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THE ECONOMIC CHOICE OF THE TRANSPORTATION ROUTES FOR LOGISTICS MATERIELS

by

Kim, Sook Han

March, 1991

Thesis Advisor: Richard E. Rosenthal

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THE ECONOMIC CHOICE OF THE TRANSPORTATION ROUTES FOR LOGISTICS MATERIELS

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ABSTRACT

Light Vehicle Battalions are used to transport logistic materiels from supply depots to combat units, on orders from high level logistics command. This thesis develops a linear programming model to determine which LVB should take which route, how much materiel it should carry, and within what specific time it should travel to minimize transportation and storage costs. The linear programming model is derived from a peacetime scenario where each combat unit's demand varies seasonly. We report computational experience on a realistic problem using GAMS (the General Algebraic Modeling System).

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I. INTRODUCTION

A. INTRODUCTION AND MOTIVATION

Following orders from the Logistics Support Headquarters (LSHQ), the Light Vehicle Battalion (LVB) transports requested logistics materiels stored in supply depots to combat units. In order to provide the requested service, there are many possible routes available to the LVB. It is the duty of the LSHQ logistics staff officers to determine both the routes to be taken and the number of trucks to be used. Currently, the LSHQ's method of scheduling trucks and routes is based solely on past experience.

This thesis provides a linear programming model developed with GAMS (The General Algebraic Modeling System) [Ref. 1], as an aid to the Logistics Support Headquarters (LSHQ). The developed model is introduced to select the most economical transportation routes under various constraints.

B. SCENARIO

The model developed in this thesis is demonstrated on a realistic problem derived from personal experience. Based on this experience, values are estimated for the amount of available logistics materiels stored at supply depots, the amount of logistics materiels requested by combat units, and the number of available LVB trucks. In addition to these

quantities, we also estimate the storage cost for supply depots, intermediate supply points (ISPs), and combat units. All transportation and movement costs are derived from the field manual U.S. FM 101-10-1 [Ref. 4].

C. PREVIOUS STUDIES

Two optimization approaches ([Ref. 7], [Ref. 9]) similar to this research have been performed. They are summarized in Table 1 where the contribution of this thesis is also demonstrated.

TABLE 1. SUMMARY OF PAST OPTIMIZATION APPROACHES

	Korea	U.S.	This Thesis
Purpose	Decide economic emplacement of supply depot	Find the best location of ammunition distribution point	Find economic transportati -on routes
Scale	Battalion	Corps	Battalion
Condition	War	War	Peace
Important Constraints	Capability of battalions	Capability of points and reliability of each area	Transport ng period ar Road conditions
Data	Estimated	Estimated	Estimated
Tool	Fortran	GAMS	GAMS
Objective	Min distance	Max utility	Min cost
Year	1988	1987	1990

D. OUTLINE

This thesis presents a mathematical model which minimizes the LVB's cost of providing service. Chapter II more fully introduces the LVB transportation system. Chapter III presents our mathematical models and estimated data. Computational experience with the model is discussed in Chapter IV. Finally, conclusions are offered in Chapter V.

II. LIGHT VEHICLE BATTALION (LVB) TRANSPORTATION SYSTEM

A. COMMAND FLOW FROM LOGISTICS SUPPORT HEADQUARTERS TO LVB

1. Combat Unit Request Procedure

In order to sustain combat readiness, combat units generally make yearly requests to Logistics Support Headquarters (LSHQ) for logistics materiels which are then allocated on a quarterly basis. The logistics requirements may change from time to time, sometimes even within the same year because of the introduction of a new weapon system, new tactics, or the occurrence of unexpected exercises or catastrophes. At the end of each quarter, unconsumed materiels are kept by the combat units. Storage facilities are readily available at a price.

2. Logistics Support Headquarters Order Procedure

Logistics Support Headquarters (LSHQ) quarterly sends required logistics materiels, which are stored at supply depots, to various combat units using the Light Vehicle Battalions (LVBs). As previously stated, the LVB's delivery schedule is planned by the LSHQ logistics staff officer.

When developing the delivery schedule, the LSHQ logistics staff officer considers: the number of available vehicles in each LVB, the distance from each combat unit to each LVB, safety factors, and time. While restricted by these

factors, the LSHQ logistics staff officer seeks to minimize storage and transportation costs.

The above procedure is summarized as a flow chart shown in Figure 1. [Ref. 6]

