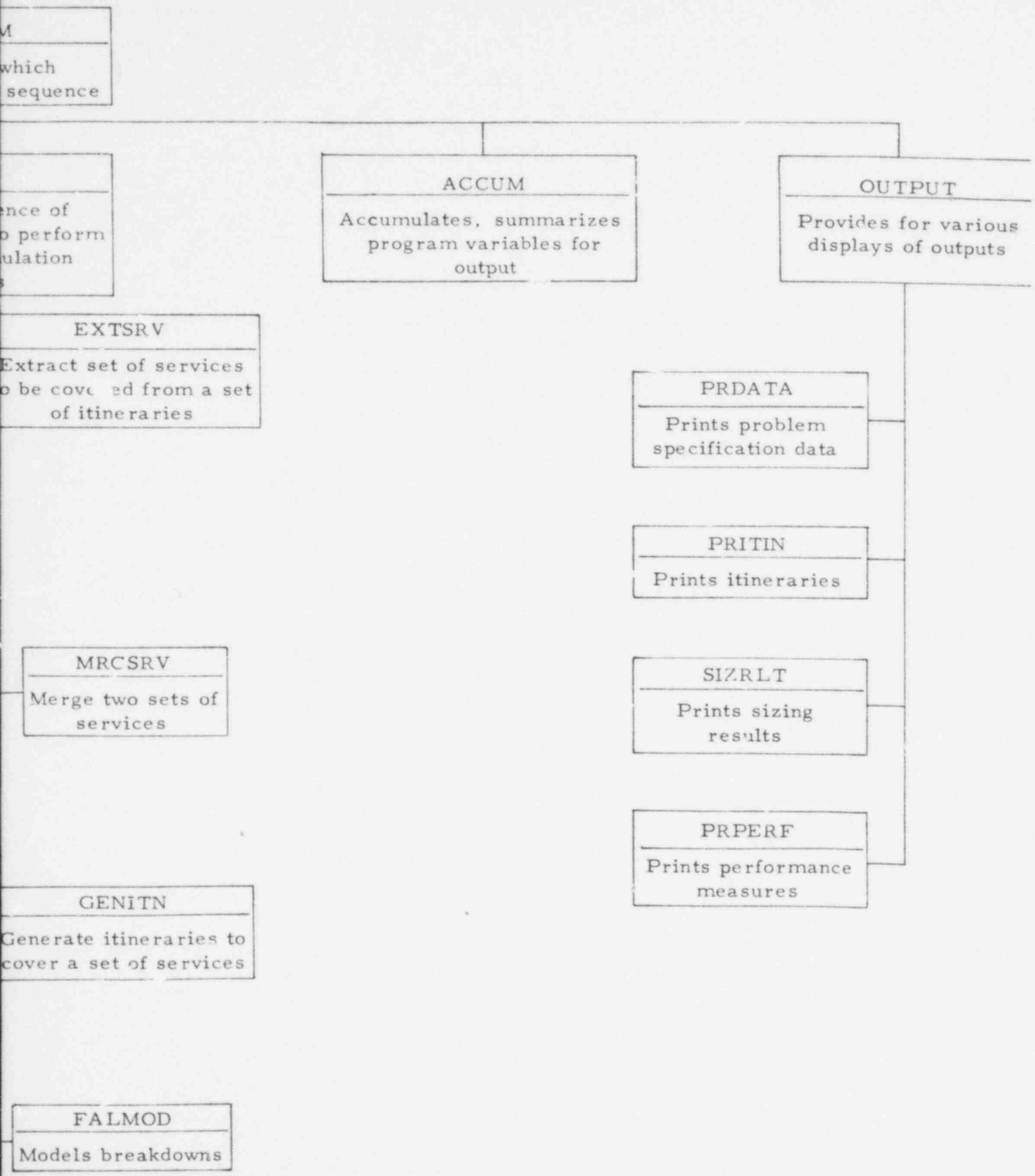


Figure 5.1 Transport Mo



del Code Structure

