CONCEPTS, DATA REQUIREMENTS, AND USES OF THE LOC INTERDICITION MODEL AS APPLIED TO NORTH VIETNAM

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PREFACE

The Lines of Communication (LOC) Interdiction Model was developed to examine interdiction campaigns against North Vietnam. It was part of the work of a joint study group comprised of personnel from Hq USAF (primarily Operations Analysis) and RAND. The authors, Dr. Richard D. Wollmer of RAND and Captain Michael Ondrasek of Hq USAF Directorate of Operations, drew on previous RAND work\(^{(1, 2)}\) but the present model includes additional elements that better define the complexity of a ground transportation network and its behavior under attack. The mathematical foundation is described in Reference 3, and the model is presented in Reference 4.

This Memorandum is intended as a handbook for the user or potential user who needs to know the types of information required by the model, the nature and significance of the output, the questions the model is capable of answering and how valid these answers can be.

The discussion, like the model itself, is written with the Vietnamese conflict in mind, although the model can be applied to interdiction by air attack of any reasonably small transportation network. Explanations are intentionally kept nonmathematical. To readers interested in network modeling as such, rather than in specific applications, References 3 and 4 will be more useful than this Memorandum. These two references are also required by those who decide to acquire and use the model.

The methods for determining the input parameters for individual links are discussed here in sufficient detail to permit the reader to estimate the effort required to obtain this information. Other RAND research, as yet unpublished, describes procedures devised for other inputs. The model has been run on the Hq USAF IBM 7090/7094 computer system. The IBM 360/65 version of the program appears in Reference 4 with a sample problem.

Some differences in terminology will be noted between Reference 4 and this Memorandum in which the terms used follow current practice of model users in Hq USAF Operations Analysis and at RAND. They do not necessarily follow standard network-modeling terminology.
SUMMARY

The LOC Interdiction Model is a representation of the flow of tonnage through a ground transportation network, the assignment of interdiction attacks against fixed facilities in the network, and the changes in flow capacity, routings and costs which result from these interdiction attacks. The model was designed as an aid to answering two questions about air interdiction effectiveness against North Vietnamese transportation of military supplies: 1) whether attacks on certain fixed facilities could reduce flow capacity below requirements; and, 2) whether these attacks could impose a significant strain on the manpower supply by increasing the labor requirements for moving goods and repairing damage. Attacks on targets such as trucks and storage depots are outside the scope of the model.

The model requires detailed inputs on individual sections, or links, of the transportation network. Original or pre-interdiction inputs are link capacity in tons per day, and link cost in man-days per ton of cargo moved over the link. A target must be selected for each link; this may be a critical bridge, or may be the surface of a road where it is vulnerable to cratering. The remaining inputs for the link are based on this selected target, the type of damage that can be caused by a successful attack on it, and the effect of this damage on transportation operations. Damaged link capacity is the number of tons per day that can be moved over the link after it has been damaged by air attack. Damaged link cost is the number of man-days per ton required to move cargo over the damaged link when any such movement is possible. Repair cost and repair time are the number of man-days and calendar days required to restore operations at the original capacity and cost. Attack success probability is the probability that an attack unit, which may be a single sortie or several sorties, can cause this damage to the link.

Attacks are allocated against links one at a time, with each attack sent where it will cause the greatest reduction in the flow of supply tonnage through the network. If an attack cannot reduce this flow, it is sent where it will cause the greatest increase in manpower
cost, considering manpower needs for both transportation and repair. The cost criterion is also decisive when attacks on two or more links will be equally effective in reducing flow. The resulting attack pattern is not necessarily the best assignment for more than a small attack, because the model cannot consider attacks beyond the one being assigned.

Tonnage flow is routed through the network so as to achieve maximum flow from origin to destination. This flow may be the maximum permitted by the physical characteristics of links in the network, or may be artificially constrained to a lower value by the model user. When there is a choice of routes for this maximum flow, the combination selected is the one involving the minimum total transportation cost. The resulting network flows and costs are computed and printed before the first attack and after each attack. If desired, flows over individual links can be printed.

The model user specifies the number of attacks per day and the number of days in the model run. The network is updated at the beginning of each day by restoring the original characteristics of links whose repair times have expired since they were last attacked.

Attack allocations and the resulting changes to link characteristics are based on expected values of the characteristics of all links at the time of attack. These take into account the attack success probability for each link attacked. Model results represent an average situation, rather than the results of a particular campaign in which some attacks succeed and some fail.

Results printed by the model can be used directly to answer questions about network capacity, transportation cost, and repair cost. Their validity is constrained by the non-optimal nature of the attack allocation and by the simplifications necessary to modeling any complex military campaign. These results can be compared with the anticipated results of other strategies, such as attacks against vehicles. Model runs repeated with changed inputs can be used to evaluate the effectiveness of changes in interdiction tactics and weapons. They may also be used to estimate the impact on the interdiction campaign of changes in the ground transportation network and its operating policies.
CONSTRUCTING A NETWORK

Figures 1 and 2 show how the network the computer sees is derived for model use from a system of roads and railways, and clarifies some terms in the Glossary.

To use unclassified data, the sample problem is set in Southwest Colorado and Northwest New Mexico and concerns moving and interdicting the movement of supplies entering the network from other transportation systems or from storage at Silverton, Cortez and Shiprock. The supplies are destined for three areas: 1) Central New Mexico, via the towns of Cuba and Espanola, 2) storage or further transportation at Alamosa, and 3) Central Colorado, via the road north from Monte Vista. Figure 1 shows the available transportation routes. Figure 2 illustrates the network for model use.

Road links are shown –—— and numbered below 50; railway links are shown +++++++ and numbered in the 50s; transshipment links are shown ——— and numbered in the 70s; artificial links are shown ———, with those from the simulated common origin to the points of origin numbered in the 80s, links from the destination to the simulated common destination numbered in the 90s, and the universal link designated "UNIVER".

Artificial links at the destination end are set up to permit the user to allocate or control flow to groups of destinations (Colorado, New Mexico, storage at Alamosa) as well as to individual destinations. All artificial links are restricted to pass flow in one direction only (shown ————>). Railroad links converging on Alamosa are similarly restricted.

Link characteristics must be established for model runs, but this particular example has not been carried to that point. A sample case with printout is given in Ref. 4.
Fig. 1 — A sample transportation route system

Fig. 2 — The network of Fig. 1 for model use
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GLOSSARY

Some of the terms used in this Memorandum have a specific meaning for the LOC Interdiction Model and its application; some word choices differ from those of Refs. 3 and 4 and other reports on this subject. The definitions in this Glossary may be useful for identifying these specific meanings and identifying synonyms.

Air interdiation: Interdiation using bombs, rockets, air-to-surface missiles, or other weapons launched from aircraft.

Arco: Links.

Artificial link: A link in the data base input to the model which does not correspond to a real transportation route, but is needed for computational purposes.

Attack: (noun) An air interdiation mission against a single link by one or more aircraft.

(verb) To attempt to damage a link.

Attack success probability: The probability that an attack, by one attack unit, against a link that is in its original condition will cause damage to the link.

Attack unit: The number of aircraft in an attack mission. For computer inputs, each attack unit should represent approximately the same cost to the attacking force.

Capacity: The quantity of cargo that can be moved over a link in unit time, generally expressed as tons of supplies that can be moved forward over the link in one day or one daily operating period. This capacity is determined by the physical limitations of the link. The types of vehicles available may enter into capacity computation, but the number of vehicles available can be used to compute capacity only when vehicles cannot be transferred between links.