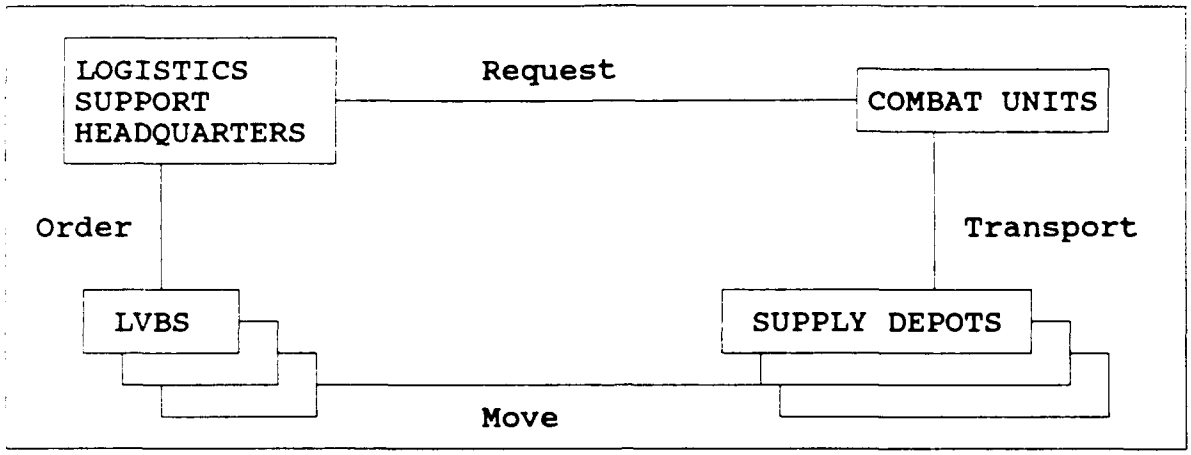

Figure 1. Logistics Support Headquarter's order procedure.

B. ORGANIZATION OF LIGHT VEHICLE BATTALION

According to the LSHQ transportation plan, the LVB battalion headquarters has various LVCs (Light Vehicle Companies) under their control. Within battalion headquarters, there are three staff sections: the Operations section, the Manpower and Management section, and the Logistics section. The operations section is involved directly in transportation operations and training soldiers to drive and fight. The Manpower and Management section takes care of all transportation documents for the LVB. The Logistics section is responsible for the logistics materiels

within the LVB. The LVB's organization is shown in Figure 2. [Ref. 6]

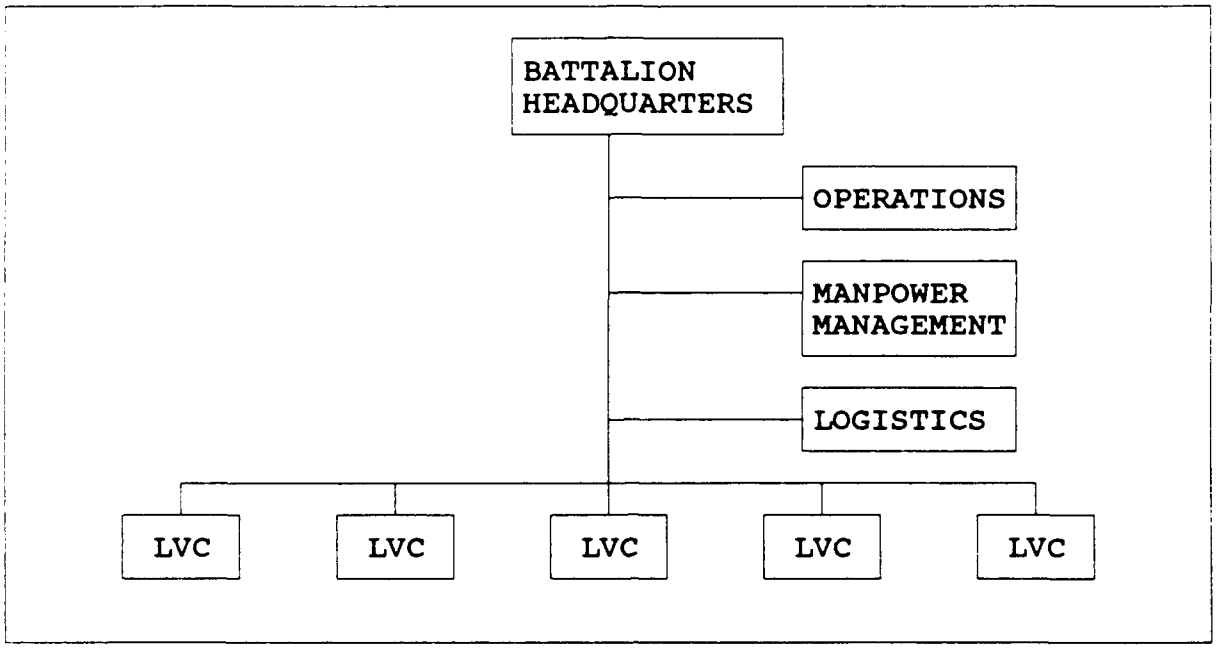

Figure 2. LVB Organization.

C. COMMAND FLOW FROM THE LVB TO LVCs

According to LSHQ transportation requirements, the LVB schedules the LVCs. To obtain LVC schedule the LVB's operations staff officer considers the number of available vehicles, conditions of the vehicles, the workload, driver availability, and standing commitments. In practice, it is desirable to have workloads evenly distributed among various LVCs.

D. TRANSPORTATION OF LVC

Every LVB transportation mission is performed by LVCs. After consulting the maintenance officer and platoon leader, the LVC commander determines whether or not he can perform the transportation mission and notifies the LVB operation's officer. If the commander undertakes a transportation mission, he orders the maintenance officer and platoon leader to prepare the number of vehicles predetermined by the LVB operations officer.

There are two kinds of transportation, i.e. direct and indirect. If the LVB transports materiels to combat units without using an intermediate supply point (ISP), this is called direct transportation. On the other hand, if the LVB uses an ISP, this is considered indirect transportation. When direct transportation is difficult, the LSHQ logistics staff officer could order the LVBs to transport materiels only to an ISP and then order the ISP to transport them to combat units. It is assumed that each ISP has sufficient storage and transportation capability for any mission.