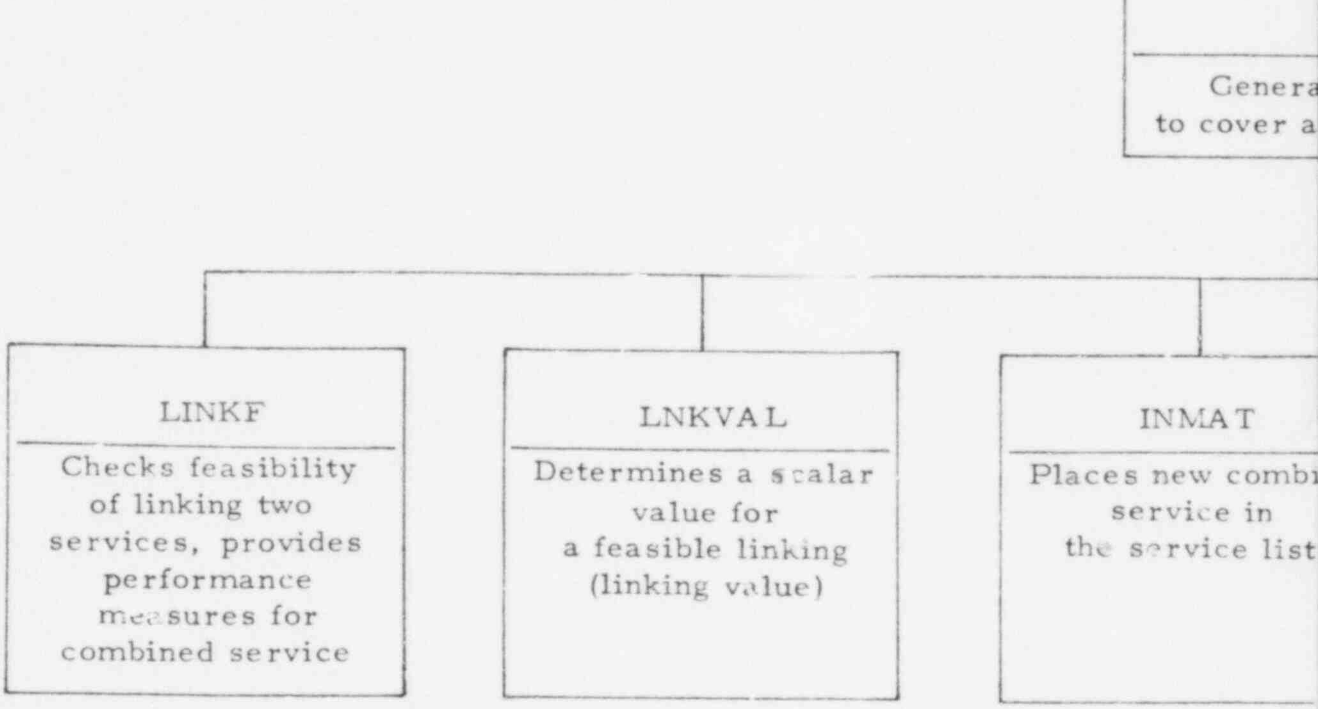
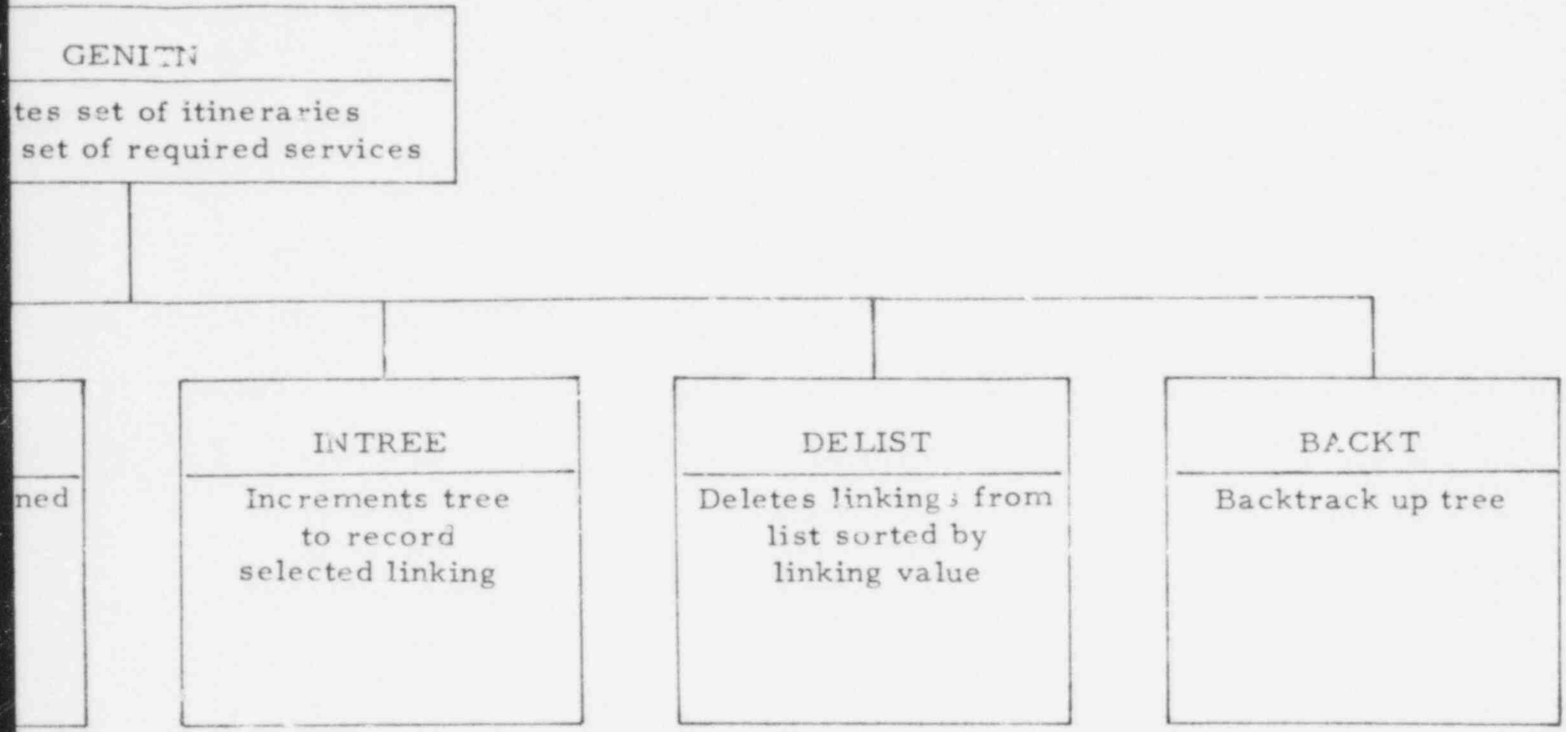


