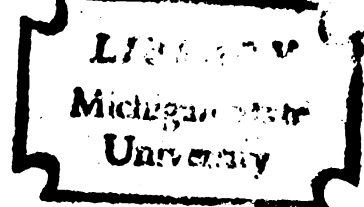


A SIMULATION APPROACH TO
MILITARY VEHICLE DESIGN

Thesis for the Degree of M. S.
MICHIGAN STATE UNIVERSITY
DENNIS L. BENCHOFF
1969

THESIS



ABSTRACT

A SIMULATION APPROACH TO MILITARY VEHICLE DESIGN

by Dennis L. Benchoff

This thesis describes the operating characteristics of a combat area and the combat area logistics system. It presents the mathematical relationships which describe the behavior of the combat area and its logistics system as a function of the design characteristics of the combat area supply vehicles. These relationships make it possible to use simulation techniques as a tool for the evaluation of supply vehicle design. A computer simulation program that models the behavior of one of the components of the system is presented in the appendices to illustrate the use of simulation as an analytical tool in vehicle design.

A SIMULATION APPROACH TO
MILITARY VEHICLE DESIGN

By

Dennis L. Benchoff

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Systems Science

1969

450 1131
6 3 17

ACKNOWLEDGMENTS

Appreciation is extended to Dr. Herman E. Koenig for his encouragement and constructive comments, to Dr. Thomas J. Manetsch for his help in initiating this research, to Dr. Martin G. Keeney for his careful and constructive review of the completed thesis, to Lt. Colonel John C. Haley, USACDCTA, and Mr. Samuel H. Fuller, USATAC, for their aid in providing reference material, and to Lt. John F. Dorsey, USNR, for his work in developing the computer program presented in the Appendix.

TABLE OF CONTENTS

LIST OF TABLES	iv
LIST OF FIGURES	v
Section	
I. INTRODUCTION	1
II. THE COMBAT AREA	3
III. THE COMBAT AREA LOGISTICS SYSTEM	10
IV. THE SYSTEM PARAMETERS	15
V. THE DEMAND SECTOR	20
VI. THE PRODUCTION SECTOR	25
VII. THE INTERACTION MODEL	32
VIII. CONCLUSION	36
LIST OF REFERENCES	40
APPENDIX A	41
APPENDIX B	59

LIST OF TABLES

Table	Page
1. Basic Units	7
2. Supply Levels	7
3. Classes of Supply	12
4. Types of Divisions	12
5. Types of Warfare	17
6. Combat Modes	17
7. Vehicle Design Characteristics	26

LIST OF FIGURES

Figure	Page
1. The Combat Area (Schematic)	5
2. Combat Area Supply Levels (Schematic)	9
3. Two Dimensional Terrain Array (Plan View) . . .	45
4. Five Routes Determined by $\text{FIRST}(A, aK, S_{\max})$ for Two Different Values of aK (Plan View) . .	48
5. Regions of Similar Terrain (Cross Section) . . .	54
6. Route Algorithm Flow Chart	57

I

INTRODUCTION

This thesis is concerned with the analysis of a military logistics system and the use of simulation in the evaluation of military supply vehicles. In particular, this study will develop and define a set of functional relationships to describe the observable behavior of the combat area supply and transportation system. A computer program is formulated from these relationships and implemented by a set of planned tactical combat operations. This digital computer simulation permits military vehicle designers to evaluate different combat area supply vehicle designs.

Each set of vehicle characteristics can be subjected to a variety of controlled combat conditions such as might be encountered in actual combat supply support operations. Data generated by the simulation will reflect the ability of a proposed vehicle to meet the demands placed upon it by the supply system while operating under the influence of a specified combat environment. This evaluation procedure will enable designers to test many more design concepts in less time and at less cost than can now be done by the current

methods which require the manufacture and testing of a small fleet of prototypes. The simulation evaluation procedure provides a means of testing which is available early in the design phase and thus eliminates the need for extensive production of prototypes. This simulation procedure also provides a more meaningful evaluation of the vehicles since the design concepts are tested under conditions generated by the appropriate logistics system. The feasibility of this approach to vehicle evaluation has been demonstrated by the author in an earlier study [1].

In the following sections the combat area logistics system will be defined and analyzed using the procedure developed by Naylor [6] for the planning of simulation experiments. A set of functional relationships will be presented which will form the basis of a future computer simulation model for the evaluation of combat area supply vehicles. An example of such a simulation model has been developed for one area of the supply system and is included in Appendix A.

II

THE COMBAT AREA

The supply vehicles whose design characteristics serve as one set of the parameters of the simulation model are those vehicles which must operate within any combat area as an integral part of the combat area logistics system. These vehicles must be designed to withstand the rigors associated with direct combat actions. They must be able to traverse unimproved roads or open terrain under a variety of adverse conditions. They must be capable of operating with a minimal amount of maintenance for extended periods of time. All of the foregoing requirements are dictated by the dynamics of the combat area.

The combat area is defined as that portion of the theater of war which lies within the boundaries of an army division. It is a portion of the earth's surface which varies in size and location according to the dynamics of the war itself. A division is the highest echelon military organization whose logistical system requires the type of supply vehicles described above. Supply vehicles used by organizations not directly engaged in combat have access to improved road nets and are usually standard commercial designs [9].

The division is organized to include its own supply and transportation elements operating under a set of established supply procedures to provide the division's subordinate elements with materiel necessary for combat operations against hostile forces. This materiel is provided to the division by the field army, the organization which controls and supports the division [2].

The division is organized primarily for combat operations with its subordinate elements being responsible for conducting ground combat operations against enemy forces. The totality of points where the division is in contact with the enemy force determines a line called the line of contact. This line is the limiting point for combat area logistical operations. The line of contact is usually a straight line perpendicular to the division's axis of movement. Since any other configuration of this line is considered in violation of military doctrine, this study will assume that it is always straight. Under this assumption the combat area can be represented schematically by Figure 1. The dimensions in kilometers represent the limiting sizes of a combat area and are determined by the activities of the division at any time during a combat operation [3].

The division is composed of combinations of subordinate elements called brigades, battalions, and companies. Normally, a division contains four brigade-sized units, but the number of battalions in a brigade and the number of

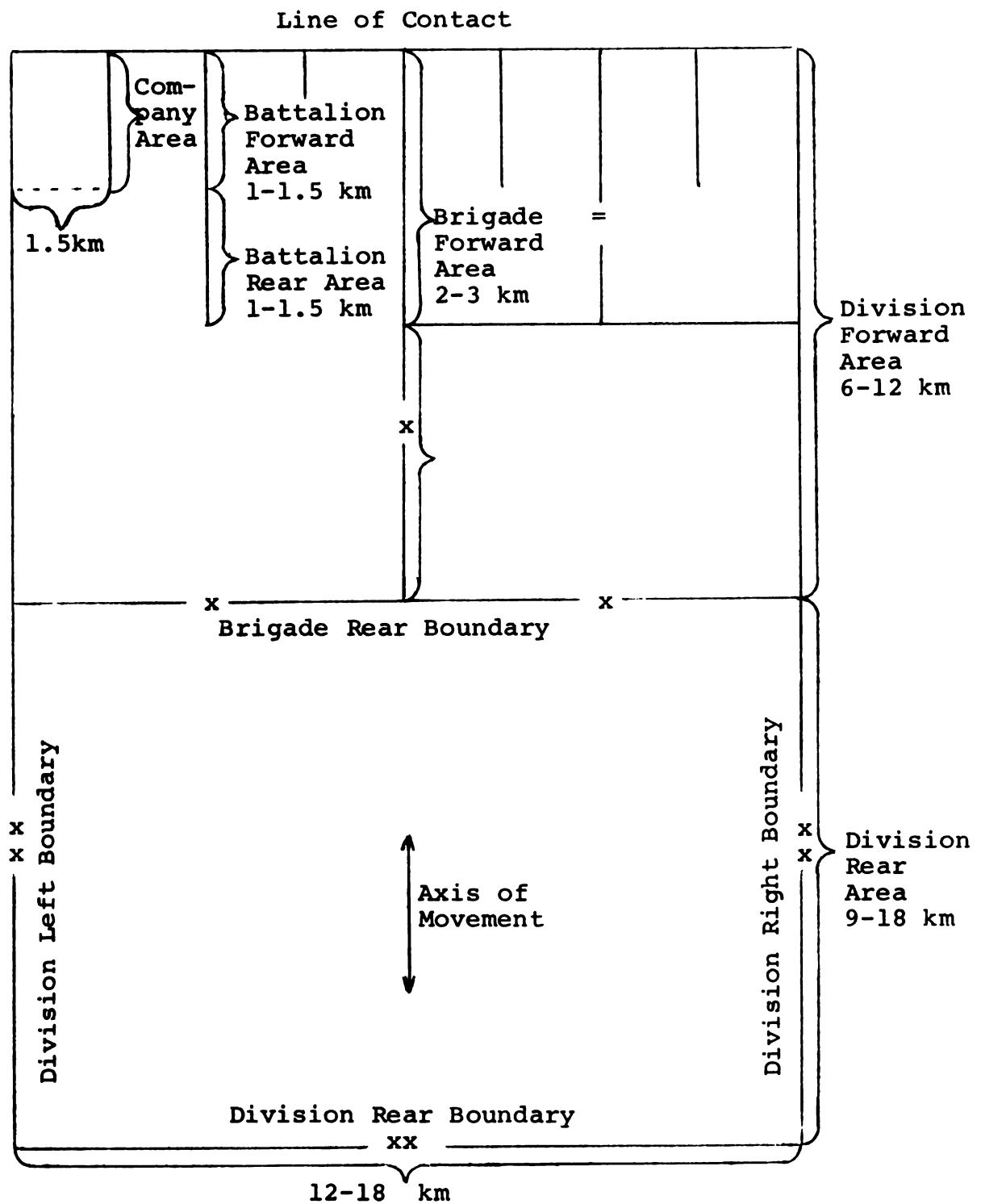


Figure 1. The Combat Area (Schematic)

companies in a battalion vary. The company, however, is the basic tactical unit within any division. The brigades and battalions are established to facilitate command and control. Each company is organized to perform one set of tasks or missions.* Any company within the division can be placed into one of three basic sets defined below. A company which is organized to close with and destroy the enemy is a combat company. A company which directly supports a group of combat companies is a combat support company, and a company which supports both combat and combat support companies is a combat service support company. It will be necessary in the development of the dynamics of the logistics system to further distinguish between the elements of the above three groups. They cannot be aggregated because of differences in internal structure. Nine sub-groupings will be used and are listed in Table 1 along with their basic characteristics [3].