In direct transportation, the LVC loads materiels at supply depots. Usually, the supply depots are located near the LVBs. In general, the supply depots have enough materiels to meet any combat unit requirements and they also have enough manpower to load materiels.

Supply depots get orders from LSHQ at the same time as the LVB. They therefore separately prepare for requested

logistics. The flow chart of the relationship among LSHQ, LVBs, supply depots, ISPs, and combat units is shown in Figure 3. [Ref. 6]

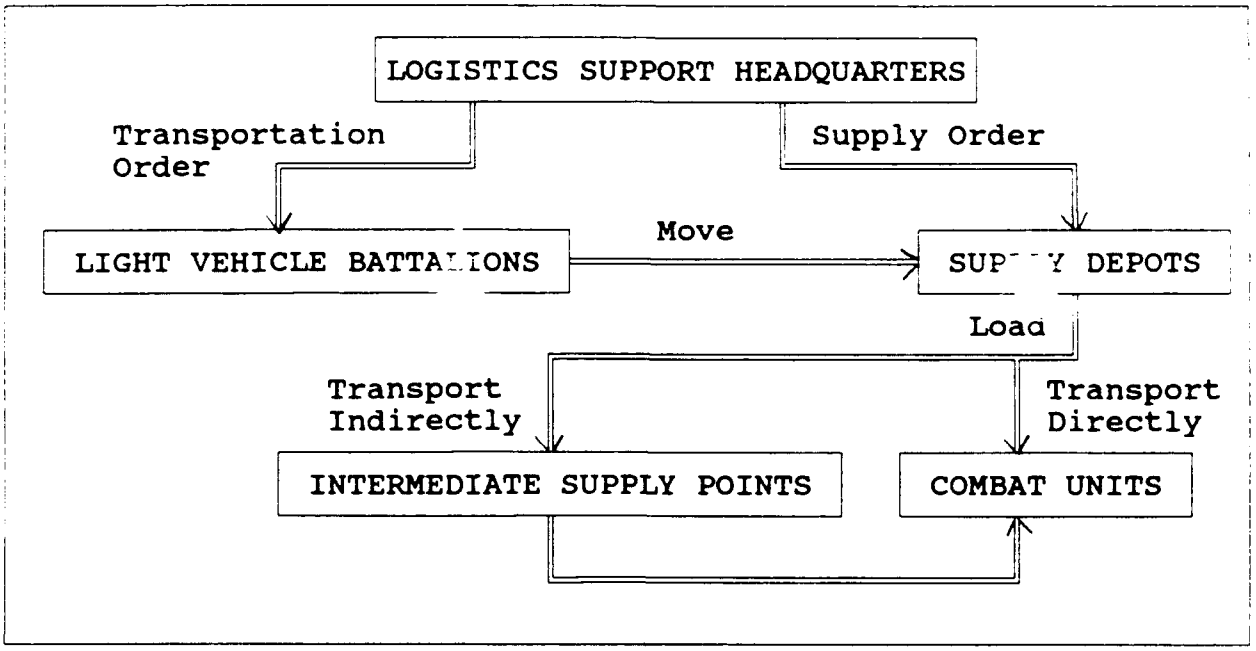

Figure 3. Relationship among LSHQ, LVBs, supply depots, ISPs, and combat units.

E. DISCUSSION

1. Cost Minimization in Peace Time

It's desirable to meet combat units' requests as soon as possible, but resources (fuel, oil, trucks etc.) are limited. Especially in peace time, cost is an important consideration. To minimize cost, the LSHQ logistics staff officers have to select the appropriate LVB, the route to take, the amount of logistics materiels to order, and the appropriate time period.

2. Linear Programming (LP) Approach

Today, the approach taken by the logistics officer is based more on judgment and experience than on any scientific principle. Since this could easily provide suboptimal planning, a linear programming (LP) model is developed to aid the logistics officer's planning. The LP formulation considers combat units' demand, available supplies at supply depots, LVBs' transportation capabilities, storage capabilities at supply depots, ISPs, and combat units, and all possible routes among LVBs, ISPs, and combat units. GAMS, the General Algebraic Modeling System [Ref. 1], is adopted to implement this formulation.

III. MODEL DEVELOPMENT AND FORMULATIONS

A. SCENARIO

1. Specific Scenario

This is a description of the scenario for which the LP model has been developed. There are two LVBs, LVB1 and LVB2, in area ALPHA. They support three combat units COM1, COM2, and COM3, located in area BETA. There are also two ISPs, ISP1, and ISP2, between the LVBs and the combat units (Figure 4 exhibits this scenario). We allow the LVBs to transport materiels directly or indirectly. The planning horizon for our model is one year.

Because some routes may be closed due to heavy rain, snow, or frozen ground, logistics officers must be able to adjust their decision-making based on these variable factors. We therefore conduct a number of runs where certain routes are closed. This allows us to further demonstrate how our models can benefit the LSHQ logistics staff officer.