Figure 5.2 Code Stru



cture for Elementary Itinerary Generator

028

Table 5.1 Model Versions

☐ Indicates new or modified feature

Component Features	Version 1	Version 2	Version 3	Version 4
Modes	$\boxed{\text{one}}$	one	$\boxed{\text{several}}$	several
Transport Unit Elements	$\boxed{\text{several}}$	several	several	several
Convoying	no	no	$\boxed{\text{yes}}$	yes
Simulation	$\boxed{\text{Yes; no breakdown}}$	Yes; no breakdown	$\boxed{\text{Yes; with breakdowns}}$	Yes; with breakdowns
Assignment Approach	$\boxed{\text{Fixed-fleet only}}$	$\boxed{\text{Fixed-fleet and nonfixed-fleet}}$	Fixed-fleet and nonfixed-fleet	Fixed-fleet and nonfixed-fleet
Special Input/Output Options	none	none	none	$\boxed{\text{Automated sensitivity analyses}}$

development, so that each version is useful for a rational set of analyses. Furthermore, proceeding from one version to the next involves only refinements and/or additional modules rather than wholesale changes to previously developed code.

Version 1 will provide for complete sizing of all transport unit types for a single mode (trucking), using a fixed-fleet oriented approach. This is a simulation approach but provision for breakdown will not be made. Provisions for a variable planning horizon will be included.

Version 2 will incorporate a non-fixed fleet approach to sizing.

Version 3 will extend the model to handle several modes (i.e., aircraft and rail in addition to trucks), convoying, and to provide for breakdowns in the simulation.

Version 4 will extend input and output options to simplify sensitivity analyses. i.e., provide for a succession of model runs and subsequent graphical displays.

Additional model development issues, not covered in these versions, include

(1) variable problem decomposition structure

(2) detailed temporal restrictions reflecting work rules pertaining to holidays, weekends, etc.

The versions indicated will use a fixed problem decomposition structure. Our recommendation is that the structure of Figure 3.11 be adopted for this purpose.

6.0 REFERENCES

1. Hasseltine, E.H., De Laquil, P. and Leary, P.L., Special Nuclear Material Flow Projections for the Commercial Nuclear Industry, Sandia Laboratories, SAND 75-8276, March 1977.

2. Hasseltine, E.H. and Leary, P.L., Trucking I, A Computerized Transportation Model, Sandia Laboratories, SAND 75-8236 July 1975.

3. Battieson, K., et. al., Physical Protection of Special Nuclear Material in the Commercial Fuel Cycle, Vol. IV, Transportation Mode Analysis, Sandia Laboratories, SAND 75-0457, March 1976.

4. Aronson, E.A., A Transportation Scheduling Algorithm, Sandia Laboratories, SAND 75-0374, July 1975.

5. Gertsback, I. and Gurevich, Yu., "Constructing an Optimal Fleet for a Transportation Schedule", Trans. Sci., Vol. 11, No. 1, pp. 20-36 (February 1977).

6. Kolesar, P.J., Rider, K.L., Crabill, T.B., and Walker, W.E., "A Queuing-Linear Programming Approach to Scheduling Police Patrol Cars", Ops. Res., Vol. 23, No. 6, pp. 1045-1062 (November-December 1975).

7. Levin, A., "Scheduling and Fleet Routing Models for Transportation Systems", Trans. Sci., Vol. 5, pp. 232-255 (1971).

8. Martin-Löff, A., "A Branch-and-Bound Algorithm for Determining the Minimal Fleet Size of a Transportation System", Trans. Sci., Vol. 4, No. 2, pp. 155-163 (May 1970).