Characteristics: Original link capacity, original link cost, damaged link capacity, damaged link cost, repair cost, repair time and attack
success probability for each link in the data base. See also minimum
flow requirement. These characteristics are determined by the model
user and are part of the data base.

Control card: A card used in runs of the model, on which the user
specifies the number of attacks per day, number of days in the cam-
paign, and certain choices about the printed output.

Cost: The resource expenditure required to move some quantity of cargo
over a link or through the transportation system from point of origin
to destination. (See also damaged link cost, original link cost.
The transportation cost required to move a given quantity of cargo
over a link is the product (number of tons moved) (link cost). "Cost"
(transportation cost) refers only to movement costs such as driver time.
Fixed costs, such as route maintenance, and repair cost are excluded
from "cost."

Critical target: A specific target on a link, used for determining
link characteristics other than original link capacity and original
link cost. The model acts as though all attacks against a link are
against the critical target.

Damage to a link: The change in a link caused by a successful attack.
Physical examples are destruction of a bridge, blockage of a road by
a bomb crater, or destruction of a ferry landing. Within the model,
damage to a link requires that the damaged link capacity and damaged
link cost, rather than the original link capacity and original link
cost, apply to any cargo movements over the link subsequent to damage
and prior to its repair. Damage to a link also requires that a repair
cost be imposed.

Damaged link capacity: The capacity of a link when damage has been
caused by an attack and has not yet been repaired; a characteristic.

Damaged link cost: The unit cost of cargo movement over a link after
that link has been damaged and before it has been repaired. For the
Vietnam application, unit cost is man-days per ton of cargo.

Destination: A point to which cargo is delivered by the transportation
system, operating over the network incorporated in the model data base.
A destination may be a point of consumption, a point where supplies
enter storage, or a point where cargo is transferred to another trans-
portation system, and is no longer considered by the model.
Expected value: An average value; a numerical value which is the average to be expected over many attacks on a link over many days of a campaign.

Fixed facilities: Non-moving portions of the transportation system, such as bridges, ferry landings, road surfaces or railway tracks.

Flow: The rate of cargo movement. In the units used in the North Vietnam application, network flow is the number of tons of supplies per day moving from all points of origin to all destinations. This is independent of the number of days required for a shipment to travel through the network; as seen by the LOC Interdiction model, the number of tons flowing from the points of origin is the same as the number of tons reaching the destinations, and this number of tons is the network flow as throughput. Similarly, a flow over a link is the number of tons per day moving from one end of the link to the other end.

Interdicted capacity: Used in Ref. 4 for damaged link capacity.

Interdicted cost: Used in Ref. 4 for damaged link cost.

Interdiction: Blocking or harassment of transportation; as used here, attacks against fixed facilities of a transportation network.

Invulnerable link: A link which has no critical target, and which cannot be damaged in a way that would affect capacity, cost, or repair cost.

Junction: A point where two or more links meet. Junctions have identifying names or numbers but have no other characteristics. The network-theory synonym is node. A junction or node served by only one link is possible, both physically and computationally, but of no value to the network, because the flow over the link serving such a junction will always be zero.

Link: A section of a transportation route (such as a road, a railway or a waterway) connecting two junctions. Links have characteristics. Each link is identified by a name or number, the name or number of the junction where it begins, and the name or number of the junction where it ends. If supplies can move in either direction over a link, the link must be input in both directions; characteristics are identical
but the beginning and ending junctions are interchanged. The network-theory synonym is arc. (See also artificial links.)

Link cost: A unit cost for cargo movement over a link. In the Vietnam application, cost is measured in man-days per unit of one ton of cargo.

Lower bound: Minimum flow requirement.

Maximum flow pattern (maximum possible flow pattern): Any combination of tonnage flows over individual links which yields the maximum throughput.

Minimum flow requirement: An optional characteristic of a link, used sometimes on artificial links as a control device but rarely on real links, and input on the link data card as zero when not used. Flow allocated over a link by the computer can never be less than the input minimum flow requirement.

Mission: One or more aircraft flying together to do a particular task, such as attacking a link.

Mode of transportation: A combination of routes and vehicles such that two different transportation modes cannot use the same link. (But links used for different modes may share common junctions, at which transshipment is permitted and transshipment costs can be disregarded. See transshipment links.)

Monte Carlo technique: A method of deciding whether an attack has been successful (when the attack success probability is neither zero nor one) by drawing random numbers, rolling dice, tossing coins, or using a similar device which does not guarantee identical results from two plays of the same situation.

Network status: At any given time, the flow over each link in the network, plus each link's expected surviving original link capacity, expected available damaged-link capacity, time remaining until repairs are completed, and cumulative repair cost.

Nodes: Junctions.

Origin: Point of origin.

Original condition: The condition of a link which has not been damaged or which has been repaired. When a link is in its original condition, flow is limited by the original link capacity and is at the original link cost.
Original link capacity (original capacity): The capacity of a link which has not been damaged or which has been repaired; a characteristic.

Original link cost: The unit cost that applies to an undamaged or repaired link; a characteristic. (See damaged link cost).

Point of origin: A point at which the transportation system picks up cargo for movement over the network incorporated in the model database. This may be a point of manufacture, a storage location, a point where cargo is transferred from a transportation system not incorporated into the model database, or just the beginning of the geographic area of interest to the model user.

Profile: A table showing the total costs of moving cargo through the network for tonnage flows which are fractions of the maximum possible flow.

Profile point: A tonnage flow through the network, less than the maximum flow, for which costs are computed and tabulated in a profile.

Real links: Links which are not artificial links.

Repair cost: The expenditure in resources required to repair damage by a successful attack on a link's critical target. In the North Vietnam application, this is the number of man-days required for this repair. This is a characteristic.

Repair time: The time required to repair damage by a successful attack on a link's critical target. In the North Vietnam application, this is the number of calendar days from the time of damage until repairs are close enough to completion for traffic to move at original link capacity and original link cost. This is a characteristic.

Sampan: A small watercraft, common on inland waterways in Southeast Asia; it is smaller than a junk but larger than a canoe.

Simulated common destination: A junction of artificial links, required if there is more than one destination in the network. Artificial links go from each destination to the simulated common destination. The universal link begins at the simulated common destination.
Simulated common origin: A junction of artificial links, required if there is more than one point of origin in the network. The universal link ends here, and artificial links go from the simulated common origin to each point of origin.

Sink: Simulated common destination; destination.

Sortie: One flight by one aircraft.

Source: Simulated common origin; point of origin.

Steady state: The situation over a fairly long period of time during which requirements, resources and the physical structure of the network remain generally constant, except as they are affected by the interdiction campaign.

Strike: An attack.

Success probability: Attack success probability.

Successful attack: An attack which damages a link so that flow over the link is constrained to damaged link capacity and moves at the damaged link cost.

Throughput: Flow through the network.

Tonnage flow: Flow.

Transportation cost: See Cost.

Transshipment: Transfer of cargo from vehicles of one mode of transportation to vehicles of another mode of transportation, for instance, from truck to sampan.

Transshipment links: Links used to introduce capacity, cost and vulnerability of transshipment into the model. Flow over a transshipment link represents the transshipment of cargo from one mode to another at a transshipment point. Transshipment link characteristics are the characteristics which apply to this transfer of cargo.

Transshipment point: A place where transshipment may take place, represented by a group of junctions and transshipment links if transshipment limitations and costs are to be considered, and by a junction if these limitations and costs are to be ignored.
UNIVER: See universal link.

Universal link: An artificial link from the simulated common destination (or from the destination if there is only one) to the simulated common origin (or to the point of origin if there is only one). The universal link has no physical existence but is necessary for operation of the model. This link is conventionally abbreviated to UNIVER.