2. Data Assumptions

Based on past data, realistic amounts of available logistics materiels in each supply depot and the quantity requested from each combat unit was estimated. The transportation costs and the movement costs were determined using U.S. FM 101-10-1 [Ref. 4]. Combat units demand was

given in 2.5-ton units, or equivalently the number of trucks. The cost of all logistics materiels was given in U.S. dollars. The amount of available logistics materiels in the three supply depots is listed in Table 2.1. The amount of logistics materiels requested from the three combat units is listed in Table 2.2.

LVBs incur movement costs when transporting empty vehicles to supply depots. The estimated cost of moving each LVB to each supply depot is shown in Table 3.1. We determined the cost as follows: The distance (in km) between each LVB and each supply depot is multiplied by 0.11 (gallons/km) to derive the amount of gas consumed. The result is then multiple 1.05 (dollars/gallon).

LVBs incur transportation costs when they transport requested logistics materiels to ISPs or combat units. The costs of transporting materiels from each supply depot to each ISP, from each supply depot to each combat unit, and from each ISP to each combat unit, are estimated in Tables 3.2.1, 3.2.2, and 3.2.3 respectively. The method used to calculate these values is as follows: The distance (in km) between locations is multiplied by 0.1305 (gallon/km) and then multiplied by 1.05 (dollar/gallon).

Each supply depot, ISP, and combat unit has its own storage space and associated storage costs. Estimated storage costs for supply depots are in Table 3.3. The storage costs for ISPs and combat units are derived by multiplying the

supply depot's storage cost by 0.9 and 0.81, respectively. All storage costs are assumed to include the cost of building maintenance, managers, guards, and materiel losses. The fixed administration and guard costs are respectively determined as the number of administrators multiplied by 3 (dollars/person) and the number of guards multiplied by 2 (dollars/guard).

The cost of building maintenance and losses are allowed to vary from season to season. The costs of a materiel's loss or malfunction are estimated by summing the costs of the associated administrators plus the costs of building maintenance plus the costs of guards, multiplied by the materiel's loss rate.

The number of trucks available at each LVB in each period is listed in Table 4.

The result of this study depends on the numeric data used. This input can always be modified by potential users.