Each company is considered to be employed as an entity and is assigned a position within the combat area according to the task that it is expected to perform. This positioning process is controlled by the combat strategy sequence which can be considered as an excitation sequence. When the combat area is divided into the division forward and rear areas, the bulk of the combat and combat support

*A company that can perform more than one set of tasks will not be considered here.

Table 1. Basic Units

Category	Characteristics	Example
Combat -	Type I Heavy combat units	Tank Company
	Type II Medium combat units	Armored Cavalry Troop
	Type III Light combat units	Infantry Company
Support -	Type I Heavy combat support units	8 in. Howitzer Battery
	Type II Medium combat support units	155 mm. Howitzer Battery
	Type III Light combat support units	Combat Engineer Company
Service -	Type I Heavy service support units	Motor Transportation Company
	Type II Medium service support units	Battalion Headquarters Company
	Type III Light service support units	Brigade Headquarters Company

Table 2. Supply Levels

Level	Characteristics	Example
Combat	Supplies consumed by combat units	Company trains area
Battalion	Supplies consumed by support units	Battalion combat trains area
Brigade	Supplies consumed by forward service units	Brigade field trains area
Division	Supplies consumed by rearward service units	Division support area
Field Army	Source of supplies for the combat area	Field Army supply points

companies occupy the former; while the bulk of the combat service support companies occupy the latter. Since the brigades and battalions are collections of companies, the entire combat area can be subdivided into company areas. Generally these company areas are arranged in rows or levels which are parallel to the line of contact. These rows, five in number, correspond to the supply levels or terminal points of the logistics system. Four of these levels are located within the combat area; while the fifth, a collection of field army supply points, is located beyond the division's rear boundary. This arrangement is depicted schematically by Figure 2. The distances between these levels vary and are related to the combat activity of the division and the maximum effective range of the division's indirect fire weapons. Since these levels are the terminal points for the delivery of all materiel, these points will also be considered to be the points of consumption of this materiel. Table 2 lists the five supply levels and the characteristics of each [8].

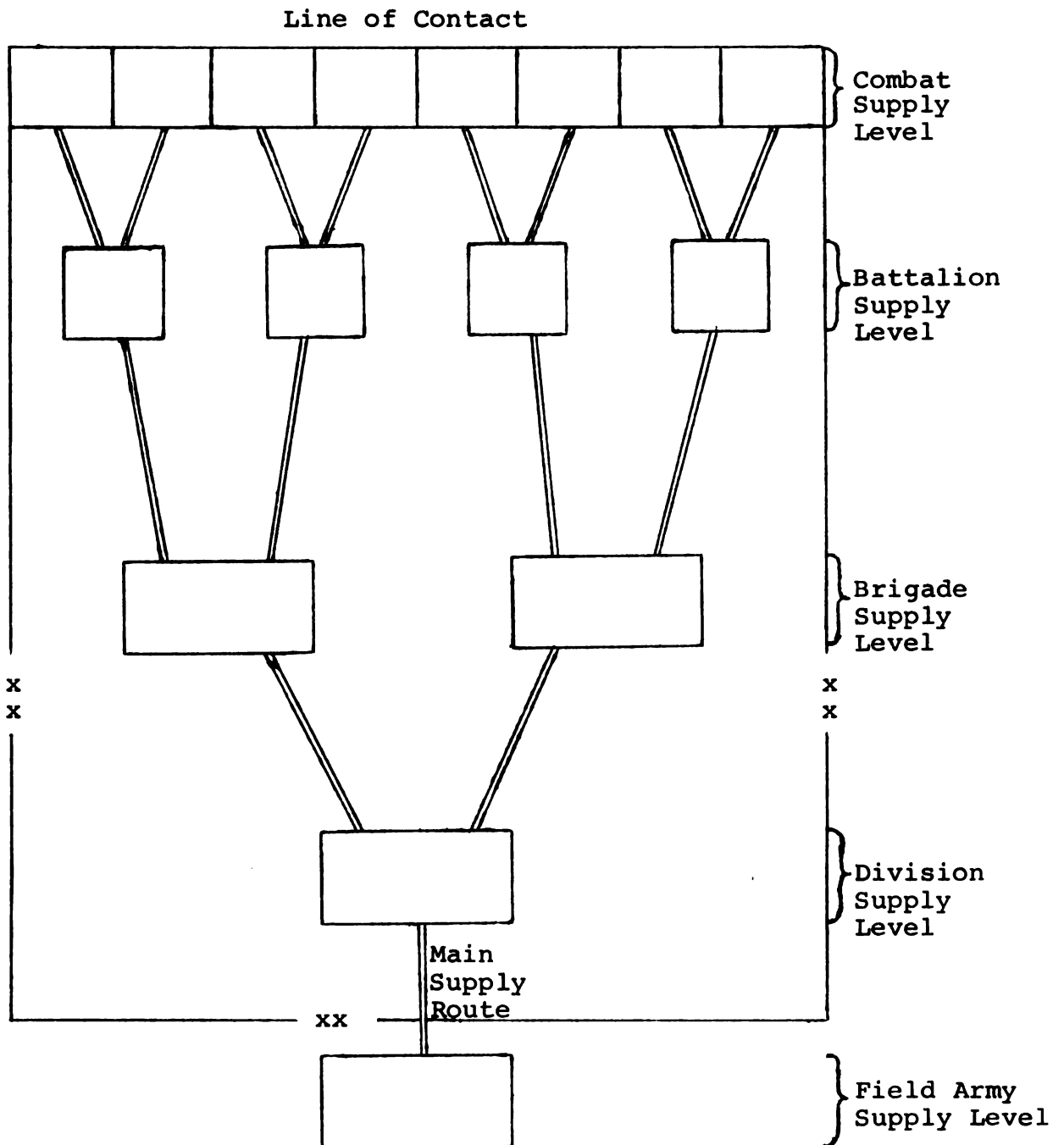


Figure 2. Combat Area Supply Levels (Schematic)

III

THE COMBAT AREA LOGISTICS SYSTEM

As mentioned earlier, the combat area logistics system is composed of a set of supply and transportation units which operate according to established supply procedures. These components of the logistics system function together to provide every company within the combat area with the materiel necessary for the accomplishment of any planned military operation. Since this study is concerned with the evaluation of supply vehicles, the supply procedures will be assumed to be optimal and will not be varied during the development of the logistics system model.

The controlling component of the logistics system is the type or class of supplies. All military materiel can be classified into five major categories according to certain distinguishing characteristics. This aggregation of all military materiel facilitates the requisitioning, handling and distribution of all supplies throughout the combat area. Two of the classes (II and IV) differ only in usage but have identical supply procedures. For the purposes of this study these two classes will be combined and considered as one class of supply as is also the practice in

the combat area logistics system. Table 3 lists the classes of supply and their characteristics.

All divisions contain two distinct types of logistical organizations and two methods of supply distribution. The division controls one type of organization; while the other type, sets of smaller units, are controlled by each of the battalions. The number of elements in these sets corresponds to the number of combat and combat support battalions which have been assigned to the division. The distribution method for some classes of supply consists of supply vehicles under divisional control transporting those classes from the field army level directly to the using companies. This method is known as unit distribution and occurs when the quantities involved are large enough to warrant the use of more than one vehicle. In the other, more normal method, the divisional supply vehicles will deliver supplies from the field army level to designated transfer and distribution points located at either the division or brigade level. This method is called supply point distribution and involves a transfer operation. The supply vehicles of the battalion then use unit distribution to deliver the supplies from these transfer points to their own using companies. In some cases the battalion supply vehicles may be required to obtain a certain class of supply at the field army level and to transport it to their own using units. Therefore, the distribution procedure used is a function of the class of supply.

Table 3. Classes of Supply

Category	Characteristics	Example
Class I	Items with uniform consumption rates	Rations
Class II-IV	Organizational equipment	Weapons
Class III	Bulk liquid fuels	Gasoline
Class V	Munitions and explosives	Hand grenades

Table 4. Types of Divisions

Type	Characteristics	Example
Heavy	More Combat Type I units than Combat Type II units	Armored Division
Medium	More Combat Type II units than Combat Type I units	Mechanized Division
Light	More Combat Type III units than Combat Type I units	Infantry Division

Another component of the logistics system is the distribution route. These are called the main supply routes and are the principal arteries for supply distribution between any two supply levels. These routes are illustrated schematically in Figure 2. Should suitable improved roads exist within the combat area, one road connecting each pair of supply levels is designated as a main supply route. If there are no improved roads, a main supply route is established by the engineers. Ideally, any route which serves as a main supply route should be the least distance between each two levels. These routes are extended and improved as the division displaces forward. Since all supplies generally flow from the rear areas and parallel the axis of movement, there is no lateral distribution of supplies and, therefore, no supply routes parallel to the line of contact at any level. It is evident that the condition of these routes has a considerable amount of influence upon the performance of the supply vehicles. It will be assumed that no improved roads exist within any specified combat area. This will require that the simulation evaluate the supply vehicle's ability to operate cross-country.