9. Orloff, C.S., "Route Constrained Fleet Scheduling", Trans. Sci., Vol. 10, No. 2, pp. 149-168 (May 1976).

10. Appelgren, H.H., "Integer Programming Methods for a Vessel Scheduling Problem", Trans. Sci., Vol. 5, pp. 64-78, (1971).

11. Gavish, B. and Schweitzer, P., "An Algorithm for Combining Truck Trips", *Trans. Sci.*, Vol. 8, No. 1, pp. 13-23 (February 1974).

12. Dantzig, G. B., Maier, S. F., and Lansdowne, Z. F., *The Application of Decomposition to Transportation Network Analysis*, Department of Transportation, DOT-TSC-OST-76-26, October 1976.

13. Ford, L. R., and Fulkerson, D. R., *Flows in Networks*, Princeton University Press, Princeton, N. J., 1962.

14. Wells, M. B., *Elements of Combinational Computing*, Pergamon Press, New York, 1971.

15. Schmitendorf, W. E., "Cooperative Games and Vector-Valued Criteria Problems". *IEEE Trans. Automat. Contr.*, Vol. AC-18, pp. 139-144, April 1973.

16. Wirth, N., *Algorithms + Data Structures = Programs*, Prentice Hall, Englewood Cliffs, N. J., 1976.

Appendix A

BIBLIOGRAPHY

A considerable number of papers and reports were reviewed in the course of this effort. This appendix lists these papers and reports in two sections. The first is an anotated bibliography of those papers and reports that appear to be of direct relavence to the development of a computerized model for the nuclear fuel cycle material transportation system. The second section lists those papers and reports that do not appear to be directly relavent to this effort. Included in this latter group are references which discuss procedures for estimating costs of various types of transportation systems. If cost extimates are required, some of these items may be moved to the directly relavent category.

780 035

A.1 Directly Relevant Papers and Reports

Papers and reports of possible direct value to transportation network design and scheduling.

1. Applegren, H.H., "Integer Programming Methods for a Vessel Scheduling Problem," Trans. Sci., Vol. 5, pp. 64-78 (1971).

   Goal is to schedule fixed fleet of ships to optimize revenue. Presents two integer programming algorithms to solve problem. The emphasis is placed on a branch and bound algorithm which is used to eliminate noninteger solutions to linear programming solutions. This is basically the Land and Doig method. Also discusses a cutting plane algorithm which was not as effective.

2. Aronson, E.A., "A Transportation Scheduling Algorithm", Sandia Laboratories, SAND 75-0374, July 1975.

   This is a heuristic scheduling algorithm which can incorporate constraints such as maintenance. This is the only constraint treated here. The payoff is minimum cost. Neglecting maintenance, this heuristic algorithm is compared with optimal linear programming solution.

3. Baligh, H.H, Dellinger, D.C., and Volpp, L.D., "An Algebra for the Design of Transportation Networks," Trans. Sci., Vol. 6, No. 4, pp. 354-378 (November 1972).

   An abstract algebra is presented. It includes time coordinates for scheduling as well as space coordinates. Probably too general and abstract to be of much direct value to us.

780 034

4. Bellmore, M., Bennington, G. and Lubore, S., "A Multivehicle Tanker Scheduling Problem," Trans. Sci., Vol. 4, pp. 36-37, (1970).

Sets up as an integer linear programming problem with bundle constraints. Discusses cutting plane method for solving problem and concludes that these are not adequate. Discusses and recommends Land and Doig branch and bound approach. No examples are given.

5. Blomeke, J.O., Kee, C.W., and Salmon, R., "Shipments in the Nuclear Fuel Cycle Projected to the Year 2000", Nuclear News, Vol. 8, June 1975, pp. 62-65.

Presents a summary of the projected nuclear fuel cycle shipments up to the year 2000. Separate treatment given to fresh fuel, spent fuel, plutonium, high level waste, cladding waste, noble gas fission products, fission-product iodine, tritium, alpha solid wastes, alpha-beta-gamma solid wastes, and beta-gamma wastes. In all cases gives shipments per year and vehicles in transit.

6. Bodin, L.D., Kydes, A.S., and Rosenfield, D.B., "Approximation Techniques for Automated Manpower Scheduling", Report No. UPS/UMTA-1, Program for Urban and Policy Sciences, State Univ. of New York, Stony Brook, New York, 11794, February 25, 1975 (presented at Workshop on Automated Techniques for Scheduling of Vehicle Operations for Urban Public Transportation Services, Chicago, Il., April 27-29, 1975).