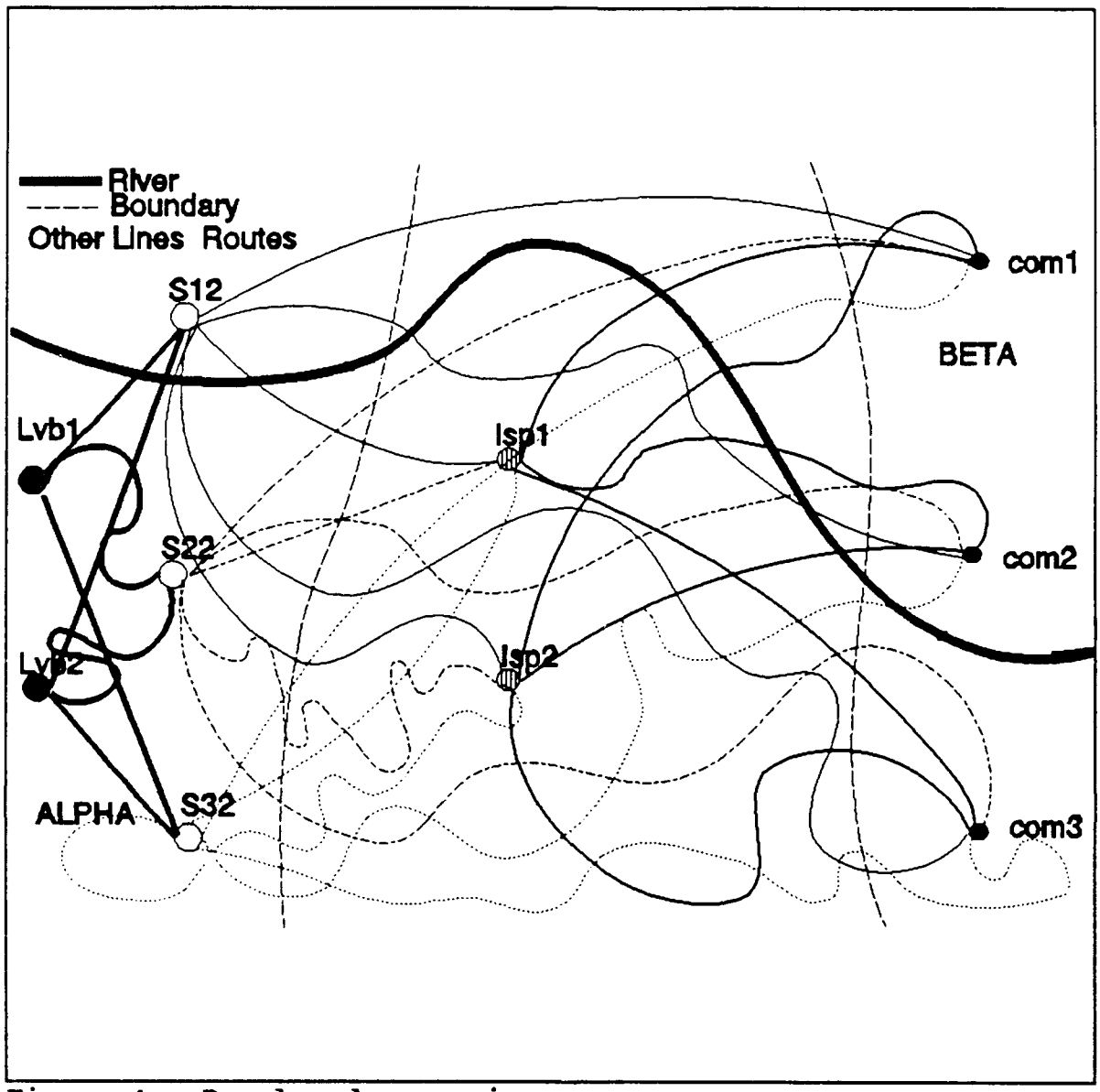

Figure 4. Developed scenario

[KEY : CEM = cement, AMM = ammunition, EX = exchange-items,
WP = weapon, MM = medical materiels, RP = repair-parts,
NP = non-military programs]

TABLE 2.1. AVAILABLE LOGISTIC MATERIELS AT SUPPLY DEPOTS.

	SPRING	SUMMER	FALL	WINTER
S12 - FOOD	22	33	25	39
S12 - CLOTH	27	44	57	28
S12 - OIL	22	29	13	75
S12 - CEM	22	33	25	39
S12 - AMM	27	44	57	28
S12 - EX	22	33	25	39
S12 - WP	27	44	57	28
S12 - MM	22	29	13	75
S12 - RP	22	33	25	39
S12 - NP	27	44	57	28
S22 - FOOD	83	44	25	37
S22 - CLOTH	52	13	24	65
S22 - OIL	32	42	31	16
S22 - CEM	83	44	25	37
S22 - AMM	52	13	24	65
S22 - EX	3	44	25	37
S22 - WP	52	13	24	65
S22 - MM	32	42	31	16
S22 - RP	83	44	25	37
S22 - NP	52	13	24	65
S32 - FOOD	32	23	15	15
S32 - CLOTH	43	72	91	34
S32 - OIL	50	63	52	87
S32 - CEM	32	23	15	15
S32 - AMM	43	72	91	34

S32 - EX	32	23	15	15
S32 - WP	43	72	91	34
S32 - MM	50	63	52	87
S32 - RP	32	23	15	15
S32 - NP	43	72	91	34

TABLE 2.2. COMBAT UNITS' LOGISTIC MATERIELS REQUEST.

	SPRING	SUMMER	FALL	WINTER
COM1 - FOOD	10	20	25	20
COM1 - CLOTH	20	25	33	23
COM1 - OIL	22	13	10	25
COM1 - CEM	10	20	25	20
COM1 - AMM	20	25	33	23
COM1 - EX	10	20	25	20
COM1 - WP	20	25	33	23
COM1 - MM	22	13	10	25
COM1 - RP	10	20	25	20
COM1 - NP	20	25	33	23
COM2 - FOOD	10	20	25	20
COM2 - CLOTH	20	25	33	23
COM2 - OIL	22	13	10	25
COM2 - CEM	10	20	25	20
COM2 - AMM	20	25	33	23
COM2 - EX	10	20	25	20
COM2 - WP	20	25	33	23
COM2 - MM	22	13	10	25
COM2 - RP	10	20	25	20
COM2 - NP	20	25	33	23
COM3 - FOOD	10	20	25	20
COM3 - CLOTH	20	25	33	23

COM3 - OIL	22	13	10	25
COM3 - CEM	10	20	25	20
COM3 - AMM	20	25	33	23
COM3 - EX	10	20	25	20
COM3 - WP	20	25	33	23
COM3 - MM	22	13	10	25
COM3 - RP	10	20	25	20
COM3 - NP	20	25	33	23

[Key : DIS = distance, GAL = gallon]

TABLE 3.1. MOVEMENT COST : LVBs TO SUPPLY DEPOTS.

	S12			S22			S32		
	DIS	GAL	COST	DIS	GAL	COST	DIS	GAL	COST
LVB1	.5	.055	.058	1	.110	.116	0.75	.098	.100
LVB2	1	.110	.116	.5	.055	.058	0.75	.098	.100

TABLE 3.2.1. TRANSPORTATION COST : SUPPLY DEPOTS TO ISPs.

	ISP1			ISP2		
	DIS	GAL	COST	IS	GAL	COST
S12	17.5	2.28	2.39	35	4.57	4.80
S22	16.5	2.15	2.26	40	5.22	5.48
S32	14.5	1.89	1.98	43	5.61	5.89

TABLE 3.2.2. TRANSPORTATION COST : SUPPLY DEPOTS TO COMBAT UNITS.

	COM1			COM2			COM3		
	DIS	GAL	COST	DIS	GAL	COST	DIS	GAL	COST
S12	35	4.57	4.80	57	7.44	7.81	75	9.79	10.28
S22	42	5.48	5.75	56	7.31	7.68	68	8.87	9.31
S32	47	6.13	6.44	55	7.18	7.54		7.44	7.81

TABLE 3.2.3. TRANSPORTATION COST : ISPs TO COMBAT UNITS.