Every logistical organization contains a specified quantity of supply vehicles and related equipment depending upon the supply mission of the organization. This quantity is the minimum necessary for the successful performance of the mission. Similarly, only the minimum amount of supplies

necessary for the accomplishment of an operation is issued by the supply facilities at the field army supply level. The fluid nature of the combat situation and the proximity to enemy forces prohibit the accumulation or storage of large quantities of materiel in the combat area. Only a limited amount of reserve supplies for combat emergencies is authorized to be stored by combat area units, and these reserves cannot be consumed unless authorized by the appropriate commander. Although the use of storage facilities at some or all the supply levels would provide some flexibility in the distribution of supplies, the disadvantages listed above make such an alternative unfeasible. As a result, the vehicles in the logistics system must operate to supply the needs of the combat area units on a day by day basis. It is for this reason that the performance of the supply vehicles is so important. In certain situations the failure of the supply vehicles to maintain the required flow of supplies to the using units can cause combat losses to the extent that the division ceases to function as an organized force.

IV

THE SYSTEM PARAMETERS

The foregoing analysis of the properties of the combat area and its logistics system reveals that the behavior of the logistics system in a combat area is a function of four variables. These will serve as parameters in the development of the simulation model and will indicate what types of data will be necessary for the conduct of any simulation experiment. The operating characteristics of the system depend upon the type of division, the type of warfare, the geographical location of the theater of operations, and the combat strategy employed by the military planners. Once these variables have been specified, the combat area logistics system is defined in sufficient detail to insure that a simulation model will adequately represent the behavior of the logistics system.

Although the division described in Section II illustrates the basic properties of any army division, it is by no means a complete description. All divisions are not identical, but they can be classified into three basic categories which are listed in Table 4. The main difference exists in the degree of combat power and mobility inherent in each

divisional organization. This degree of combat power and mobility is reflected in the types and quantities of the basic combat units which are assigned to a division prior to a military operation. The variations in combat power and mobility affect the consumption rates of each class of supply. As a result, the type of division must be specified if the simulation is to produce valid results. Normally, the type of division used in a combat operation depends upon the field army commander's strategy which is based upon the area of operations and information concerning the combat power and mobility of the enemy force. Once established, the type of division does not change.

The division is capable of conducting combat operations under any set of conditions. However, supply consumption rates depend in large part upon the level of combat intensity which occurs during the military operation. These levels of intensity correspond to general types of warfare and are listed in Table 5. In the course of an operation a division may encounter more than one level of intensity, but such changes can be anticipated and handled in the simulation.

The geographical location of the theater of operations also indicates what set of environmental conditions exists in the combat area and, therefore, indicates possible changes in the supply consumption rate of classes of supply which are dependent upon weather and terrain. Of great importance is the terrain profile of the combat area and how it changes

Table 5. Types of Warfare

Category	Characteristics	Example
High Intensity	Nuclear warfare	None
Mid-Intensity	Non-nuclear warfare	World War II
Low Intensity	Insurgent warfare	Viet Nam War

Table 6. Combat Modes

Category	Characteristics	Example
Offense-Type I	Heavy combat and limited forward movement	Penetration
Offense-Type II	Light combat and moderate forward movement	Pursuit
Defense-Type I	Heavy combat and no movement	Area Defense
Defense-Type II	Moderate combat and limited movement	Mobile Defense
Retrograde-Type I	Heavy combat and limited rearward movement	Delay
Retrograde-Type II	Light combat and moderate rearward movement	Withdrawal
Inactive-Type I	No combat with units in contact	Inactive Defense
Inactive-Type II	No combat and units not in contact	Reserve

as the location of the combat area changes. Although the size of the combat area has limiting values, the lengths of the main supply routes may double or triple from one region to the next as a result of different terrain profiles. Also associated with a particular geographical area is a surface soil type and cyclic climatic conditions. These act together to vary the load bearing conditions of the surface. Certain combinations of soil type and amount of precipitation will drastically reduce vehicular movement if the vehicles have not been designed to cope with these conditions. When the geographical area is designated, actual environmental conditions can be simulated to insure a valid evaluation of the operating characteristics of the supply vehicles.

The combat strategy sequence is a list of planned combat actions that the division is to perform during the conduct of the military operation. The length of the sequence determines the length of the simulation. This sequence is based on the strategy developed by the field army commander and his staff. As a result of this strategy, the sequence assigns to each company a position at one level within the combat area and a combat task or mode for each consecutive time period. Table 6 identifies the different combat modes that will be considered in this study. Thus the internal structure or state of the logistics system during each time period is completely determined by the

combat strategy sequence since the location and behavior of every company and the location of all supply levels are specified.

In effect the variables described above determine the quantities of each class of supply required by each company for each interval of the combat strategy sequence. These are the dynamic demands placed on the logistics system and on the supply vehicles. In order to have the division operate as desired, the combat area logistics system must meet these demands for supplies when and where they occur.

V

THE DEMAND SECTOR

The functional relationships which describe the interaction of the variables and components of the combat area and its logistics system can be separated into two distinct groups. Each group of relationships, called a sector, provides a means for describing the behavior of that portion of the system in mathematical terms. The first group of relationships, the demand sector, expresses the demands for quantities of combat materiel which are necessary for the successful completion of planned military operations. These demands are a function of the type of basic unit, its location within the combat area, the combat mode, and the combat potential during each interval of time.

It will be necessary to compute the quantity of materiel by its supply class and its location at a particular supply level within the combat area. This quantity is denoted by the symbol $D_{ij}(n)$ where the subscript i represents one of the four classes listed in Table 3 and the subscript j represents one of the first four supply levels listed in Table 2. The letter n indicates that the demand is a

function of a time period which is specified by the combat strategy sequence. The quantities $D_{ij}(n)$ are functions of the state of the units in the combat area for each time interval. At the beginning of each interval the combat strategy sequence assigns each company a combat mode and a location within the combat area. Before any activity can be successfully completed, the unit must have immediately available the demanded quantity of each class of supply.

Each company is composed of specific numbers of personnel and equipment. This organization will enable it to carry out its assigned tasks. This structure also gives the company the potential to consume materiel if it is to perform any tasks. The quantity of each class of supply required is a function of the combat mode and the combat potential of each company during the n th time period. The combat potential reflects the changes in the organization of a unit caused by losses or gains in personnel and equipment.

At the beginning of a combat operation, denoted by $n=n_0$, the number of men and equipment assigned to a company is defined to be the authorized strength of the unit and is denoted by the symbol $AS_k(n_0)$, where the subscript k represents one of the nine types of basic units listed in Table 1. The operational strength of a company, $OS_k(n)$, is defined to be the quantity of men and equipment present in the unit

at the end of the n th time period. The operational strength is given by the recursive equation

$$OS_k(n) = OS_k(n-1) - LS_k(n) + LS_k(n-m). \quad (1)$$

The quantity $LS_k(n)$ represents the losses resulting from the combat mode specified during the n th time period. The quantity $LS_k(n-m)$ represents the gains acquired by replacing the losses that occurred m time periods before. The value of m characterizes the time delay in the replacement process and is usually three to six time periods. The value of the variable $LS_k(n)$ is determined by the type of basic unit and the four parameters described in Section IV. The values of this variable must be specified before the simulation is begun or computed from other data during the simulation.

The combat potential, $CP_k(n)$, is defined by the equation

$$CP_k(n) = \frac{OS_k(n)}{AS_k(n_0)} \quad (2)$$

to be the ratio of the organizational strength to the authorized strength. It is a scalar quantity which has a limited range of values. It may assume any value within the interval $[.60, 1.05]$. At the lower limit the unit is ineffective and must be placed in the Inactive Type II combat mode until its combat potential exceeds .80. At the upper limit the replacement process does not function as long as the increment of operational strength $(-LS_k(n) + LS_k(n-m))$ added to the unit causes the value of its combat potential to exceed 1.05.

A consumption rate in tons per time period, denoted by the symbol $CR_{ik}(n)$ can be established for each type of unit and class of supply. The value of this rate changes with each change of combat mode. These rates are also determined by the four parameters listed in Section IV and must be specified before the simulation or computed from other data during the simulation.

The general form of the equation for determining the variable $D_{ij}(n)$ is given by

$$D_{ij}(n) = \sum_{k=1}^9 \alpha_{jk}(n) CR_{ik}(n) CP_k(n). \quad (3)$$

The quantity $\alpha_{jk}(n)$ represents the number of the k th type of units which are located at the j th level during the n th time period. Summing $D_{ij}(n)$ over all values of i will give the total quantity of all classes of supply at each supply level while summing $D_{ij}(n)$ over all values of j will give the total quantity of each class of supply required by the units within the combat area. The double summation over i and j will give the total quantity of all combat materiel required by the division during each time period.

Each combat mode corresponds to a different level of excitation and, therefore, generates a different consumption rate. The mode which corresponds to the lowest level of excitation and requires the minimum amount of all classes of supply is the Inactive Type II mode. This minimum materiel requirement can be computed by equation (3) by assigning to all basic units, this mode and a combat potential of 1.00.