Upper bound: The capacity of a link. This will be the original link capacity, if the link has not been attacked, or has been repaired since last attacked; the damaged link capacity if the link has been attacked successfully; and an expected-value combination of original and damaged link capacities if the link has been attacked, but may or may not have been damaged.

Vulnerable link: A link which can be damaged by an attack.
I. INTRODUCTION

Interdiction attacks on transportation were a major component of the United States air effort against North Vietnam. Fixed facilities, vehicles, storage sites and personnel are among the types of targets vulnerable to air strikes. The model described here is concerned with attacks on facilities such as bridges, roads, railway track and transshipment points. While it can be applied to any transportation system comparable in size, the model was designed to be as representative of the North Vietnamese situation as possible, and assist in answering two questions:

1) Can attacks on fixed transportation facilities reduce North Vietnamese capacity to move supplies to the combat area to a level insufficient to meet military requirements?

2) Can such attacks increase the requirements for North Vietnamese supply movement manpower to the point where they impose a significant strain on the North Vietnamese economy?

Section II is concerned with the actual world treated by the model; Section III is concerned with how the model sees this world. Section IV defines the characteristics of network links, and the data required by the model to deal with them. Section V deals with the model's rationale for the selection of links for attack. Section VI describes the control devices and techniques for conducting model runs; Section VII lists the results that can be expected from the model. Finally, Section VIII lists the questions the model will answer.
II. THE WORLD TREATED BY THE MODEL

SUPPLY MOVEMENT

Cargo of various types is being moved over the ground transportation network. Of primary interest are the military supplies moving from the Hanoi-Haiphong area southward to the South Vietnamese border and into Laos. Additional supplies are moving to intermediate points, where they are used to support the flow of supplies to the south or for other military purposes.

This transportation activity consumes resources of several types. Manpower is needed to move goods, to maintain routes and facilities, to repair damage, to extend the network, to repair vehicles. Vehicles and repair parts, gasoline and diesel fuel must be imported. Other supplies, such as food for drivers and laborers, coal and wood for railway locomotives, and wood and gravel for bridge, road, and sampan repairs need not be imported, but may have to be moved locally within North Vietnam or from North Vietnam to Laos.

Several criteria are used to route traffic over the transportation network. One of these is cost. Because resources are limited, it is natural for the transportation planners to use routes that require the lowest combination of operating and repair costs, and to allocate traffic on a lowest-cost basis between roads, inland and coastal waterways, and the railway line. Costs for shipments using more than one transportation mode must include transshipment cost between modes. Some of the other criteria are cost-related. Safety from attack is in itself a criterion for routing, and also reflects the costs of replacing lost supplies and of delayed delivery. Several parallel routes may be used to reduce disruption from attack, to use local labor along these routes, to guarantee that alternate routes are kept open, or to satisfy operational convenience. Supply storage locations may dictate the choice of routes.

The entire operation of the North Vietnamese transportation system has been adapted to the possibility of air attack. This is evident not only in route selection, but also in night operations, standby ferries or temporary bridges available at river crossings, canopies over some roads, and defenses.
AIR ATTACK

Air strikes were directed against the transportation system, with fixed facilities, vehicles, and storage depots among the most popular targets. The most desirable outcome of the air campaign would have been the total stopping of the flow of supplies to the combat area, whether through blocking routes, destroying vehicles, or destroying supplies. If this could not be done, a second choice objective was to reduce the flow enough for supply limitations to have a restrictive effect on North Vietnamese military plans and capabilities, to the extent that they could not carry out major offensives and could not support their forces in major defensive engagements. Concurrent with the limitation of flow, another objective of the air campaign was to make waging war in the south so costly to the North Vietnamese government that the latter would elect to reduce its scale of operations or end the war -- or, at least, discontinue the active participation of organized North Vietnamese army units.

The United States also had limited resources. It was not possible to keep all targets continuously under attack; it was necessary to allocate attacks among individual targets and among types of targets, and to determine when to repeat an attack. Attacks were not always successful, and successful attacks on fixed facilities do not always stop traffic.

INTERPLAY OF MOVEMENT AND ATTACK

The North Vietnamese transportation system might respond to air attacks by rerouting traffic by alternate modes or routes, or by delaying movement until repairs to the network are made.

The interdiction campaign might follow a successful attack on the lowest-cost route by attacking the lowest cost alternate routes for the ground transportation system. It might also respond by observing the new flow pattern and attacking actively used new routes.

The trend in a campaign of this type is for flow to decrease or costs to increase as facilities are attacked, and for flow to increase or costs to decrease as damaged links are repaired. A given daily level of attacks should reduce the ground transportation network to
a smaller, lower capacity network with many sections sufficiently damaged to be unusable, or to be usable only at high transportation cost. As the attack level is increased, the network should approach a capacity level at which further attack would be unproductive. At this point, the network may be completely blocked; or it may be used only at low capacity, employing only those links which cannot be completely closed by air attack. However, this may not be feasible. Seasonal and daily weather variations may prevent prompt reattack and permit flow to resume over repaired links. And the North Vietnamese may alter the ground transportation network by construction of new links, or by modification of existing links to reduce their vulnerability.
III. THE MODEL’S VIEW OF THE WORLD

SUPPLY MOVEMENT

Supply tonnage is moved from one or more points of origin to one or more destinations over a network of transportation links, using the lowest-cost routes feasible. Each link has individual characteristics:

A. Original (pre-interdiction) capacity and cost,
B. Capacity and cost when damaged,
C. Repair time and repair cost for returning the link from damaged to original condition;
D. The probability that an attack against the link will cause it to be damaged.

The model treats all supplies simply as tonnage, regardless of their nature. Tons may flow from any point of origin to any destination. Only one measure of cost may be used. In the present application, this measure is man-days. Transportation costs are measured in man-days per ton, repair costs as man-days to repair the damage caused by a successful attack on a link.

Flow over a link may be restricted to one direction, or may be permitted in either direction. Flow through the network and over individual links is measured in tons of cargo per day. This is treated by the model as though all cargo leaves the network on the same day that it enters, with no specific provision for enroute storage.

Damaged-link capacity and cost are the capacity and cost of transportation operations required to move cargo over the link despite the damage to it from a successful attack. If there is no way for cargo

* A glossary follows the Summary. The choice of terms in the present paper is somewhat different from that of Reference 4, which uses standard network terminology; terms used here are oriented more toward the physical situation being modeled. Synonyms are noted in the glossary.
to move over the link when an attack has been successful, the damaged
link capacity is zero and there is no damaged link cost.

ATTACKS

An attack leading to successful interdiction would change the
characteristics of the link attacked by substituting damaged link
capacity for original link capacity, damaged link cost for original
link cost (except when damaged link capacity is zero), and by im-
posing the cost of repair.

If the probability of an attack's success is less than certainty,
the link's characteristics after attack incorporate both the original
value and the damaged values computed on an expected-value basis. The
link's status takes into account the probability that the link has
been damaged, and tonnage flow restricted to the damaged link ca-
pacity at the damaged link cost. It also considers the probability
that the attack was unsuccessful and left the link in its original
undamaged condition. Mathematical expressions are given in Eqs. 2,
3, and 4 of Reference 4.

The capacity of a link which has been attacked has two components.
One of these is the expected surviving portion of the original link
capacity. This is the product of (original link capacity) and (proba-
bility that none of the attacks against the link has been successful).
The other component is the product of (damaged link capacity) and
(probability that at least one attack against the link has been suc-
cessful).