	COM1			COM2			COM3		
	DIS	GAL	COST	DIS	GAL	COST	DIS	GAL	COST
ISP1	17.5	2.28	2.39	35	4.56	4.79	50	6.52	6.85
ISP2	32.5	4.24	4.45	20	2.61	2.74	25	3.26	3.26

[KEY : SPR = spring, SUM = summer, WIN = winter,
MAINT = maintenance, TCOS = total cost]

TABLE 3.3. STORAGE COSTS FOR SUPPLY DEPOTS.

		MANAGEMENT PERSONNEL		BUILD ING-MAINT	GUARDS		LOSS		TCOS
		#	$	COST	#	$	RATE	$	$
FOOD	SPR	1	3	0.3	1.0	2	0.01	0.053	5.35
	SUM	2	6	0.4	1.0	2	0.02	0.168	8.57
	FALL	1	3	0.3	1.0	2	0.01	0.053	5.35
	WIN	2	6	0.5	1.0	2	0.02	0.170	8.67
CLOTH	SPR	1	3	0.3	1.0	2	0.01	0.053	5.35
	SUM	1	3	0.4	1.0	2	0.02	0.108	5.51
	FALL	1	3	0.3	1.0	2	0.01	0.053	5.35
	WIN	1	3	0.5	1.0	2	0.01	0.055	5.56
OIL	SPR	1	3	0.3	1.0	2	0.01	0.053	5.35
	SUM	2	6	0.4	1.0	2	0.01	0.084	8.48
	FALL	1	3	0.3	1.0	2	0.01	0.053	5.35
	WIN	2	6	0.5	1.0	2	0.01	0.085	8.59
CEM	SPR	1	3	0.2	1.0	2	0.01	0.052	5.25
	SUM	1	3	0.2	1.0	2	0.01	0.052	5.25
	FALL	1	3	0.2	1.0	2	0.01	0.052	5.25
	WIN	1	3	0.2	1.0	2	0.01	0.052	5.25
AMM	SPR	2	6	0.3	1.5	3	0.02	0.186	9.49

	SUM	2	6	0.4	1.5	3	0.02	0.188	9.59
	FALL	2	6	0.3	1.5	3	0.02	0.186	9.49
	WIN	2	6	0.5	1.5	3	0.02	0.190	9.69
EX	SPR	1	3	0.1	1.0	2	0.01	0.051	5.15
	SUM	1	3	0.1	1.0	2	0.01	0.051	5.15
	FALL	1	3	0.1	1.0	2	0.01	0.051	5.15
	WIN	1	3	0.1	1.0	2	0.01	0.051	5.15
WP	SPR	2	6	0.3	1.5	3	0.03	0.279	9.58
	SUM	2	6	0.3	1.5	3	0.03	0.279	9.58
	FALL	2	6	0.3	1.5	3	0.03	0.279	9.58
	WIN	2	6	0.3	1.5	3	0.03	0.279	9.58
MM	SPR	1	3	0.2	1.0	2	0.02	0.104	5.30
	SUM	2	6	0.2	1.0	2	0.02	0.164	8.36
	FALL	1	3	0.2	1.0	2	0.02	0.104	5.30
	WIN	2	6	0.2	1.0	2	0.02	0.164	8.36
RP	SPR	1	3	0.1	1.0	2	0.02	0.102	5.20
	SUM	1	3	0.1	1.0	2	0.02	0.102	5.20
	FALL	1	3	0.1	1.0	2	0.02	0.102	5.20
	WIN	1	3	0.1	1.0	2	0.02	0.102	5.20
NP	SPR	1	3	0.1	1.0	2	0.01	0.102	5.20
	SUM	1	3	0.1	1.0	2	0.01	0.102	5.20
	FALL	1	3	0.1	1.0	2	0.01	0.102	5.20
	WIN	1	3	0.1	1.0	2	0.01	0.102	5.20

TABLE 4. NUMBER OF TRUCKS AVAILABLE AT LVBs.

	SPRING	SUMMER	FALL	WINTER	TOTAL
LVB1	500	500	500	500	2000
LVB2	500	500	500	500	2000
TOTAL	1000	1000	1000	1000	4000

B. FORMULATIONS

Two GAMS programs were developed and executed to address the points of this thesis. PROGRAM-1 determines the most economical LVB transportation routes. Specifically, the program minimizes overall costs during the specified time period. PROGRAM-2 determines the number of trucks needed by the LVBs to perform proper transportation operations during specific time periods. Each of these programs reflects a specific model (MODEL-1 and MODEL-2) of the given scenario.

1. FORMULATION FOR MODEL-1

a) INDICES

i : Light Vehicle Battalion(LVB1, LVB2)

j : Supply Depot(S12, S22, S23)

k : Intermediate Supply Point(ISP1, ISP2)

c : Combat unit(COM1,COM2,COM3)

m : Logistic materiel(FOOD, CLOTH, OIL, CEM(cement), AMM(ammunition), EX(exchange-items), WP(weapon), MM(medical materiels), RP(repair-parts), NP(non-military programs))

t : Period(SPRING, SUMMER, FALL, WINTER)

b) **GIVEN DATA**

$TAVAIL_{jmt}$: available logistics materiel m at supply depot j in period t

DEM_{cmt} : demand for logistics materiel m from combat unit c in period t

$SJCOST_{jmt}$: storage cost of logistics materiel m at supply depot j in period t