This mode and combat potential will be used to specify the initial conditions for the simulation experiment during the initial time period n_0 . These conditions also establish the minimum supply vehicle performance criteria.

The data required in order to use these mathematical relationships to simulate the behavior of the demand sector are available from historical information for combat operations in the mid and low intensity warfare situations. In the case of high intensity warfare situations where no historical data exists, estimates of consumption and loss rates have been projected from test data [4]. Tables of organization and equipment are available for each type of company to provide the values of $AS_k(n_0)$ needed for the computation of $CP_k(n)$.

VI

THE PRODUCTION SECTOR

The second group of relationships compose the production sector, which determines the quantity of all materiel transported from the supply distribution points at the field army level to the individual companies located throughout the combat area. The quantity of each class of supply delivered to any position is a function of the vehicle's design characteristics, the supply procedures associated with each class of supply, and the environmental conditions which affect the combat area.

The basic vehicle design characteristics which are necessary for a proper evaluation by simulation experiments are listed in Table 7. Each characteristic is a function of the vehicle's operation time, velocity, or payload [7]. The supply procedures determine the distribution routes and the scheduling which every supply vehicle will follow during each time period. The environmental conditions of the combat area will affect the behavior of the logistics system by changing the conditions under which the vehicles must operate.

In the case of Class I supplies, the divisional supply vehicles must transport the entire quantity demanded by the

Table 7. Vehicle Design Characteristics

Characteristic	Definition
Curb Weight	Weight of fully equipped vehicle less cargo
Payload Weight	Maximum weight of cargo
Rated Velocity	Maximum cruising speed on a hard, flat and dry surface
Service Time	Length of time of the maintenance period
Gradeability	Maximum slope a fully loaded vehicle can negotiate
Ground pressure	Pressure applied by the vehicle to the ground

combat area from the field army supply level to distribution points at the brigade and division supply levels. The battalion supply vehicles must then transport the quantities required by their companies from these distribution points to the using units at the battalion and combat levels. Class II-IV and Class III supplies follow a similar distribution procedure except that large quantities of Class II-IV supplies are delivered directly to the using units at their locations. This eliminates the time consuming transfer operation at the brigade supply level. Class V supplies must be transported by the battalion vehicles from the field army supply level directly to the using units.

Class III and Class V supplies account for more than 80 per cent of the total quantity of materiel consumed in the combat area. These supplies are also the most critical to the successful completion of combat operations. The transportation of these classes has priority over the transportation of Class I and Class II-IV supplies. All supplies should flow at a uniform rate during each time period. This is accomplished by assigning vehicles to deliver classes of supply in the same ratio as the quantity for each supply class to the total quantity required. Fractional values are rounded off in favor of the priority classes of supply. When partial loads of Class I and Class II-IV supplies occur, they may be transported on the same vehicle since their methods of distribution are similar.

Class III vehicles may be designed to preclude the use of the vehicle for the transportation of all but liquid fuels. Such constraints will be reflected in the tables of equipment of each company that contain supply vehicles. If the design incorporates changeable load platforms, these vehicles may be used to transport any class of supply. When vehicles that have been assigned to deliver one particular class of supply have completed the assignment, they are assigned to the delivery of any class of supply which still remains undelivered.

The determining factor in the amount of supplies that is delivered is the number of return trips that the vehicles can complete during the time allotted for the delivery of supplies for any given time period. This delivery period is less than the time period specified by the combat strategy sequence although in emergencies the delivery period might equal the time period. The capabilities of the crew determine the amount of difference between the delivery period and the time period.

The relationship which represents the time of a complete return trip is given by the equation

$$CT_{j,j^*}(n) = 2\{TT_{j,j^*}(n) + LT_i\} + ST. \quad (4)$$

The subscripts j and j^* designate the end points of each distribution route. The symbol $TT_{j,j^*}(n)$ denotes the travel time between the end points of the route. The symbol LT_i denotes the transfer time for each class of supply and

depends upon the loading and unloading facilities that are available at each transfer point. The symbol ST represents the service time of the supply vehicle and must be added when the vehicle exceeds the service range.

The travel time is the most critical portion of the time necessary for a complete return trip since it is subject to the variable conditions presented by the weather and terrain. The combat strategy sequence specifies the straight line distance between each supply level. At the rated velocity, the time required to travel this distance is readily computed. However, the terrain profile, the weather and the soil conditions act to delay the vehicle. These effects can be interpreted as either increasing the distance between two supply levels, decreasing the rated velocity of the vehicle, or a combination of both. Therefore, the general form of the equation for determining the trip time is given by

$$TT_{j,j^*(n)} = \frac{\{SD_{j,j^*(n)} + DD_{j,j^*(n)}\}}{\{RV + DV_{j,j^*(n)}\}}. \quad (5)$$

The symbol $SD_{j,j^*(n)}$ represents the specified distance between the j th and j^* th supply levels while $DD_{j,j^*(n)}$ represents the added incremental distance caused by the terrain profile between those levels. The symbol RV represents the rated velocity of the vehicle which is a constant while $DV_{j,j^*(n)}$ represents the incremental amount of velocity that the vehicle loses due to the effects of the weather and soil conditions. Near ideal conditions the values of $DD_{j,j^*(n)}$

and $DV_{j,j^*}(n)$ are approximately equal to zero, and, therefore, $CT_{j,j^*}(n)$ approaches its minimum value.

Appendix A contains an algorithm developed to simulate the effects of weather and terrain on the trip time of a supply vehicle. The approach used in the development of the algorithm was to compute a correction factor which when multiplied by the straight line distance between two supply levels would give an equivalent distance that the vehicle would have to travel to account for the effects of the weather and terrain. All adverse effects are expressed as increments of distance which are added to the specified distance. Using the assumption presented earlier, that in areas devoid of roads the best route is one of minimum distance and minimum slope, along with the data available on the soil, weather and terrain profile of specific geographical locations, the algorithm produces an equivalent route. Using data from the characteristics of current military supply vehicles, this model found that the equivalent routes were as much as 50 per cent longer than the straight line distances. The corresponding increase in trip time caused by these conditions significantly affects the time required to complete a return trip.

The number of complete trips made in a time period is that integer value which is the maximum number of trips with a total trip time less than the trip period. The quantity

of materiel delivered, $P_{ij}(n)$, is the product of the payload capacity of the vehicle and the number of complete trips the vehicle can make during each time period.

VII

THE INTERACTION MODEL

The interaction of the demand and production sectors is described by the equation

$$P_{ij}(n) - D_{ij}(n) = 0. \quad (6)$$

This relationship states that the production sector must satisfy the needs of the demand sector by class of supply and supply level during each time period in order for the military operation to proceed as planned. The length of the time period is arbitrary, but since logistics operations are carried out on a daily basis, the time interval most suited for the simulation is the 24 hour day. If the assumption is made that only one combat mode will be assigned to a unit in one 24 hour period, then the programming will be simplified.

Several other assumptions must be made at this time in order to make use of equation (6) in the evaluation of combat area supply vehicles. One assumption made earlier was that the supply and distribution procedures were fixed and optimal. Another assumption is that the field army supply level has available for the division sufficient quantities of each class of supply whenever they are required. These two assumptions make the performance of the division dependent

upon the performance of the supply vehicles alone. Another assumption is that the quantity $D_{ij}(n)$ is independent of the type of supply vehicle used by the logistics system. This assumption can be made when extremes in the design of the supply vehicles are avoided. For example, any vehicle which requires a large operating crew and many service personnel would significantly affect the requirements for Class I and Class II-IV supplies. The class of supplies which is most affected by vehicle design characteristics is Class III. However, the current supply vehicles only consume one per cent of the combat area's total requirement so this assumption is valid.

Using equation (6) to evaluate supply vehicle performance reduces to a process of examining its values over the length of the simulation. The results obtained from equation (6) during each time period can be displayed as a four by four array whose rows and columns correspond to the indices i and j . An array which contains all negative entries indicates that the vehicle does not possess design characteristics which are adequate to meet the needs of the logistics system. Since the production sector only transports the required amount of supplies, an array with all zero or small positive entries indicates a vehicle design which is acceptable. However, data must be kept on the amount of time the vehicle is idle during each time period. Large amounts of idle time appearing at every time period indicate

characteristics which far exceed the needs of the logistics system. These vehicles also require redesign. If the array contains both negative and zero entries, an analysis of the conditions within the combat area during these particular time periods will indicate which characteristics need to be modified to increase vehicle performance.

The length of the simulation depends upon the variation of the dynamic conditions. The designers that use the simulation experiments may examine the effects of any realistic set of environmental and combat conditions. In cases where these conditions are fairly constant, the number of time periods can be less than in cases which contain extremes in both conditions.

Although only a small number of basic design characteristics were included as a description of the vehicle's performance, any design characteristic which can be related to the vehicle's payload or rated velocity can be evaluated. For example, the type of armor added to protect the crew or cargo can be specified as an addition to the curb weight. This increase in weight might require that the payload be reduced or that the rated velocity be reduced. If the armor protection is an absolute necessity, then some other component, such as the propulsion or suspension system, must be redesigned to compensate for the increase in weight.

An analysis of the data supplied by the simulation model may indicate the need for two sets of vehicles with

different design characteristics. The experiments may also show a need for vehicles designed to transport only one class of supply. To determine which vehicle design or group of vehicles is the best requires the analysis of the related costs of designing, developing and producing each candidate vehicle. This cost analysis is another simulation problem in itself and will not be developed here.