First considers two procedures for approximating size of workforce: (1) a lower bound estimate (very simple) and (2) an approximate procedure that operates on schedule. Then presents five scheduling methods: (1) exact (not practical)

(2) sequential, (3) concurrent, (4) batch concurrent, (5) sequence of assignment problems. In the latter, the idea of "aggregating" services is used to reduce computation. Discusses use of sequential and concurrent methods for simulation, with extensions. Then briefly discusses composite procedures using service aggregation techniques.

7. Dantzig, G. B., Maier, S. F., and Lansdowne, Z. F., "The Application of Decomposition to Transportation Network Analysis", Rept. No. DOT-TSC-OST-76-26, Control Analysis Corp. Palo Alto, California, October 1976.

   Discusses how decomposition methods can be applied to five specific network problems in transportation a) traffic assignment with fixed demands b) traffic assignment with elastic demands c) network design d) optimal staging of investments over time and e) sub-area focusing. Emphasis is on decomposition into geographical regions using Generalized Binders decomposition. Main section of interest is section 6 on Solving Traffic Assignment and Sub-Area Focussing Problems by Geographic Decomposition.

8. Gavish, B. and Schweitzer, P., "An Algorithm for Combining Truck Trips," *Trans. Sci.*, Vol. 8, No. 1, pp.13-23 (February 1974).

   Considers large number of trucks and how to assign them to jobs to minimize "deadheading". Jobs or schedules are fixed. A number of unique constraints are present. These include: 1) jobs i and j cannot be combined sequentially if it would mean that the truck arrives too early at j ; 2) certain jobs cannot be combined due to their nature; and 3) certain jobs cannot be combined due to unique truck requirements. Each type of truck considered separately. One week planning horizon used. Formulates as integer linear programming problem. Then converts it to a classical transportation problem. Describes computational tricks used to speed convergence.

9. Gertsback, I. and Gurevich, Yu., "Constructing an Optimal Fleet for a Transportation Schedule," Trans. Sci., Vol. 11, No. 1, pp. 20-36 (February 1977).

   Uses "deficit function" technique to optimize fleet size for a fixed schedule. Emphasizes periodic schedules. Includes brief discussion of problems with flexibility in arrival and departure times. This is the only reference in English which treats this deficit function approach. The only references on this method listed in the paper are in Russian (2) or in a proceedings of a foreign conference. Apparently this method has been used in the USSR.

10. Glover, F. and Klastorin, T. D., "A Generalized Recursive Algorithm for a Class of Non-stationary Regeneration (Scheduling) Problems," Nav. Res. Log. Quart., Vol. 21, No. 2, pp. 239-246 (June 1974).

    Considers nonlinear formulation of a passenger transportation problem. Presents a general dynamic programming algorithm for its solution. No specific examples given.

11. Glover, F., Klingman, D., and Ross, G. T., "Finding Equivalent Transportation Formulations for Constrained Transportation Problems," Nav. Res. Log. Quart., Vol. 21, No. 2, pp. 247-254 (June 1974).

    Presents method for transforming transportation problem with additional constraints into standard problem. Probably not of much use to study.

12. Hasseltine, E.H., De laquil, P., and Leary, P.L., "Special Nuclear Material Flow Projections for the Commercial Nuclear Industry", Sandia Laboratories, SAND 75-8276, March 1977.

Presents projections of the flows of special nuclear material with the commercial power industry. Based on power levels and reactor types, subject to assumptions regarding plant load factors and recycle of reactor products, total monthly material flows between operating fuel cycle facilities from 1976 to 2000 are examined. Projected yearly flows of special nuclear material are presented and the yearly numbers of single shipments are calculated assuming conventional truck carriers.

13. Hasseltine, E.H., and Leary, P.L., "Trucking I, A Computerized Transportation Model", Sandia Laboratories, SAND 75-8236, July 1975.

This is a fixed-fleet sizing type algorithm. Number of vehicles incremented until minimum fleet size found. Scheduling is according to specific rules with priority given on any day to shipments made available earlier, but not yet assigned a truck. Assumes one truck per shipment. Maintenance based on time is included. Results of several sensitivity studies presented.

14. Klingman, D. and Russell, R., "Solving Constrained Transportation Problems," Ops. Res., Vol. 23, No. 1 pp. 75-106 (January-February 1975).

Presents specialized method (primal simplex) for solving transportation problems with several additional linear constraints.

15. Kolesar, P. J., Rider, K. L., Crabill, T. B., and Walker, W. E., "A Queuing-Linear Programming Approach to Scheduling Police Patrol Cars," Ops. Res., Vol. 23, No. 6, pp. 1045-1062 (November-December 1975).

Goal is to minimize number of patrol cars while maintaining performance standards. Required service times are random. Uses integer linear programming for generating schedules. Unique feature is random demand for service.