The flow of tonnage up to the limit of surviving original ca-
pacity moves at the original cost of transportation flow. Any flow
in excess of the surviving original capacity moves at the damaged-
link cost.

Repair cost is assessed similarly on an expected value basis,
and is accumulated as attacks are allocated against the link. The
repair cost applicable to a particular attack is the product of (in-
put repair cost for the link), (probability that the attack in ques-
tion will be successful), and (probability that all previous attacks
against the link have been unsuccessful).
Previous attacks considered in generating these link characteristics are those allocated against the link since the last time that repairs to that link were completed and its original characteristics restored.

When an attack is made against a link, the capacity available for use at the original cost is reduced, the damaged link capacity available for use (at the damaged link cost) is increased (unless it is input as zero), and a portion of the repair cost is imposed. As attacks continue, the effect of each new attack in reducing original capacity, increasing usable damaged link capacity, and imposing repair cost, is somewhat less than the effect of the preceding attack. As the process continues, the expected capacity at the original cost approaches zero, the expected available damaged link capacity approaches the input damaged link capacity, and the expected cumulative repair cost approaches the input repair cost. Because it is always possible that all attacks against the link have failed, the expected link characteristics never quite achieve the input values for post-attack characteristics. Eventually, the convergence process is stopped by integer arithmetic and rounding within the model.

REALLOCATION OF FLOW

A new flow pattern, influenced by the changed characteristics of the attacked link, is established by the model after each attack. This pattern provides the maximum possible flow. If there is more than one maximum possible flow pattern, the model will select the one involving the lowest transportation cost.

For strike allocation and cost computation purposes, the model is programmed to reroute flow instantaneously after each strike, so as to conform to the new expected status of the network. The instant rerouting is not as unrealistic as it may seem, as most strikes against fixed targets will be made during daylight hours and traffic moves at night. The only pertinent network status for flow routing and cost is that existing after the last strike of the day. The flow pattern and cost represent an average over a long campaign.
REPAIR AND RESTORATION OF LINKS

Repair time is a link characteristic that is not part of the expected value computation. A link with a repair time of \( N \) days is restored to its original pre-attack condition at the beginning of the \( N \)th day after the last attack sent against it. Restorations take place at the beginning of each day, before traffic moves and before attacks are allocated.
IV. LINK CHARACTERISTICS AND DATA REQUIREMENTS

ORIGINAL CHARACTERISTICS

Original Link Capacity

Each network link is assigned a capacity value representing the number of tons per day that can be moved over it in one direction. Several methods of capacity estimation for road and railway links exist. Those currently used by the Defense Intelligence Agency were established jointly by United States and British agencies for use throughout NATO. RAND research has generated a different methodology for estimating road capacity. (5, 6)

Generally the capacity value of a link must be based on its physical characteristics rather than on the number and availability of vehicles used to move cargo over it, because vehicles can be shifted from one link to another. Both the US-UK method and the RAND method use the physical characteristics of roads: terrain, surface type, condition, road width, and seasonal climate. The US-UK method also considers the type of subgrade and width of shoulders. Similarly, the NATO railway capacity methodology uses operating speeds and passing siding spacing and length, but not the number of locomotives and cars available. Average or typical vehicle capacities must be considered for both railway and road links, even though the number of vehicles is excluded from the computation.

Waterways present a difficult case. Except for those inland waterways with locks that have a limited capacity in watercraft moved per day, there is generally no limit to the number of tons that can be moved. Loading facility limitations are applicable only to traffic that must be transshipped at one end of the waterway link; boats can be shifted between links as required. For the North Vietnamese application, it appears sufficient to use a capacity value high enough not to be constraining, and to compare waterway movements in the model output with known watercraft inventories to determine whether or not the model's allocation of traffic to waterways is unreasonably high.
Link capacities must in every case allow for the return of empty vehicles, either over the same links (with consequent reduction of the link's capacities to move tonnage forward), or over other links (which then must be restricted to return movements only, and are not available for moving tonnage forward).

The link capacity need not be measured in tons per day; however, the unit used must be a single measure of quantity during a unit of time compatible with the repair of links attacked. The same unit of measure must be used for all transport modes. A "day" is assumed to be a calendar day, not necessarily 24 hours of uninterrupted use of the road. During the 24 clock hours, time may have to be set aside for maintenance and for nonmilitary traffic. Also, there may be only 8 to 10 hours of operation if truck travel must be restricted to specific hours or conditions.

Original Link Cost

In the North Vietnam application, the cost of moving unit (one ton) of cargo over a link is measured in man-days of labor, that is, link cost = man-days per ton over the link. Only the costs generated by the movement of cargo, such as driver costs and repair of vehicles.* The fixed costs required to keep the road open whether it is used or not must be calculated separately and are not included under link cost. Note that link cost is treated here as independent of the number of tons moved over the link, that is, the cost in man-days per ton is not subject to economies of scale. This implies good vehicle dispatching and control. In other applications it might be more reasonable to use vehicle-days per ton, gallons of POL per ton, dollars per ton, or some other resource that must be consumed if tonnage is to be moved. However, the model cannot use two different types of resources and select which is to be expended in a particular case. Even the allocation of traffic between road and waterway links requires use of a

*Note that trucks, POL, and spare parts are furnished to North Vietnam at no cost to the North Vietnamese government.
common cost measure -- man-days per ton of flow in the North Vietnamese case -- rather than two independent measures, such as truck-days and sampan-days. The factors used to compute North Vietnamese link costs are the following:

1) Average travel time over the link (a function of a link's length and its condition);
2) Average travel hours in one operating day (determined by operating policies, including the time allowed for loading and unloading).
3) Number of men required and average tons per vehicle.

This can be expressed as:

$$\frac{2 \cdot (\text{Length of link, in miles}) \cdot (\text{Men in crew of vehicle})}{(\text{Av. speed, mph}) \cdot (\text{Hrs. of travel/day}) \cdot (\text{Tons carried/vehicle})}$$

The factor of 2 allows time to return the empty vehicle and its crew. It is sometimes convenient to combine average speed and hours of travel per day into miles traveled per day. A vehicle can be a truck, a sampan or a train, a porter, an elephant, or an aircraft -- in short, any medium used to carry supplies. The cost of supervision and communications can be incorporated in original link cost by adding perhaps 10% to the driver manpower costs.

DAMAGED LINK CHARACTERISTICS

Estimating the Nature of Damage

The post-attack characteristics of a link depend on the type and extent of damage it will sustain from a successful attack. Some links have one or more critical targets, often bridges; some can be damaged only by cratering roadways. Some may be invulnerable to damage by conventional air attack. Each link must be analyzed to determine the types of interdiction that are feasible, select the most promising target, and determine what the link characteristics will be after a successful attack.

Post-attack characteristics for an "invulnerable" link (for instance, a river or a dirt road through dry country where cross-country mobility is as good as road mobility) are the same as their original characteristics. The following discussion is limited to situations in which air attack can reduce link capacity, raise the link transportation cost or impose a link repair cost. The post-attack or damaged link characteristics apply from the time of a successful attack until the completion
of repairs, at which time the original characteristics are restored by the model. Because the attack success probability is usually less than 1.00, the link characteristics after an attack lie somewhere between the original and damaged link characteristics. This follows from the expected-value nature of the model, as discussed in Sec. VII.

Damaged link characteristics are derived from the enemy's options for moving traffic over the link after it has been damaged. Some options permit vehicular traffic to continue, while others allow tonnage to flow but do not permit trucks or trains to traverse the links damaged section.