$SKCOST_{kmt}$: storage cost of logistics materiel m at ISP k in period t

$SCCOST_{cmt}$: storage cost of logistics materiel m at combat unit c in period t

$MCOST_{ijt}$: the cost of moving an empty truck from LVB i to supply depot j in period t

$TJKCOST_{jk}$: the cost of transporting any materiel from supply depot j to ISP k

$TKCCOST_{kc}$: the cost of transportation from ISP k to combat unit c

$TJCCOST_{jc}$: the cost of transportation from supply depot j to combat unit c

$TRUCK_{it}$: number of available trucks at LVB i in period t

c) **DECISION VARIABLES**

TSC : Total storage cost

TTC : Total transportation cost

TMC : Total movement cost

TC : Total cost

$JKTRANS_{jkmt}$: amount of logistics materiel m transported from supply depot j to ISP k in period t

$JCTRANS_{jcmt}$: amount of logistics materiel m transported from supply depot j to combat unit c in period t

$KCTRANS_{kcmt}$: amount of logistics materiel m transported from ISP k to combat unit c in period t

$JSTORE_{jmt}$: amount of logistics materiel m stored at supply depot j in period t

$KSTORE_{kmt}$: amount of logistics materiel m stored at ISP k in period t

$CSTORE_{cmt}$: amount of logistics materiel m stored at combat unit c in period t

$TRUCKUSE_{ijt}$: number of trunks moved from LVB i to supply depot j in period t

d) **OBJECTIVE FUNCTION**

- **TOTAL COST** : The objective of the MODEL-1 study is to minimize the overall cost which consists of three components: storage cost(TSC), transportation cost(TTC), movement cost(TMC), TC (Total Cost) = TSC + TTC + TMC.

- **STORAGE COST** : There are three levels of storage, i.e. depot level, ISP level, and combat unit level. The total storage cost is the sum of keeping the materiels at each levels over all periods. Mathematically, the total storage cost is expressed as follows:

$$TSC = \sum_{j}\sum_{m}\sum_{t} J \times SJ + \sum_{k}\sum_{m}\sum_{t} K \times SK + \sum_{c}\sum_{m}\sum_{t} C \times SC$$

$$J = JSTORE_{jmt},\ K = KSTORE_{kmt},\ C = CSTORE_{cmt},$$

$$SJ = SJCOST_{jm},\ SK = SKCOST_{kmt},\ SC = SCCOST_{cmt}.$$

- **TRANSPORTATION COST** : There are three transportation costs which are incurred when travel is demanded from either supply depots to ISPs, supply depots to combat units or ISPs to combat units. The total transportation cost consists of these three cost components. Mathematically, the total transportation cost is expressed as follows:

$$TTC = \sum_{j}\sum_{k}\sum_{m}\sum_{t} JK \times JKC + \sum_{j}\sum_{c}\sum_{m}\sum_{t} JC \times JCC + \sum_{k}\sum_{c}\sum_{m}\sum_{t} KC \times KCC$$

$$JK = JKTRANS_{jkmt},\ JC = JCTRANS_{jcmt},\ KC = KCTRANS_{kcmt}$$

$$JKC = TJKCOST_{jk},\ JCC = TJCCOST_{jc},\ KCC = TKCCOST_{kc}$$

- **MOVEMENT COST** : Movement costs occur when empty trucks move from LVBs to supply depots. Taken over all periods, the total movement cost is expressed mathematically as follows:

$$TMC = \sum_i \sum_j \sum_t TRUCKUSE_{ijt} \times MCOST_{ijt}$$

e) **CONSTRAINTS**

- **AVAILABILITY** : The availability constraint specifies that the amount of materiels removed from a depot must not exceed what is available. Specifically, the amount of various materiels issued to ISPs and combat units have to be less than or equal to the sum of inventory at hand and the amount of available materiels at supply depots. Any supply depot excess is stored for the next period. Mathematically, the availability is expressed as follows:

$$-J_{-1} + \sum_k JK + \sum_c JC \leq TA + J \quad \forall \; j, m, t$$

$$J_{-1} = JSTORE_{jm,t-1}, \; TA = TAVAIL_{jmt}, \; J = JSTORE_{jmt}$$

- **DEMAND** : This constraint specifies that the amount of materiels needed by the combat units must be provided by a combination of stored and transported materiel. Any excess transported in period t is stored in period t+1. Mathematically, the demand is expressed as follows:

$$-C_{-1} + \sum_j JC + \sum_k KC \geq DEM + C \quad \forall \; c, m, t$$

$$C_{-1} = CSTORE_{cm,t-1}, \; DEM = DEM_{cmt}, \; C = CSTORE_{cmt}$$

- **BALANCE** : For ISP locations, the amount of materiel that enters must equal the amount of materiel that leaves and is stored. Mathematically, the balance is expressed as follows:

$$K_{-1} + \sum_{j} JK = \sum_{c} KC + K \quad \forall \; k, m, t$$

$$K_{-1} = KSTORE_{km,t-1}, \; K = KSTORE_{kmt}$$

- **TRUCK DEMAND** : The number of trucks used to transport from supply depots must equal the number of LVB trucks used. Mathematically, the truck demand is expressed as follows:

$$\sum_{k}\sum_{m} JK + \sum_{c}\sum_{m} JC = \sum_{i} TU \quad \forall \; j, t$$

$$TU = TRUCKUSE_{ijt}$$

- **TRUCK AVAILABILITY** : The number of LVB trucks moved to supply depots has to be less than or equal the number of trucks available. Mathematically, the truck availability is expressed as follows:

$$\sum_{j} TRUCKUSE_{ijt} \leq TRUCK_{it} \quad \forall \; i, t$$

f) SUMMARIZED FORM

MODEL-1's formulation is given below.