VIII

CONCLUSION

This study has described and analyzed the dynamics of the combat area and the operating characteristics of the combat area logistics system. The consumption and the delivery of materiel by units in the combat area were viewed as two independent sectors, and their operating characteristics were developed individually. Four parameters were defined that determine the state of the logistics system. When the design characteristics of a supply vehicle are specified, the logistics system exhibits a particular behavior which is a function of the vehicle's design and provides some insight into the vehicle's performance.

Since the vehicle's ability to meet the required demands is described by a set of difference equations, the logistics system is a discrete state system. The model developed from this system will be of the microdynamic form since the model provides information on each supply vehicle by producing time paths of the results of equation (6).

The model was developed to relate vehicle performance to the velocity and payload of the vehicle. The simulation program presented in Appendix A illustrates that it is possible to relate the effects that combat conditions have

on the velocity and payload so that all of these conditions can be included in any evaluation of vehicle performance. This approach, which makes maximum use of simulation techniques, will enable vehicle designers to compare the performance of various vehicle designs under one set of conditions or to compare the performance of one design under a wide range of conditions.

LIST OF REFERENCES

LIST OF REFERENCES

1. Benchoff, D. L. "Combat Area Class III Supply Vehicle Simulation." Unpublished term paper, Michigan State University, 1968.
2. Department of the Army Field Manual. FM 54-2, The Division Support Command. Washington, D. C.: US Government Printing Office, September 1965.
3. Department of the Army Field Manual. FM 61-100, The Division. Washington, D. C.: US Government Printing Office, June 1965.
4. Department of the Army Field Manual. FM 101-10-1, Staff Officers' Field Manual--Organization, Technical and Logistical Data (Unclassified). Washington, D. C.: US Government Printing Office, January 1966.
5. McCracken, Daniel D. A Guide to FORTRAN IV Programming. New York: John Wiley and Sons, Inc., 1965.
6. Naylor, T. H., Balintfy, J. L., Burdick, D. S. and Chu, K. Computer Simulation Techniques. New York: John Wiley and Sons, Inc., 1966.
7. Shotter, J. D. and Brown, E. S. Vehicle Cross-Country Mobility. Fort Eustis, Va.: US Army Transportation Combat Development Group.
8. US Army Infantry School Publication. Combat Logistics Handbook. Fort Benning, Ga.: USAIS, 1967.
9. US Army Infantry School Publication. Tactical Operations Handbook. Fort Benning, Ga.: USAIS, September 1966.

APPENDICES

APPENDIX A

THE ROUTE ALGORITHM

I. INTRODUCTION

The purpose of this appendix is to develop a means of simulating the terrain and weather conditions which exist within the combat area and to estimate the effects of these conditions on the performance of the combat area supply vehicles. Performance will mean, almost exclusively, the speed that the vehicle can maintain along a route. Thus, the main concern will be to estimate the effects of the weather and terrain on the speed at which the supply vehicle can deliver a payload over a route within the combat area. For the purposes of this appendix weather and terrain will be defined as follows. Weather is the temperature and moisture content of the surface soil, and terrain is the type and configuration of the surface soil. In addition to these definitions it is assumed that the contour and the soil type of the terrain are known, that the weather is known, that there are no roads within the combat area, and that the design characteristics of the supply vehicles are known. The design characteristics that will be used here are the gradeability, the rated speed and the curb and payload weights.

The method of estimation will be the following.

Define as a standard route a route over a flat, hard and dry surface on which the vehicle can maintain the rated speed claimed as a basic assumption. Then, given a point of departure and destination within the combat area, the length of an actual route between the two points is estimated by taking into account the contour of that particular terrain and the overland capabilities of the vehicle. This route length is then converted to an equivalent standard route by considering the weather, terrain and vehicle characteristics. The travel time is the length of the equivalent standard route divided by the rated speed of the vehicle. The development of a method to compute this equivalent route is the aim of this appendix.

II. ROUTE ESTIMATION FOR SMALL TERRAIN AREAS

A convenient method of describing the contour of a given area of terrain is readily available on all military maps in the form of a north-south, east-west, 1000 meter grid coordinate system. For a given area of terrain, form a two dimensional array whose entries are the elevations above sea level in meters taken from the points of intersection of the orthogonal grid lines. For generality label the horizontal grid lines NI through $NI+p$ and the vertical grid lines NJ through $NJ+m$. Let the elevation entry for the k th row and i th column be denoted by $a_{NI+k, NJ+i}$. It is now desired to pick a route from point $A=a_{NI+k, NJ}$ across

the array to any point in column NJ+m. As a first estimate, using right triangles, calculate the slope and distance from point A to each point in column NJ+1 of the array. These slopes and distances are given by equations (7) and (8) and are labeled by the row coordinate of the associated point.

$$DIST_{NI+k} = \{ (a_{NI+k, NJ} - a_{NI+j, NJ+1})^2 + (1000)^2 + (k-j)^2 (1000)^2 \}^{1/2} \quad (7)$$

$$SL_{NI+k} = \frac{(a_{NI+k, NJ} - a_{NI+j, NJ+1})}{\{ (1000)^2 + (1000)^2 (k-j)^2 \}^{1/2}} \quad (8)$$

Having calculated these values, the next point on the route is selected in column NJ+1 by the following method:

- (1) Select all those points whose associated slopes are less than the maximum slope the vehicle can negotiate.
- (2) From the points selected by step (1), choose the point which is the shortest distance from point A.
- (3) If none of the slopes are less than the maximum slope, then choose the point with the minimum slope.

Having selected a point in column NJ+1, call it B, calculate the slope and distance from B to all the points of column NJ+2. Using the above selection criteria, choose a point in column NJ+2. By repeated applications of this procedure, a route from point A to a point in column NJ+m is eventually determined. The procedure or algorithm by which this route was selected will be denoted by FIRST(A, lK, S) where A denotes

the initial point, $1K$ denotes a step of 1000 meters, and S denotes the slope criterion. The terrain array and the results of this procedure are illustrated by Figure 3.

Depending on the nature of the terrain, the routes and their associated distances determined by this algorithm may be very good or very bad approximations of actual routes and distances over the chosen area of terrain. For extremely flat terrain the approximation will be fairly accurate while being less accurate for extremely uneven terrain. To improve on this method of selecting a route the algorithm $FIRST(A,1K,S)$ will be slightly altered.

The speed that a loaded combat supply vehicle can maintain decreases rapidly as the route it traverses becomes more uneven. This arises from the fact that the time the vehicle loses on steep up-grades can never be recovered on the down-grades. This is especially true on unimproved terrain. Therefore, if an alternate route exists in this area of terrain for which all the slopes are sufficiently small, this route may be more efficient than the one chosen above even though it is longer. The determining factor will be how much longer the alternate route is. It is obvious that if the alternate route is significantly more level than the initial route, the vehicle can maintain the rated speed and, therefore, travel the longer route in an equal or lesser time. However, if the alternate route is too much longer, no time will be saved. For the sake of computation, assume

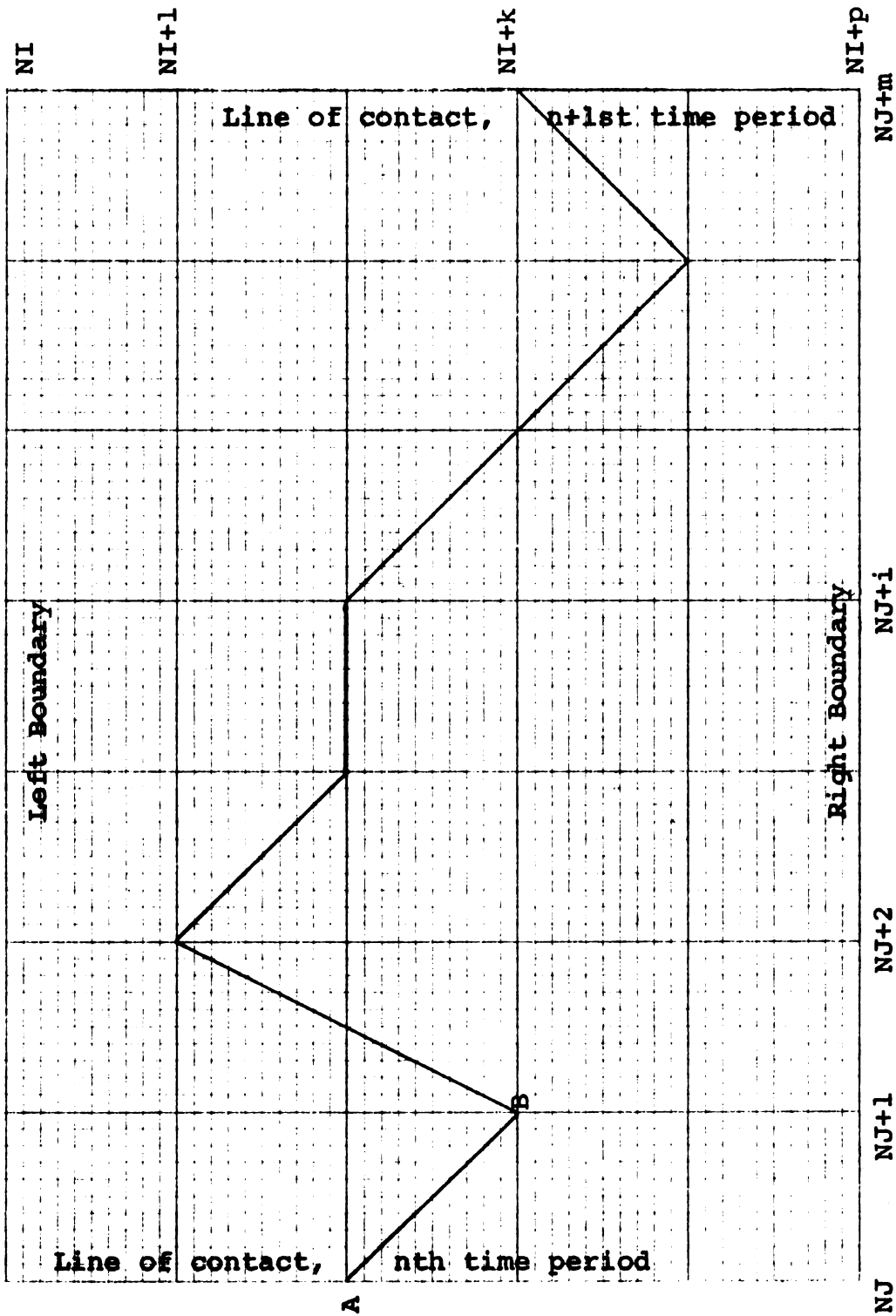


Figure 3. Two Dimensional Terrain Array (Plan View)