16. Levin, A., "Scheduling and Fleet Routing Models for Transportation Systems," Trans Sci., Vol. 5, pp. 232-255 (1971).

Goal is to minimize fleet size of air-transportation system. Use "bipartiate" graph technique which matches departure and terminal stations. Time is included. First considers fixed schedule. Then treats variable schedule using "bundle constraints". Solves as linear programming problem with a Land and Doig algorithm (branch and bound) to eliminate noninteger solutions.

17. Levin, A., "Solving the Airline Crew Scheduling Problem by a Land and Doig Type Algorithm", M. I. T. Flight Transportation Laboratory, Memo FTL-M69-2, Nov. 1969.

Good example of the application of the Land and Doig type algorithm to the crew scheduling problem.

18. Manington, B., and Wren, A., "A General Computer Method for Bus Crew Scheduling", Operational Research Unit, Centre for Computer Studies, Univ. of Leeds, Leeds LS2 9JT (presented at Workshop on Automated Techniques for Scheduling of Vehicle Operators for Urban Public Transportation Services, Chicago, Il., April 27-29, 1975).

780 039

Presents heruistic techniques for crew scheduling. Interesting factor is the different extremes in union rules that must be treated as constraints. In many cases the computer generated schedules were not as good as those generated manually.

19. Martin-Löf, A., "A Branch-and-Bound Algorithm for Determining the Minimal Fleet Size of a Transportation System," Trans. Sci., Vol. 4, No. 2, pp. 155-163 (May 1970).

A concise treatment of a branch and bound algorithm for finding minimum fleet size of a transportation system. Problem is set up as an integer linear programming problem. Example presented for shuttle line between two stations.

20. McKay, M. D. and Hartley, H. D., "Computerized Scheduling of Seagoing Tankers," Nav. Res. Log. Quart., Vol. 21, No. 2, pp. 255-266, (June 1976).

Integer linear programming formulation is solved using linear programming to minimize total cost. Explains how to eliminate noninteger solutions.

21. Nicoletti, B., "Automatic Crew Rostering," Trans. Sci., Vol. 8, No. 1, pp. 37-42, (February 1975).

Uses graph theory to solve problem. Connects "crewmen" nodes with "assignment" nodes, associating cost with each arc. Cost based on past activities, particular assignment and consequences on future. Uses "minimum flow" algorithm to solve problem. Has potential value for crew assignment.

22. Orloff, C.S., "Route Constrained Fleet Scheduling", Trans. Sci., Vol. 10, No. 2, pp. 149-168 (May 1976).

Discusses school bus schedules with both fixed and flexible arrival times. Want minimum cost (labor) fleet. No rigid constraints. Concludes that no efficient algorithms have or can be devised for general fleet scheduling problems. Must focus on heuristic methods instead.

23. Rhoads, R.D., "An Overview of Transportation in the Nuclear Fuel Cycle", Battelle Pacific Northwest Laboratories, BNWL-2066, May 1977.

This is a good summary of the packaging and transportation modes that are currently used and envisioned for the nuclear fuel cyclw. Detailed treatment is given to each type of shipment. An Appendix gives the government regulations pertaining to the transportation of radioactive materials.

24. Rubin, J., "A Technique for the Solution of Massive Set Covering Problems, with Application to Airline Crew Scheduling", Trans. Sci., Vol. 7, No. 1, pp. 34-48, (1973).

Gives heuristic method for solving massive set covering problems. This is done by solving series of subproblems considering high cost columns first. Examples given.

25. Simpson, R.W., "Scheduling and Routing Models for Airline Systems", M.I.T. Dept. of Aeronautics and Astronautics, Flight Transportation Laboratory, Report No. R68-3, December 1969.

A comprehensive review of the state-of-the-art in 1969 of the optimal computer models concerned with scheduling and routing problems for passenger air transportation systems.

Models include 1) fleet assignment, 2) fleet planning 3) dispatching, 4) vehicle routing and 5) fleet routing. Excellent list of references for each model class.

26. Srinivasan, V., and Thompson, G. L., "Determining Cost vs. Pareto-Optimal Frontiers in Multi-nodal Transportation Problems", Trans. Sci., Vol. 11, No. 1, pp. 1-19, (1977).

Very theoretical theorem-proof paper. Payoff weights cost and time. Uses parameter to generate cost vs. time tradeoffs.

27. West, L. E., "An Information System for Management and Allocation of Transportation Resources", Sandia Laboratories, SAND 76-0571, December 1976.

A detailed description of the information system required to manage the transportation system for nuclear material is presented. It includes a description of a process in which itineraries are produced. Flow diagram presented for scheduling, but no specific algorithms.

28. Wilhelm, E. G., "Overview of the Rucus Package Driver Run Cutting Program - RUNS", Mitre Corp., (Presented at workshop on Automated Techniques for Scheduling of Vehicles Operators for Urban Public Transportation Services, Chicago, Ill, April 27-29, 1975.