**Damaged Link Capacity**

The capacity of a link after a successful attack may be the link's original capacity, or it may be the capacity of the improvised method used after the attack to move cargo past the break, whichever is less. If cargo cannot move until the link is repaired, the damaged link's capacity is zero.

The capacities of certain cargo movement methods can be established with some precision. One example is a vehicular ferry of known capacity and travel time. A porter or porter-and-sampan operation, though, may not have a firm capacity limit. It may be possible to maintain the original link capacity after a successful attack by assigning additional laborers. In this event, it may be necessary to estimate the capacity of the transshipment operation on the basis of the space available to unload, load, and turn trucks or trains. Alternatively, a limit could be assumed beyond which a high level of confusion and congestion causes a decrease in link capacity. A third possibility is that there is a limit on the number of men available for cargo transshipment in the area.

Minor bottlenecks, such as a reduction from two lanes to one to avoid a crater, will not generally limit road capacity for the type of traffic considered in this application. Military traffic moves in spaced convoys — with spacing increased where dust is significant —
and allowances are made for temporary road closings for routine maintenance, interference from cross-traffic, and the like. Spacing can be reduced at bottlenecks at the cost of breathing more dust for a few hundred feet. Also, cross-traffic can be diverted to other crossing points, routine maintenance work deferred, and the general efficiency of traffic movement improved for this short distance by closer control. The situation is quite different from that produced by a bottleneck on a busy civilian highway. There, the mixture of unsupervised competition for space in open lanes and curiosity about the obstruction can reduce vehicle flow by a quantity disproportionately greater than would be assumed from the reduction in the number of traffic lanes. Of course, if the model is applied to a transportation network in which operations more closely resemble uncontrolled automobile traffic, a damaged link capacity may be used that represents the reduced capacity of a highway where traffic lanes must merge at the point of damage.

**Damaged Link Cost**

One way of computing the link cost (movement cost for one unit of cargo) for a link that has been attacked, but through which some tonnage flow is still possible (damaged link capacity greater than zero), is to determine the per-ton cost of moving cargo around the point of damage, and to add this to the original link cost. This additional cost may be negligible if vehicle flow can be maintained. However, there may be delays; if so, vehicle waiting time will generate additional driver manpower costs. Also, the cost of a nonvehicular operation will be higher, because it involves loading, unloading and porter labor, and perhaps boat crews. These costs must be calculated on the basis of target intelligence, and the enemy's options for moving cargo around the break.

**Repair Time**

Repair time is defined as the time required to restore the link to its original capacity and cost. This can be limited by physical requirements, such as the time needed to bring in concrete for a new bridge pier, pour it, and let it cure. More often, repair time depends on the number of workers or the type and quantity of equipment
assigned to the job, and is controlled by the ground transportation operator. Repair time inputs are therefore likely to reflect normal practice, rather than minimum possible time.

Because the model restores a link to its original condition when its programmed repair time has run out, it demands that the link be in one of two states -- damaged or repaired. This may not be realistic under operational conditions. Some links may be restored in two stages: first by temporary repairs or establishment of a vehicular ferry service; and later by reconstruction of a bridge. Thus, post-attack transportation operations are begun with one set of conditions, improved to a second set, and finally restored to the pre-attack set. In this case, the model requires a compromise set of values for post-attack operations and repair time. If a link has permanent bridges that are costly to repair but which can be bypassed by temporary bridges, ferries or fords, the original capacity and cost of operation over the link may be those which apply when the temporary crossings are used, rather than those employing the unrepaired permanent bridge. Then, repair time and cost will be the values appropriate for establishing the temporary crossing, as is the case with many North Vietnamese transportation links since 1965.

**Repair Cost**

Manpower costs associated with repairing a link can be treated in a more satisfactory way than repair time, because the factors involved are physical requirements rather than labor assignment and priority decisions. These requirements will vary, depending on the type and quantity of equipment available to the repair force as well as the nature and extent of the damage and repair work required.

Repair cost should include all manpower necessary to restore the link to the condition needed for continued transportation operations at the original capacity and cost, including the transportation of materials and travel time for the work force, as well as time actually spent at the repair site.
CHARACTERISTICS OF THE ATTACK

Damaged link capacity, damaged link cost, repair time and repair cost are based on a specific type and degree of damage to a critical target on a particular link. The probability that one interdiction attack will accomplish this type and amount of damage is defined as the attack success probability.

Success probabilities are based on: 1) number of aircraft making the attack; 2) number and types of weapons carried per aircraft; 3) delivery accuracy; and 4) weapons effects. The number of aircraft sent against a particular target varies in an actual campaign. For purposes of the model an attack unit is selected upon which to base the attack success probabilities. Attack units sent against different targets need not be identical, but should represent similar expenditures of the resources of the greatest concern to the attacker. One example is total tonnage of bombs expended, which would permit a flight of four small aircraft to be used instead of a flight of two larger aircraft if the mission bomb load is essentially the same.

The size of the attack unit should probably be based on the tactical doctrines of the attacking force insofar as the equal cost rule permits. If too large an attack unit is selected, the interdiction effort will be concentrated, perhaps unrealistically, on relatively few targets. Too small an attack unit -- a single aircraft for instance -- will cause an unnecessary increase in computer running time.

Target defenses can be introduced into the model by modifying success probabilities if a link-by-link analysis is made of the expected defenses and of the attacker's countermeasures. Close-in defenses may require the attacker to release weapons further away from the target, thereby degrading delivery accuracy and reducing the probability of success. Also, some aircraft in an attack unit may be used for flak-suppression, fighter cover, or ECM, rather than for delivering ordnance.

The model assumes that a target is either hit or missed; thus, the only gain to the attacker for delivering more than a single bomb in a target area is the increased probability of a direct hit on a critical target, such as a bridge.
TRANSSHIPMENT LINKS

Separate links can be created to assess the costs of transferring cargo from one transportation mode to another at junction points. Such costs include labor necessary to unload vehicles of one mode, carry cargo between loading points, and load vehicles of the second mode. Supervision is included when this is a function of tonnage handled, as is vehicle crew waiting time if this is not employed for another useful purpose.

Although space restrictions may conceivably limit the capacity of a North Vietnamese transshipment point, the non-mechanized cargo transfer methods of less-developed countries do not require permanent docks or platforms to be effective. Hence, there may be no way of assigning a capacity limit to a Vietnamese road-to-waterway transfer link. Railway station capacities may be limited by the number and lengths of tracks on which freight cars may be spotted for loading and unloading. Another possible capacity limitation to all transportation modes is the quantity of cargo that can be moved by the available labor force in one day.

The primitive nature of transshipment facilities reduces their vulnerability to attack. For instance, they are probably not vulnerable except to time-delay weapons that deny the area to work parties for a day or more. Vehicles, supplies, and the labor force may be useful targets at transshipment points, even though they are outside the scope of the LOC interdiction model.
V. ALLOCATION OF ATTACKS

CRITERIA

Criteria for the selection of links to be attacked are:

1) The most desirable attack is that which most sharply reduces tonnage flow through the network. The measure of its expected effectiveness is the product of [the anticipated reduction in network flow] times [the number of days required to repair the link].

2) Under some circumstances, criterion 1) may indicate that two or more links are equally profitable (or unprofitable) to attack. For instance, the model may indicate that no single attack on any link can reduce tonnage flow; or that the potential for reduction of tonnage flow engendered by attacks on two or more links is identical. When either of these situations occurs, the second criterion is applied; the decisions as to which link should be attacked is based on the increase the attack will cause to the cost of operating and repairing the transportation network. The measure of effectiveness is the sum of the product [(the increase in total cost of flow) times (the number of days required to repair the link)] and the cost of repair.