that the route can be ten per cent longer if chosen with slopes which are, in general, one third the maximum slope denoted by $S_{\max}$ that the vehicle can climb, and five per cent longer if chosen with slopes which are two thirds the maximum slope. Under these constraints the route across the terrain array can be determined as follows:

- (1) Using the procedure $\text{FIRST}(A, lK, S_{\max})$ calculate the length of the route across the array denoted by $L_{S_{\max}}$.
- (2) Let the slope, S , equal some small constant increment Δs .
- (3) Using $\text{FIRST}(A, lK, S)$ calculate the length, L_S , of the route across the array.
- (4) Compare the route length, L_S , and the slope, S , with the criteria established above. That is,
 - (a) If $S \leq 1/3 S_{\max}$ and $L_S \leq (1.1) L_{S_{\max}}$, choose the route.
 - (b) If (a) is not satisfied, but $S \leq 2/3 S_{\max}$ and $L_S \leq (1.05) L_{S_{\max}}$, choose the route.
- (5) If neither (a) nor (b) is satisfied and $S < 2/3 S_{\max}$, then increment S by letting $S = S + \Delta s$, and repeat steps (3) and (4).
- (6) If $S = 2/3 S_{\max}$ and the criteria of (4) are not satisfied, then choose the route determined by $S_{\max}$.

The above procedure consists of applying $\text{FIRST}(A, lK, S_{\max})$ to establish $L_{S_{\max}}$, and then applying $\text{FIRST}(A, lK, S)$ to the incremented values of S , passing each result through a

route grate where it is either selected or rejected. The route selection grate used here is only established for computational convenience. Using $\text{GRATE}(L_{S_{\max}}, L_S)$ to denote the class of such selection criteria algorithms, the above procedure can be generalized by replacing steps (3) and (4) by the general algorithm $\text{GRATE}(L_{S_{\max}}, L_S)$. The procedure is to calculate a route length and a slope using FIRST and then pass it through GRATE. According to the response of GRATE the route is either accepted or a new route is calculated by FIRST for the next value of S , and the selection process is repeated. This general algorithm, the combination of FIRST and GRATE, will be called $\text{ROUTE}(A, aK, S, S_{\max}, \Delta s)$ where the symbol aK denotes the step size in meters. Such algorithms have obvious potential for machine computation. Figure 4 shows the results of using this method to find five routes across a 5 by 15 kilometer area of jungle terrain in VietNam. The only difference in the program is in the determination of the route length, $L_{S_{\max}}$. In this case $\text{FIRST}(A, aK, S_{\max})$ was calculated for five starting points along the first row separated by 1000 meters. The value of $L_{S_{\max}}$ was determined as the average of these five routes. In all other aspects the program was identical to the procedure outlined above. The computation was done for an aK with values of 1.0 and .10 and used a Δs of 0.01. The terrain was chosen for its extreme uneven profile for the purpose of determining whether 100 meter grid squares were small enough to approximate an

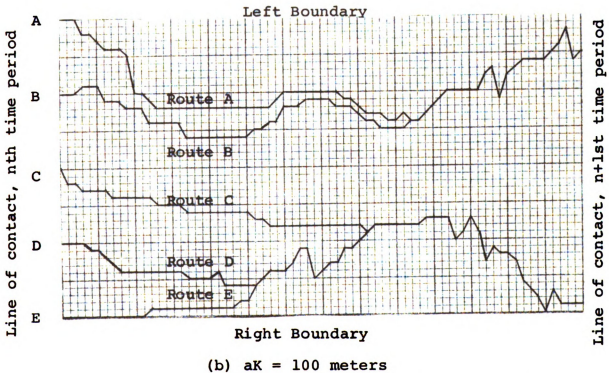
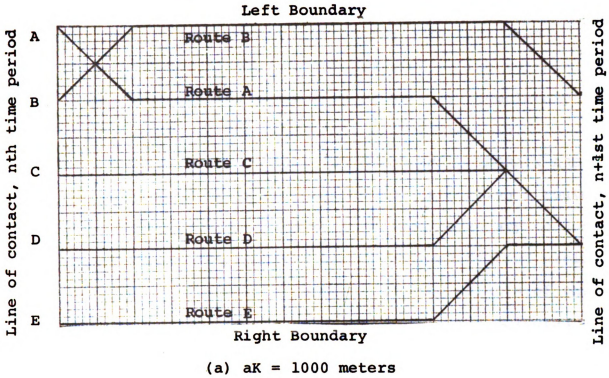


Figure 4. Five Routes Determined by $\text{FIRST}(A, aK, S_{\max})$
for Two Different Values of aK (Plan View)

actual route. The plotted routes of Figure 4(a) when compared with the actual contour features of the terrain indicated that the 100 meter grid squares are completely adequate to compute routes in this type of terrain.

III. THE EQUIVALENT STANDARD ROUTE FOR SMALL TERRAIN AREAS

Having established a method for estimating a route across a given area of terrain, it is now necessary to consider the equivalent standard route that was defined earlier. That is, it is necessary to account for the effects of the weather on the soil on the selected route. The selected route thus far is characterized by its length and slope. The essential features of the weather were chosen to be the ground temperature and the moisture content of the soil. These two weather parameters are a very efficient characterization for the purposes of this development. The complete description of the condition of the soil, as well as the effect the weather has on the speed of the vehicle, immediately follows from the moisture content of the soil and the ground temperature. The other two factors affecting the vehicle's speed are the soil type and the vehicle itself. The vehicle, for present purposes, is adequately characterized by the ground pressure it exerts. In general, five factors bear upon the speed the vehicle will be able to maintain along a given route. These are the general slopes, s , encountered along the route, the ground temperature, t , the moisture content of the soil, m , the soil type, g , and the ground

pressure, p , which is exerted by the vehicle. The variable s uses that value of the slope used by FIRST, and the values of the rest of the variables are assumed to exist.

The effect of these five variables on the determined route is to increase its length by some factor, $k > 1$, which gives the desired equivalent standard route. Ideally then, it is desired to find a functional relationship of the form $F(s, t, m, g, p) = k$. This could be a difficult relationship to establish, but one approach that offers some hope of solution is the following. Since soil types are not a continuum, they can be grouped into several different types. Similarly, the other four variables can be represented by a finite set of values. The interval of ground pressures can be subdivided into subintervals of pressures which have the same effect on vehicle performance.

For a given soil type the ground pressure can be divided into two sets of temperatures at the temperature, t_0 , at which the ground pressure of the vehicle causes the ground to thaw. For all temperatures below t_0 the ground behaves much like a hard surface. For temperatures above t_0 the effect is a function of the moisture content of the soil.

The argument for assigning discrete values to intervals of moisture content is much the same although not as clear cut. Dry soil is independent of temperature. On the other hand, for temperatures above t_0 , once the moisture

content reaches a certain level, m_0 , the effect of the increase in moisture content on the vehicle is almost negligible. In short, beyond m_0 the soft soil caused by the moisture cannot support the weight of the vehicle. It should be a reasonable task to divide the continuum between zero moisture content and the point m_0 into a group of intervals each of which has approximately the same effect upon the vehicle.

For the slope variable, s , the critical point is already established by $S_{\max}$. It should be possible to break the interval $[0, S_{\max}]$ into a number of intervals each having approximately the same effect on the rated speed of the vehicle. One immediate method is to use the values of the slope from the GRATE algorithm as the end points of these subintervals.

The above procedure, while not perfectly accurate, should in the particular case under study provide a reasonable approximation. Once the sacrifice is made, these simplifying assumptions seem worthwhile in terms of making the model easy to construct. By assigning integral values to the discrete intervals of each variable, the function $F(s, t, m, g, p)$ reduces to a function whose values are all integral and whose range is a finite collection of real numbers. This appears to be an important help both in establishing by practical tests the capabilities of actual

vehicles and in translating theoretical requirements into real capabilities. Of course the advantages of such a function for use in a digital computer are obvious. In its simplified form, $F(s,t,m,g,p)$ is easily handled by a five dimensional array.

In summary, the following procedures have been used to calculate the equivalent standard route:

(1) Using algorithms $FIRST(A,aK,S)$ and $GRATE(L_{S_{max}}, L_S)$ an approximate route was determined for the given area of terrain. These two algorithms were formally combined to form $ROUTE(A,aK,S,S_{max},\Delta s)$.