Deals with basic program design and flow, and techniques used to develop driver schedules. RUNS consists of five operations (1) process and check input data (includes schedule of vehicle blocks and travel times between driver relied points) (2) initial schedule of runs (1 and 2 pirce) (3) eliminate "left-overs" or trippers in legal manner (4) run cost min

(5) eliminate "trippers" in any manner possible. Labor rules used to generate initial schedule. Also run cost is calculated. First schedules one-piece runs, then two-piece runs. Whole process is heuristic in nature.

A.2 Other Papers and Reports

The following papers and reports were reviewed and it was determined that they have little direct value in developing the computerized model for the nuclear fuel cycle transportation system.

1. Cook, J. D., "Profitability Analysis in the Motor Carrier Industry", Management Accounting, Vol. 54, May 1973.

2. De Neufville, R., Hoffmeister, J., and Shpilberg, D., "Investment Strategies for Developing Areas: Models of Transport", Dept. of Civil Engineering, M.I.T., Cambridge, Massachusetts 02139, RPT R72-48 (PB 219 292).

3. Eads, G., Nerlove, M., and Raduchel, W., "A Long-Run Cost Function for the Local Service Airline Industry: An Experiment in Non-Linear Estimation", Rev. of Economics and Statistics, Vol. 51, No. 3, August 1969, pp. 258-270.

4. Fitchie, J. W., "The Problems of Financing Transport Systems", Aeronautical Journal, Vol. 77, April 1973, pp. 163-169.

5. Folk, J. F., "Studies in Railroad Operations and Economics, Vol. 7. A Brief Review of Various Network Models", PB-244 124, M.I.T. Trans. Sys. Div., Dept. of Civil Engineering, June 1972, (M.I.T. RPT 72-42).

6. Harvey, R. P. and Robinson, D. W., "Computer Code for Transportation Network Design and Analysis", PRT No. DOT-TSC-OST-77-39, Control Analysis Corp, Palo Alto, California, May 1977.

7. Heising, C., "A Determistic Model to Asses LWR Expansion Strategy Costs", Unpublished Sandia (?) paper, 1977 (?).

8. Krokalk, P., Felts, W., and Necson, J., "A Man-Machine Approach Toward Solving the Generalized Truck-Dispatching Problem", Trans. Sci., Vol. 6, No. 2, May 1972, pp. 149-170.

9. Lingaraj, B. P., Chatterjee, A. and Sinha, K. C., "An Optimization Model for Determining Headways for Transit Routes", PB-237 233, August 1974, Urban Trns. Pror., Marquette U., Milwaukee, Wisconsin.

10. Love, R. F., and Morris, J. O., "Mathematical Models of Road Travel Distances",Math. Res. Cntr., U. of Wisconsin-Madison, February 1977, MRC Tech. Summary RPT #1719.

11. Martin-Vega, L. A. and Ratliff, H. D., "Scheduling Rules for a Class of Fixed Route Freight Scheduling Problems",Research RPT No. 75-3, Dept. of Indus. & Sys. Engr., U. of Florida, Gainsville, Florida 32611, June 1975.

12. Medeiros, M. F., Jr., "En Route Air Traffic Flow Simulation", AD751929, DOT, Trans, Sys. Cntr., Cambridge, January 1971.

13. Melton, R. E., "Quest: A Simulation Model for the Navy Quicktrans System User's Manual", OTNSRDC, Comp. and Math. Dept. R&D RPT #4358, December 1975.

14. Meyer, J. R., & Kraft, G., "The Evaluation of Statistical Costing Techniques as Applied in the Transportation Industry", Am. Economic Rev., Vol. 51, No. 2, May 1961, pp. 313-334.

15. Miller, James C. III, "A Time-of-Day Model for Aircraft Scheduling", Trans. Sci., Vol. 6, No. 3, August 1972, pp. 221-246.

16. Moberly, K. D., and Gorychka, T. C., "A Mathematical Model for Determining Lugair Flight Schedules", AFIT MS Thesis SLSR 27-76A ADA031295.

17. Pollack, M., "Some Aspects of the Aircraft Scheduling Problem", Trans. Res., Vol. 8, No. 3, August 1974, pp. 233-243.

18. Salzburn, Franz J. M., "Optimum Bus Scheduling", Trans. Sci., Vol. 6, No. 2, May 1972, pp. 137-148.

19. Seneca, R.S., "Inherent Advantage, Costs, and Resource Allocation in the Transportation Industry", Am. Economic Rev., Vol. 63, No. 5, December 1973, pp. 945-956.

20. Toye, C.R., "Automated Guideway Ground Transportation Network Simulation", PB 246 758 (DOT-TSC-UMTA-75-18) D.O.T. (Trans. Sys. Center) Cambridge, Massachusetts 02142, August 1975.