If target options remain equally attractive after applying the second criterion, selection is arbitrary, depending on the order of the link data cards in the deck.

Because link selection is based on the effect of an attack on total network flow and cost, not on flow and cost over the link attacked, the selection process involves a series of trial computations. Each link that is a candidate for attack is tested by establishing the maximum-flow, minimum-cost transportation movement pattern that will apply if the next attack is sent against it.

SEQUENCE OF ATTACK ALLOCATION

Attacks are allocated one at a time. The first is launched against the link most desirable to attack, as determined by the above criteria. Characteristics of the link attacked are then changed to the expected values which apply after the link has been attacked once. Links under
consideration for allocation of the second attack include the link already attacked (with its modified characteristics) as well as all other links in the network. This process does not include any consideration of the number of attacks still to be allocated; each allocation is optimal for only one attack. The consideration of all possible allocations of several strikes is beyond the capability of this model.

Selection of links for attack at the beginning of the second and later days of a campaign is similar to that for the first day. However, the computer restores any links on which repairs have been completed to their original characteristics at the beginning of each day. A repaired link is equally vulnerable to attack (with the same original and damaged link characteristics) as before any attacks were sent against it.

**COMPUTATIONAL METHOD**

The model combines reductions in network flow and increases in network cost into a single, cost-maximizing function. A high negative cost-per-ton of flow is input for the artificial return link or "universal link" discussed in the next section. As a consequence, any attack that will reduce the network flow will also reduce the total of this high negative cost. Thus, the effect of tonnage flow reduction on total cost (as perceived by the computer) when flow can be reduced by an attack, is much greater than the effect of increases in cost over a given link, or of rerouting, or of repair efforts, when the attack being considered will not change tonnage flow.

This computational method causes the model to behave as though it were observing two criteria -- flow reduction and cost increase. Cost increase is used only if application of the flow reduction criterion gives an ambiguous answer.

The function the model seeks to maximize is the sum of \[ \text{(increase in total cost of flow) times (days until the link is repaired)} \] plus \[ \text{(cost of repair)} \]. The increase in total cost of flow incorporates the reduction in negative cost that accompanies flow reductions.
ARTIFICIAL LINKS

Requirements

The LOC Interdiction Model perceives the flow of tonnage as a continuous flow, from a single point of origin to a single destination and return. This return flow "travels" over artificial links, which must be incorporated into the data base to provide continuity. These artificial links can also be used to control forward tonnage flow in several ways, as outlined in this section.

The following artificial links are required:

1) A network with only one point of origin and one destination for tonnage flow requires a single artificial link from the destination to the origin.

2) If there are several points of origin, each must be connected to a common simulated point of origin by an artificial link or chain of links.

3) Artificial links must connect all actual destinations to a simulated destination. A single artificial link from the common destination to the common origin is always required. In current versions of the model, it is referred to as the universal link (UNIVER).

 Capacities and Minimum Flow Requirements

Universal Link. A capacity constraint on UNIVER restricts total flow through the network to this maximum. If the requirement for cargo delivered to destination points in the network is less than network physical capacity, the requirement in tons per day can be input as the original capacity of the universal link. The resulting flow patterns and network costs will then be applicable to this required tonnage, rather than to maximum network capacity. Attack allocations will be based on increases in transportation and repair cost, unless a single attack can reduce network capacity below the capacity input for UNIVER. When, as in many networks, the lowest-cost links are also those with highest capacity, the model tends to allocate attacks against these links on a cost-increase basis until their capacities have been
sufficiently reduced to impose a constraint on network flow. It then bases further attack allocations on the criterion of reductions of flow.

Links from Simulated Common Origin to Individual Points of Origin. The user may also set a capacity limit on flow from the simulated common origin to an individual origin. This has the effect of limiting the tonnage that can flow from this actual point of origin to other points in the network. This method can be used to simulate a limited load-and-dispatch capacity at an originating depot or warehouse, or to allow for limitations on the flow of goods in a section of the transportation system excluded from the model data base.

A minimum-flow requirement can be imposed, but is useful only in special circumstances; for example, when tonnage moving through the system must include cargo of a type available at only one point of origin. Then the artificial link leading from the simulated common origin to this actual point of origin can have imposed on it a minimum flow requirement equal to the daily requirement for this particular type of cargo.

It is possible to use two or more artificial links in a chain; this permits placing requirements or limitations on tonnage flow from groups of actual points of origin.

Links From Individual Destinations to the Common Destination. Capacity constraints and minimum flow requirements can be imposed on links at the destination end of the network to distribute tonnage among the several actual destinations, and to counteract the model's tendency to send the maximum tonnage flow to those destinations which can be reached at the lowest transportation cost. The values to be used for capacity and minimum flow can be chosen from the parameters of the physical network. For example, capacity may be chosen to reflect the ability of the destination unit to receive and store supplies; minimum flow may be imposed to represent daily requirements. It is also possible to use arbitrarily selected values to prevent concentration of deliveries at one or two destinations having low-cost access routes.

Transportation of supplies used at intermediate points in the network can be treated by using an artificial link from each intermediate
point of consumption to the simulated common destination. Inputs are selected so as to force a fixed level of flow over each such artificial link. One method of selecting inputs is to use consumption at the intermediate point as the artificial link's capacity and its minimum flow requirement. The day's attacks will then stop whenever the minimum flow requirement cannot be met at any destination or at any intermediate consumption point. The capacities of such artificial links can also be set to consumption requirements, with the minimum flow requirements equal to zero, and each artificial link assigned a high negative cost. The flow over each artificial link will then be as great as the condition of the remainder of the network permits whenever full-capacity flow (representing desired deliveries for consumption) is not possible. Supplies for intermediate consumption must be specified in tons per day, not in fractions (or percentages) of the total network flow.

Other Characteristics

Artificial links are not vulnerable to attack. Thus, attack success probabilities for these should be entered as zero. Damaged link capacity, damaged link cost, repair time and repair cost have no significance for an artificial link and can be omitted from the data deck.

MINIMUM FLOW REQUIREMENTS ON REAL LINKS

The model permits establishment of a minimum flow requirement on any real link. This is not usually done, as there is no reason for the receiving unit to be concerned with the route over which the cargo it receives is moved. If desired, minimum flows could be imposed either to reflect a physical situation or to permit combination of a real and an artificial link into one, so as to reduce the size of the data deck.

CONTROL CARD INPUTS

The number of attacks per day and the number of days in the campaign to be run are specified in the control card. The model will follow this except when no link is worth attacking, for instance when
all links have been destroyed. In this case, it will skip to the next
day, restore any newly repaired links to their pre-attack character-
istics and resume the attack allocation sequence.

Two optional additions to the output are selected by appropriate
control card entries: (1) "Profiles" showing network transportation
costs for flows below maximum; and, (2) listings of current network
states, characteristics and flow for each link. The nature and use
of these output features are explained in Sec. VII. Control card
entries for the profile option include the number of "profile points"
(intermediate levels of flow) for which costs are to be computed and
tabulated, and whether these tables are to appear after each attack,
or only at the beginning of each day and at the end of the campaign.
The control card entry for network status printouts specifies whether
these detailed listings appear after each attack, at the beginning of
each day and the end of the campaign, or not at all.

Control cards also include an entry to specify the security classi-
fication to be printed on each page of the printout.