(2) Five variables were established as forming a sufficient basis for estimating the effect of weather and soil type on the rated speed of the vehicle.

(3) The five variables of (2) were combined into a real-valued function, F , whose range is a finite set of factors for converting the length of the route determined in (1) into an equivalent standard route, ESR, where ESR is the product of $ROUTE(A,aK,S)$ and $F(s,t,m,g,p)$.

IV. ROUTE ESTIMATION FOR LARGE TERRAIN AREA

Thus far, this study provides a method for computing equivalent standard route lengths for small areas of terrain. In a large scale combat operation of the type under consideration, the combat area may cover an area whose length is a thousand or more kilometers. It is impractical, if not impossible, to specify every elevation in this area of terrain.

One solution to this problem is developed here. Figure 5 shows a profile of a possible combat area for an entire combat operation. The vertical lines divide this profile into regions of similar terrain. These regions may vary in length from a few to several hundred kilometers, depending on the particular terrain traversed. For each terrain area a representative section of terrain is selected whose size is approximately 5 by 15 kilometers, and these areas are translated into arrays as before. Whenever a route is to be calculated in a particular region of the combat area, the following procedure is used:

(1) The sample terrain array corresponding to that region is selected.

(2) Using the procedure previously developed, $ROUTE(A, aK, S, S_{max}, \Delta s)$, an equivalent route is determined for the sample terrain array.

(3) The length of the equivalent route is divided by the length of the sample array to obtain a multiplication factor, RF , for the route.

(4) Considering the combat area to be a plane, the straight line distance between the initial and end points of the desired route is calculated.

(5) The straight line distance of (4) is multiplied by the computed factor, RF , to give the desired equivalent standard route.

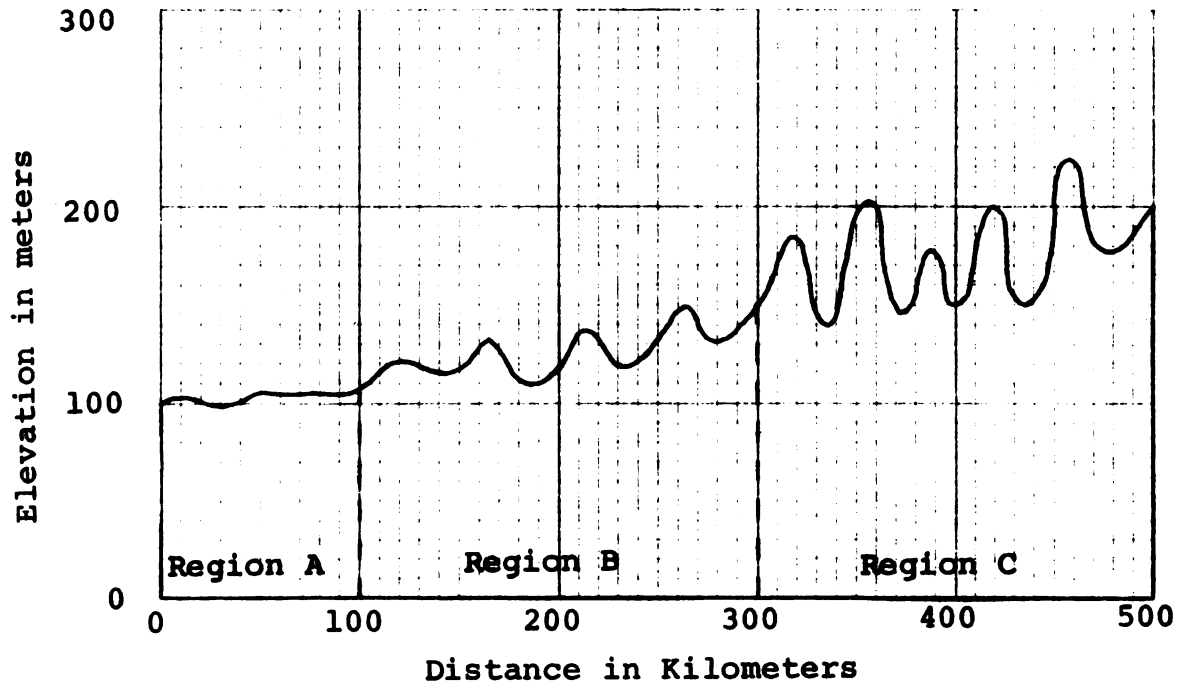


Figure 5. Regions of Similar Terrain (Cross Section)

The determination of the size of the sample arrays as 5 by 15 is based on the fact that 15 kilometers is the average length of the longest segment of the main supply route within the combat area. Since these routes run parallel to the division's axis of movement, a corridor of five kilometers is used.

In computer usage these sample terrain arrays could easily be stored in a three dimensional array by stacking them along one coordinate axis. The fact that some arrays would be 100 meter grid squares and that others would be 1000 meter grid squares could be easily overcome by making the array 5 by 151 by k and entering values for a particular k at every tenth entry for the 1000 meter arrays.

In summary, the method of calculating the equivalent route is as follows:

- (1) From the position of the actual route in the combat area, determine the sample terrain array to be used.
- (2) Using the sample data array and $ROUTE(A, aK, S, S_{max}, \Delta s)$, find the length of the route across the array.
- (3) Using the algorithms F and ROUTE, calculate the length of the equivalent route.
- (4) Using the length of the equivalent route and the length of the sample array, calculate the multiplication factor, RF.
- (5) Using the multiplication factor and the straight

line distance between the start and end points, calculate the equivalent standard route.

A computer program implementing the above procedures is listed in Appendix B. A flow chart of the algorithm is given in Figure 6. This program employs the above procedures with the exceptions listed below:

(1) $\text{FIRST}(A, aK, S_{\max})$ is evaluated at points $(1,1)$, $(11,1)$, $\dots$, $(NI+p,1)$, and an average value is used for $L_{S_{\max}}$ in the subroutine $\text{GRATE}(L_{S_{\max}}, L_S)$.

(2) Subroutine RMULT1 performs steps (2) and (3). It calculates the lengths of routes determined from five different starting points and determines the average length.

(3) Subroutines SLOPE , TEMP and WETBACK select the integral values of the variables s , t , and m respectively. The value of the variable g is called from the array IAB for the corresponding terrain areas. The ground pressure is assumed to be constant.

(4) Since the FORTRAN programming language does not provide for four dimensional arrays, two three dimensional arrays were formed, one for values of $t_o \leq 20^\circ \text{ F.}$ and one for values of $t_o > 20^\circ \text{ F.}$

(5) The weather is stored in a 2 by 30 array containing 30 temperatures and 30 associated changes in soil moisture content. For each day of the problem a random

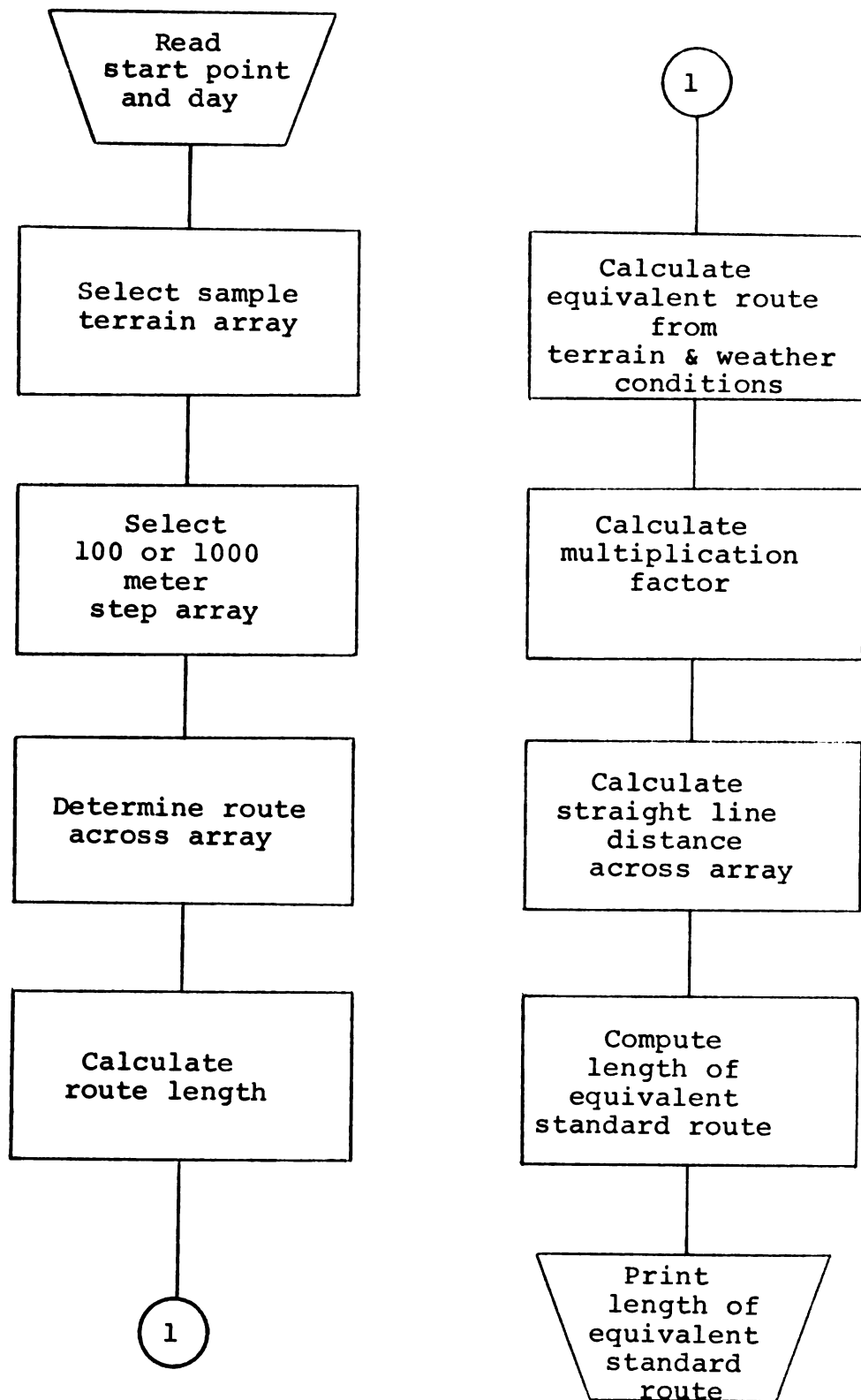


Figure 6. Route Algorithm Flow Chart

number, RN, is selected. The temperature and change in soil moisture content for that day are read from the locations (1,RN) and (2,RN) of the weather array. The moisture content is taken as the accumulated changes in moisture for the elapsed days of the problem.