21. Trygar, T.A., "Two Stochastic Simulators for Testing Fixed Route and Demand Actuated Transportation System Routing and Scheduling Policies", PB 252 647, U. of Pitt. Ph.D. Dissert. 1974.

22. Young, D.R., "Scheduling a Fixed-Schedule, Common Carrier Passenger Transportation System", Trans. Sci., Vol. 4, No. 3, August 1970, pp. 243-269.

23. Vogt, W.G., and Mickle, M.H., "Comparison of Variable and Fixed Routes for Demand Actuated Transportation Systems", PB 252 888, U. of Pitt. Dept. of E.E., August 31, 1974 (SETEC EE 74 10).

24. Vogt, W.G., and Mickle, M.H., "Pints Documentation (Pitt Network Transportation Simulator)", PB 252 889, U. of Pitt. Dept. of E.E., August 31, 1974.

25. Comsis Corp., "Traffic Assignment August 1973. Methods, Applications and Products", Prepared for Fed. Hwy. Admin., August 1973, PB 244 954.

26. Ellis, R.S., and Rishel, R.W., "An Application of Stochastic Optimal Control Theory to the Optimal Rescheduling of Airplanes", IEEE Transactions on Automatic Control, Vol. AC-19, No. 2, April 1974, pp. 139-142.

27. Berkbigler, K.P., "Estimating the Availability of LLEA Officers", Sandia Laboratories, SAND 77-8626, July 1977.

28. Brobst, W., "Transportation of Nuclear Fuel and Waste", Nuclear Technology, Vol. 24, December 1974, pp. 343-355.

29. Gallagher, R.J., Stimmel, K.G., and Wagner, N.R., "The Configuration of Road Convoys: A Simulation Study", Sandia Laboratories, SAND 77-8625, July 1977 (presented at 18th annual meeting of Nuclear Materials Management, Washington, D.C., June 28-30, 1977).

30. Keeton, S. C., and De Laquil, P., "Conflict Simulation for Surface Transport Systems", Sandia Laboratiries, SAND 77-8624, July 1977.

31. "Alternatives for Managing Wastes from Reactors and Post-Fission Operations in the LWR Fuel Cycle", ERPA 76-43 Vol. 3 (3 of 5 volumes), May 1976.

UNLIMITED RELEASE

INITIAL DISTRIBUTION

NRC-RS (222)
T. B. Cook, Jr., 8000, Attn: W. J. Spencer, 8100
A. N. Blackwell, 8200
L. Gutierrez, 8400
R. L. Rinne, 8201
B. F. Murphey, 8300, Attn: T. S. Gold, 8320
K. P. Berkbigler, 8331 (5)
Publications and Public Information Division, 8265, for TIC (2)
F. J. Cupps, 8265/Technical Library Processes Division, 3141
Technical Library Processes Division, 3141
Library and Security Classification Division, 8266-2 (3)

780 045

NRC FORM 335
(7-77)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER *(Assigned by DDC)*
NUREG/CR-0925

4. TITLE AND SUBTITLE *(Add Volume No., if appropriate)*
Development of a Transport Network Model for the NRC Physical Protection Project

2. *(Leave blank)*

3. RECIPIENT'S ACCESSION NO.

7. AUTHOR(S)
G. M. Anderson and H. J. Payne, ORINCON

5. DATE REPORT COMPLETED
MONTH August 24 YEAR 1977

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
ORINCON Corporation
3366 No. Torrey Pines, Ct., Suite 320
La Jolla, CA 92037

DATE REPORT ISSUED
MONTH July YEAR 1979

6. *(Leave blank)*

8. *(Leave blank)*

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, D.C. 20555

10. PROJECT/TASK/WORK UNIT NO.
A1173

11. CONTRACT NO.
87-9964

13. TYPE OF REPORT
Scientific and Technical

PERIOD COVERED *(Inclusive dates)*

15. SUPPLEMENTARY NOTES
Contractor Report

14. *(Leave blank)*

16. ABSTRACT *(200 words or less)*

The assessment of the requirements for a transportation system to transport special nuclear materials, due to the complexities deriving from schedule size and flexibility, convoy components and maintenance requirements, requires a well-formulated model and an associated computer package not presently available. Here, we detail the problem of sizing the transportation system, present several approaches to modeling this system, and provide recommendations for development of a computerized model.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

Transportation
Safeguards
Computer Modeling

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT
Unlimited Release

19. SECURITY CLASS *(This report)*
Unclassified

21. NO. OF PAGES
119

20. SECURITY CLASS *(This page)*
Unclassified

22. PRICE
$

NRC FORM 335 (7-77)

780 049

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

POSTAGE AND FEES PAID
U.S. NUCLEAR REGULATORY
COMMISSION

U.S. MAIL

POOR ORIGINAL

780 050