The Hq USAF version of the model was modified in late 1968 to
accept coded inputs for attack success probability. Data cards for
individual links contain a one-digit code; the success probability
corresponding to these codes is entered on a second control card.
This permits changing the attack success probability for an entire
group of links by a single change to the data deck rather than by
changing individual cards for all affected links. This makes it
easier to analyze the results of changes in weapon types, delivery
accuracy, and similar parameters incorporated in attack success proba-
bility inputs. Other changes in control card format are likely when
runs are made on different computers.
VII. MODEL RESULTS

OUTPUT

The LOC Interdiction Model provides a list of targets selected for attack, in order of preference, for the number of days and number of attacks per day specified by the user. After each attack, the model output shows maximum possible flow through the network, transportation cost of this flow, using the minimum-cost route pattern, and cumulative repair costs incurred to date. This maximum flow computation is based on current expected characteristics of links in the network, together with any capacity constraints the user has imposed on artificial links, as discussed in the previous section. Flow and cost information is also given at the beginning of each operating day, at the time repaired links are restored to their original characteristics.

If the "profile" option has been requested on the control card, the output will also include tables showing transportation costs for moving less than the maximum level of supplies through the network. The number of entries in each of these tables is set by the number of "profile points" specified on the control card. If three profile points are specified, each table will show costs of moving one-third and two-thirds of the maximum level of flow. The cost for each intermediate level of flow is computed for the least-cost routing of that tonnage through the network. This feature allows the user to estimate the tonnage that can be moved for a given transportation cost. It also permits estimating the costs of below-maximum flows, indicating the extent to which costs per ton rise as more tons are moved through the network, efficient routes become used to capacity, and secondary routes may be utilized for the excess. Costs shown do not include those transport system costs which are independent of traffic flows and must be generated outside the model.

Optional printout of characteristics and flows for each individual link permits the user to see which routes the model is selecting, and to trace the effects of attacks on the traffic routing pattern. Several variations of this network status request are available, as
full network status printouts require much printing time for a large network and provide more data than can be analyzed easily. This is also true of the profile subroutine. A printout that shows profiles after every cut and the full network status for each profile point is unmanageable for all but the smallest networks. A printout of the full network status at the beginning or end of each day can be quite useful in campaign-analysis; anything more detailed is likely to be unnecessary, except for debugging and demonstration. One modification helpful in network status printouts is to print data for each link only at the beginning of the campaign, and thereafter show only those links which are currently carrying supplies.

The designator and terminal points of an attacked link, the changes to the characteristics of this link, and the new network flow and cost totals are given for each attack, whether or not full network status is requested.

SIGNIFICANCE AND LIMITATIONS

The Attack Sequence

The attack plan is not likely to represent the best possible allocation of the attack effort, because the model works with one attack at a time, and successive optimal assignments of single attacks do not necessarily lead to the optimal overall attack allocation.

Analysis of the model's strike allocations and their resulting flow and cost changes may help the user generate a strike plan superior to the model-generated allocations. The model can be used to compute the results of a user-generated strike allocation and to extend the campaign by allocating additional strikes, but at present this can be done only by changing the original link inputs.

The Expected-Value Approach

Link characteristics as shown in the model output after an attack do not exactly parallel the actual situation during a campaign in which some attacks have been successful and some not. Rather, they
are expected values, generated by the application of attack success probabilities to the input original and damaged link characteristics. The model generates a continuous estimate of the average target and transportation situation during a long, steady-state campaign. It does not purport to give an actual situation report for any given day. However, the results should closely approximate the total of real targets damaged and actual reductions in supply tonnage flow over the period.

The montecarlo approach to this situation would use random numbers to determine which strikes were successful on the basis of the input attack success probabilities. This method was rejected primarily because repeated runs are needed to determine a distribution of results. Even without this limitation, the montecarlo method is less attractive than it at first appeared. In the real world, tonnage takes several days to move through the network. During this time, links will be attacked and damaged, repaired, attacked and missed, reattacked and damaged, and be open for traffic for a time period that is reasonably well represented by "expected values." A road passable one-tenth of the time during the interdiction campaign can pass at least one-tenth of its normal tonnage capacity. This is true whether or not other roads in the network happen to be closed on the days that the road in question is open.

The user of this model can explore the implications of the expected-value approach by making a series of hand montecarlo runs of the model-generated attack plan and seeing which routes are open and what network capacity is available after the attacks. This requires that the user decide whether or not the attacks on each link in the first day's attack plan were successful. The user applies the cumulative success probability for the number of attacks the model has allocated against that link to determine whether or not the link has been successfully attacked. Dice or a table of random numbers may be used.

Tonnage flow over the resulting network can be determined by hand; or, if the network is complex or transportation flow costs are desired, the input data cards may be changed for links successfully attacked. If network flow is estimated without using the model, it is not difficult
to simulate tonnage movement over undamaged portions of the network toward the destination, even when routes are not open over their entire lengths. Results from montecarlo campaigns are variable; different results can be expected from each run, even though inputs are identical.

Input Data

Whether or not a computer model is used, any analysis is vulnerable to data errors and omissions. Capacity estimates, damaged link characteristics, repair times and repair costs are based on reconnaissance information, which can become obsolete. Transportation costs depend partly on link characteristics and partly on operating policies which are not always well known. Also, attack success probabilities are estimates. Significant changes in transportation capabilities can result from the construction of new links or from improvements to the defenses or bypasses on old links. Consequently, an old data base can be quite misleading.

Certain link characteristics are variables, but must nevertheless be input as constants. This cannot be cured by improvements in intelligence collection and processing:

The repair process is an example; the model restores each link to its original characteristics in one step when the repair time has expired. In practice, the link may be gradually improved (see Sec. IV).

Link costs (the costs of moving a unit of cargo over the link) are considered as independent of link capacity and the number of units of cargo moved. No allowance is made for possible changes in unit cost, for example, an increase in cost because of the congestion that would accompany near-capacity operation.

Occasionally tonnage flow can exceed the normal steady-state link capacity for a day or two. One of the factors used in computing capacity is that the road must be released for maintenance part of the time.

This need not be the same number of hours each calendar day, however.

Also, attack success probabilities are not the same for different types of aircraft. It is possible to adjust for this factor by changing the size of the attack unit, sending more aircraft per attack when the aircraft are less accurate, or carrying fewer bombs.
These factors all require careful selection of inputs reflecting average or typical conditions, rather than inputs representing an ideal or extreme situation.

Model Simplifications

The model's simplified view of the real world is discussed in Sec. III. Certain conventions are invented and substituted for some real world values. They are assumed to apply to all times. The following are examples:

1) Repair policy must be predetermined for each link. The model admits only two possibilities: always repair the link (which is the usual approach) or never repair the link. Links that are not to be repaired may arbitrarily be assigned a repair time longer than the duration of the campaign and zero repair cost. Unfortunately this may distort the attack allocation sequence, but this is unavoidable if it is desired to include unrepaired links. The model cannot select which links should be repaired and which should be left in damaged condition after attack.

2) The model considers each link to be vulnerable at only one point. Additional attacks against it are useful only in that they increase the probability that this critical target has been successfully attacked. The model does not provide for damage that would make bypassing the target more difficult, or increase the time and cost of repair, such as cratering several areas, damaging more than one bridge, or damaging two piers of the same bridge.

3) Link cost and link repair computations outlined in Sec. IV assume that truck drivers, loading and unloading crews and repair crews will be usefully employed on other tasks when their efforts are not needed on their usual transportation system jobs. For instance, when the roads are blocked, truck drivers may perform maintenance on their vehicles, or drive over another road link. Similarly, porters and bridge repair workers originally recruited from other labor forces are returned to their jobs. Although this assumption was input to the North Vietnamese data base, alternate labor allocations might be realistic for other situations. For example, bridge repair crews might be assumed to sit idle on standby
status between repair jobs. In this event, an attack does not increase link manpower requirements, and the repair manpower is treated as a fixed cost, accumulated by means other than the model.