APPENDIX B

A FORTRAN PROGRAM FOR THE ROUTE SIMULATION MODEL

This appendix contains the listing of the FORTRAN program that was formulated from the algorithm described in Appendix A. The output variable, DIST, gives the length of the equivalent standard route in meters.

```

PROGRAM THRU
COMMON A(51,160,2),R(160),C(160),D(160),SL(160),
1 ICOORD(160),ROUTE(160),NJ1,TR1(4,10,4),TR2(4,10,4),
2 ACC(30),WTH(2,100),AL(160),IAB(10),TEST,ILVL,MS,DMS
READ(60,1) ((A(I,J,1),J=1,101,10)I=1,41,10)
1 FORMAT(11F4.0)
READ(60,2) ((A(I,J,2),J=1,100)I=1,41)
READ(60,2) (A(I,101,2),I=1,41)
2 FORMAT(20F4.0)
READ(60,3) (IAB(I),I=1,10)
3 FORMAT(10I1)
READ(60,4) (((TR1(I,J,K),K=1,3)J=1,2)I=1,2)
READ(60,4) (((TR2(I,J,K),K=1,3)J=1,2)I=1,2)
4 FORMAT(12F3.1)
READ(60,5) (WTH(1,J),J=1,30)
READ(60,5) (WTH(2,J),J=1,30)
5 FORMAT(15F3.1)
TEST=0.0
CALL TERRAIN (1,12,2,6,100,1.0,DIST)
WRITE(61,6) DIST
6 FORMAT(1F7.2)
END THRU

```

```

SUBROUTINE TERRAIN (KJ,LJ,KI,LI,IFL,DAY,DIST)
COMMON A(51,160,2),R(160),C(160),D(160),SL(160),
1 ICOORD(160),ROUTE(160),NJ1,TR1(4,10,4),TR2(4,10,4),
2 ACC(30),WTH(2,100),AL(160),IAB(10),TEST,ILVL,MS,DMS
IF (IFL.GT.200) GO TO 10
ILVL=2
GO TO 20
10 ILVL=1
20 IF (ILVL.EQ.2) GO TO 30
MS=10
DMS=1.0
CALL RMULT1 (1,101,1,41,RF,DAY,S)
CALL MROUTE (KJ,LJ,KI,LI,RF,DIST)
RETURN
30 MS=1
DMS=0.01
CALL RMULT1 (1,101,1,41,RF,DAY,S)
CALL MROUTE (KJ,LJ,KI,LI,RF,DIST)
RETURN
END TERRAIN

```

```

      SUBROUTINE RMULT1 (NJ,MJ,NI,MI,RF,DAY,S)
      COMMON A(51,160,2),R(160),C(160),D(160),SL(160),
1 ICOORD(160),ROUTE(160),NJ1,TR1(4,10,4),TR2(4,10,4),
2 ACC(30),WTH(2,100),AL(160),IAB(10),TEST,ILVL,MS,DMS
      SMAX=0.3
      ADD=0.0
      DO 105 K=NI,MI,10
      CALL FIRST1 (NJ,MJ,NI,MI,SMAX,DIST,K)
105  ADD=ADD+DIST
      DIV=((MI-NI)/10)+1
      TPER=1.1*(ADD/DIV)
      FPER=1.05*(ADD/DIV)
      DO 200 K=NI,MI,10
      S=0.01
      TENS=1.0
101  CALL FIRST1 (NJ,MJ,NI,MI,S,DIST,K)
      CALL GRATE (S,DIST,TPER,FPER,MTOD)
      IF (MTOD.EQ.1) GO TO 93
92   TENS=TENS+1.0
      S=TENS/100.
      IF (S.GE.SMAX) GO TO 93
      GO TO 101
93   IF (TEST.EQ.DAY) GO TO 98
      TEST=DAY
      RN=((29.0)*RANF(-1))+1.0
      MW=RN
      WTH2=WTH(1,MW)
      WTH3=WTH(2,MW)
      MDAY=DAY
      ACC(MDAY)=WTH2
      DO 99 I=1,MDAY
99   ACCUM=ACCUM+ACC(I)
98   CALL WTRACK (ACCUM,ME2)
      CALL TEMP (WTH3,ME3)
      ME1=IAB(ILVL)
      CALL SLOPE (S,IS)
      IF (ME3.EQ.1) GO TO 700
      DM1=TR1(ME1,ME2,IS)
      GO TO 800
700  DM1=TR2(ME1,ME2,IS)
800  ROUTE(K)=DIST*DM1
200  CONTINUE
      SUM=0.0
      DO 210 K=NI,MI,10
210  SUM=SUM+ROUTE(K)
      SUR=(MI-NI)/10+1
      AROUTE=SUM/SUR
      SUR=(MJ-NJ)/10
      RF=AROUTE/SUR
      RETURN
      END RMULT1

```

```

SUBROUTINE FIRST1 (NJ,MJ,NI,MI,S,DIST,K)
COMMON A(51,160,2),R(160),C(160),D(160),SL(160),
1 ICOORD(160),ROUTE(160),NJ1,TR1(4,10,4),TR2(4,10,4),
2 ACC(30),WTH(2,100),AL(160),IAB(10),TEST,ILVL,MS,DMS
SMAX=0.30
N=NJ
M=K
ICOORD(NJ)=M
NJ1=NJ+MS
DO 80 J=NJ1,MJ,MS
T=10000000.0
TK=10000000.0
DO 20 I=NI,MI,MS
X=M-I
X=(X/10.0)**2
DIFF=ABS((A(M,N,ILVL)-A(I,J,ILVL))/1000.0)
R(I)=DIFF/SQRT(DMS+X)
20 C(I)=SQRT(DIFF**2+DMS+X)
SL(J)=R(NI)
NI1=NI+MS
DO 21 I=NI1,MI,MS
IF (R(I).GE.SL(J)) GO TO 21
SL(J)=R(I)
21 CONTINUE
IF (SL(J).GT.S) GO TO 65
DO 60 I=NI1,MI,MS
IF (R(I).GT.S) GO TO 60
IF (C(I).GT.T) GO TO 60
IF (C(I).EQ.T) GO TO 33
IF (C(I).LT.T) GO TO 34
33 IF (R(I).GE.TK) GO TO 60
34 TK=R(I)
T=C(I)
D(J)=C(I)
ICOORD(J)=I
60 CONTINUE
GO TO 75
65 DO 74 I=NI1,MI,MS
IF (R(I).GT.T) GO TO 74
IF (R(I).EQ.T) GO TO 73
IF (R(I).LT.T) GO TO 60
73 IF (C(I).GE.TK) GO TO 74
60 TK=C(I)
T=R(I)
ICOORD(J)=I
IF (C(I).LE.SMAX) GO TO 72
D(J)=1.5*C(I)
GO TO 74
72 D(J)=C(I)
74 CONTINUE
75 M=ICOORD(J)
N=J
80 CONTINUE

```

```

DIST=0.0
DO 91 J=NJ1,MJ,MS
91 DIST=DIST+D(J)
RETURN
END FIRST1

```

```

SUBROUTINE MROUTE (NJ,MJ,NI,MI,RF,DIST)
X=((NJ-MJ)**2+(NI-MI)**2)
SLDIST=SQRT(X)
DIST=RF*SLDIST
RETURN
END MROUTE

```

```

SUBROUTINE GRATE (S,DIST,TPER,FPER,MTOD)
IF (S.LE.0.1.AND.DIST.LE.TPER) GO TO 10
IF (S.LE.0.2.AND.DIST.LE.FPER) GO TO 10
MTOD=0
RETURN
10 MTOD=1
RETURN
END GRATE

```

```

SUBROUTINE WETBACK (ACCUM,ME2)
IF (ACCUM.LE.0.0) GO TO 10
ME2=1
RETURN
10 ME2=2
RETURN
END WETBACK

```

```

SUBROUTINE TEMP (WTH3,ME3)
IF (WTH3.LE.20.0) GO TO 20
ME3=2
RETURN
10 ME3=1
RETURN
END TEMP

```

```

SUBROUTINE SLOPE (S,IS)
IF (S.LE.0.10) GO TO 10
IF (S.LE.0.20) GO TO 20
IS=3
RETURN
10 IS=1
RETURN
20 IS=2
RETURN
END SLOPE

```

MICHIGAN STATE UNIV. LIBRARIES



31293105832616