4) The model allocates transportation and repair manpower on the assumption that vehicles and personnel can be made available as needed; it has no provision for introducing limitations on either personnel or vehicles. Costs and tonnage flow for individual links may be examined in the model output to estimate whether resource limits have been exceeded.

5) Cargo is treated simply as tonnage, with no concern for cargo priorities, or for shortages of certain items when the transportation system is constrained by link damage.

Factors Excluded

Some components of transportation activity and cost and some cost items of the interdiction campaign are completely outside the scope of this model. These include:

1) Attrition of our attack aircraft.
2) Alternative interdiction strategies, such as attacks on vehicles.
3) Delays in the enemy's on-the-ground command and control of transportation vehicles.
4) Deterioration, as the campaign progresses, of the enemy's command and control system for vehicle dispatching, vehicle repair, and personnel allocation.
5) Limitations on the supply of our preferred interdiction weapons (unless these are the only weapons used and this supply limits the number of attacks in the campaign).
6) Fixed costs of the enemy's transportation system, which are independent of tonnage moved and repairs made.

Factors Requiring Indirect or Partial Consideration

Several important elements of the ground transportation system and the interdiction campaign can be considered by the model user, but cannot be treated directly as model inputs.
1) The contribution to transportation cost of the supplies consumed by the transportation system (fuel, repair parts, and food for drivers) can be taken into account in two ways, neither entirely satisfactory: a) A fixed tonnage can be caused to flow from its point of origin to each of several intermediate points (see Sec. VI); b) costs may be increased and the capacities of certain links in the network's rear area decreased to reflect that the flow moving forward from that area is accompanied by the supplies needed enroute.

2) The model ignores all costs that cannot be converted to man-days-per-ton of flow, or to man-days for repairs. The number of routine road maintenance personnel must be treated either as a function of tonnage flow or as a fixed quantity independent of the utilization of the roads. If an unused road is to be kept open for emergencies some personnel must be assigned to its maintenance. Road surface repairs are made necessary by weather (independent of road use), wear and tear (in proportion to tonnage flow) and damage from attack (covered in computed link repair costs). It is not certain that all personnel requirements can be absorbed into the data base by these means.

3) Harassment of repair crews by direct attack during the repair period or by delayed-action weapons may prove useful to us. It is not considered by the model, but additional model runs can be made to evaluate such tactics. To do this, link repair times must be increased. Also, the number of attacks per day can be reduced to simulate the diversion of some sorties to strafing or bombing the repair crews. A substitution of delayed-action antipersonnel weapons for some of the ordnance directed at bridges or road surfaces can be treated in the model by a proportionate reduction in attack success probability.

4) Weather can be treated in several different ways. Variations between wet and dry seasons affect both the attack capabilities and the road network. These can best be handled by using separate data bases. Periods of bad weather that prevent attacks for less than a full day can be handled by reducing the attack success probability, multiplying this by the predicted probability that an attack will arrive on the target during a period when weather is good enough for delivery of ordnance. This assumes that attacks frustrated by bad weather at
the target are wasted, rather than reassigned to targets where weather is good, or made up on the next day of good weather. The model cannot handle a situation in which long periods of bad weather prevent interdiction attacks on a link when repairs are completed and traffic resumed.
VIII. QUESTIONS ANSWERED

DIRECT QUESTIONS OF FLOW AND COST

Within the limitations discussed in the previous sections, the LOC Interdiction Model will produce direct answers to such questions as the following:

- What is the average tonnage that can be moved over a ground transportation system in the face of a long-term steady state campaign directed against fixed, physical transportation facilities? How much will be cost the system to move this tonnage, in total and portion?
- What are the system transportation costs involved in maintaining any lower level of flow under the above conditions?

The answers to the above can be combined with the user's knowledge or hypotheses about enemy requirements and available manpower resources to answer other questions. Two of these are:

- What are the sortie requirements for an interdiction campaign that will reduce maximum tonnage flow to a level where enemy requirements cannot be met?
- What are the sortie requirements for an interdiction campaign that will increase the manpower requirements for transportation beyond those the enemy can meet?

Answers must be carefully interpreted in the light of the discussions of Sec. VII, since some of the model limitations can produce a distorted picture and some aspects and costs of transportation and interdiction are not covered.

COMPARATIVE CAMPAIGNS

The data provided by the LOC Interdiction Model are an aid to planning a specific type of campaign against the flow of enemy supplies. These data can be compared to those for alternate types of campaigns as a guide to their relative effectiveness. Three such alternate campaigns are vehicle-kill, search and destruction of supplies stored in the combat area after their transportation forward, and the
emplacement of some kind of physical barrier across enemy lines of communication. Evaluation of these alternative campaigns must rely on tools other than the LOC Interdiction Model.

CHANGES IN ATTACK CAPABILITIES

The effects of possible changes in strategy, tactics and weapons can be investigated by additional runs, if appropriate changes are made in the data base. The simplest such case would be a change in the number of attacks launched per day. Most other cases involve changes in the characteristics of individual links.

1) Attack success probability can be increased so that it incorporates the effects of potential or desired improvements in delivery accuracy, weapon effects radius, or the capability to attack successfully in unfavorable weather.

2) Repair costs and repair times can be increased so as to test the effect of alternate weapons that inflict greater damage to the target, or that lengthen repair time by keeping repair crews out of the target area until such delayed effect weapons have been removed, or have had time to detonate.

3) Capacity and cost values can be prepared for two situations: one permitting travel at any time and the other permitting travel only during darkness. This would permit measuring the effectiveness of a vehicle-killing program that is highly effective, but only in daylight hours.

4) Link costs can be increased to cover the added labor and lost truck time when trucks or their cargoes must be concealed during daylight.

5) Different targeting strategies can be compared if separate sets of inputs are prepared for each, with different damaged link capacities and costs, as well as different repair times and repair costs. Three examples are to attack bridges where possible, and try to crater roads only on links without bridges; to attack bridges only, and leave other links alone; to ignore bridges, and keep roads cratered.
Model runs can also be made to determine the effects on the network of increasing the demands on all or a part of the transportation system by means of military operations which require enemy combat forces to consume more supplies.

**CHANGES IN ENEMY CAPABILITIES AND OPERATIONS**

The enemy ground transportation system is also subject to change, particularly in response to an interdiction campaign. Additional model runs can be used to evaluate the impact of possible enemy responses:

1) New links may be added, and existing links may be improved, leading to increased capacity, reduced cost, and perhaps different damaged link characteristics and repair parameters.

2) Links may be made less vulnerable by constructing bypasses, prepositioning repair materials and equipment and keeping, as standby, alternate crossing facilities like vehicular ferries. Some of these measures will increase damaged link capacity or reduce damaged link cost. Others will reduce repair cost and repair time.

3) Defenses against air attack may be provided or improved, either throughout the area or at certain critical points. This may cause weapon delivery tactics to be changed, with possible reduction in attack success probability. Some aircraft may be diverted for weapons delivery against defense, flak-suppression, or electronic countermeasures, fighter cover and the like. Such factors can be handled by reducing attack success probability or, if the countermeasures are necessary in all parts of the network, by reducing the number of attacks sent against the transportation system. Links with strong point defenses which are infeasible or excessively costly to attack may be artificially treated as invulnerable (success probability of zero) or vulnerable only to road cratering.

Enemy demands for delivery of supplies to certain destinations may also be changed, as can his total requirements.