MINIMIZE

TC = TSC + TTC + TMC

SUBJECT TO

$$-J_{-1} + \sum_{k} JK + \sum_{c} JC \le TA + J \quad \forall \; j,m,t$$

$$-C_{-1} + \sum_{j} JC + \sum_{k} KC \ge DEM + C \quad \forall \; c,m,t$$

$$K_{-1} + \sum_{j} JK = \sum_{c} KC + K \quad \forall \; k,m,t$$

$$\sum_{k}\sum_{m} JK + \sum_{c}\sum_{m} JC = \sum_{i} TU \quad \forall \; j,t$$

$$\sum_{j} TRUCKUSE_{ijt} \le TRUCK_{it} \quad \forall \; i,t$$

Where $J_{-1} = JSTORE_{jm,t-1}$, $TA = TAVAIL_{jmt}$, $J = JSTORE_{jmt}$,

$C_{-1} = CSTORE_{cm,t-1}$, $DEM = DEM_{cmt}$, $C = CSTORE_{cmt}$

$K_{-1} = KSTORE_{km,t-1}$, $K = KSTORE_{kmt}$, $TU = TRUCKUSE_{ijt}$

2. FORMULATION FOR MODEL-2

a) INDICES

i : LVB, j : Supply Depot, t : Period

b) GIVEN DATA

$TAVAIL_{it}$: number trucks available to LVB i in period t

DEM_{jt} : supply depot j's demand for trucks in period t as determined by Model-1.

$MCOST_{ijt}$: the cost of moving an empty truck from LVB i to supply depot j in period t

c) **DECISION VARIABLES**

TMC : total movement cost

$TRUCKUSE_{ijt}$: number of truck moved from LVB i to supply depot j in period t

d) **OBJECTIVE FUNCTION**

- **MOVEMENT COST** : MODEL-2's objective is to minimize total movement cost. This cost is incurred whenever an empty truck is moved from LVBs to supply depots. Mathematically, the total movement cost is expressed as follows:

$$TMC = \sum_i \sum_j \sum_t TRUCKUSE_{ijt} \times MCOST_{ijt}$$

e) **CONSTRAINTS**

- **AVAILABILITY** : The number of LVB trucks moved to supply depots has to be less than or equal to the number available. Mathematically, the availability is expressed as follows:

$$\sum_j TRUCKUSE_{ijt} \leq TAVAIL_{it} \quad \forall \ i, t$$

- **DEMAND** : The number of LVB trucks moved to supply depots has to be greater than or equal to the number of trucks needed by supply depots. Mathematically, the demand is expressed as follows:

$$\sum_{i} TRUCKUSE_{ijt} \geq DEM_{jt} \quad \forall \; j, t$$

f) SUMMARIZED FORM

MODEL-2's formulation is given below.

MINIMIZE

$$TMC = \sum_{i} \sum_{j} \sum_{t} TRUCKUSE_{ijt} \times MCOST_{ijt}$$

SUBJECT TO

$$\sum_{j} TRUCKUSE_{ijt} \leq TAVAIL_{it} \quad \forall \; i, t$$

$$\sum_{i} TRUCKUSE_{ijt} \geq DEM_{jt} \quad \forall \; j, t$$

V. COMPUTATIONAL EXPERIENCE AND ANALYSIS

A. EXPLANATION OF RESULTS

We solve the described scenario as a linear program. It should be clear that such a solution is only a lower bound on the optimal solution. As the yearly demand is in truck units, the yearly truck movements are guaranteed integer. However, seasonal truck movements can be fractional. As any solution is only intended to provide a suggested schedule, the linear programming solution provides an excellent beginning, and in many cases, it also provides an integer solution. If an integer solution is absolutely required, GAMS/ZOOM can be used at increased computational effort.

MODEL-1 was implemented in GAMS. From the results of this implementation, one can determine the LVB's routes, as well as which materiels are supplied and stored at each location during each period. The output also specifies when LVB trucks should be moved to supply depots.

MODEL-2 determines the optimal number of LVB trucks which should be moved to supply depots. There are two reasons for using MODEL-2. The first reason is for verification of MODEL-1. As any run of the two programs, given the same data, should yield the same results. To provide this verification, the following data from MODEL-1 are duplicated in MODEL-2: the number of trucks available at each LVB in a specific period, the number of trucks needed at each supply depot in a specific

period, and movement costs from each LVB to each supply depot. The optimal number of trucks, calculated by both MODEL-1 and MODEL-2, should be identical if the models are programmed correctly.

The second reason for using MODEL-2 is that one can easily calculate the optimal number of trucks which should be moved from each LVB to its respective supply depot. The LSHQ logistics officers should obtain economical movement routes and transportation routes to minimize costs, and should concern themselves with determining the necessary number of trucks needed at each LVB in a specific time period in order to perform proper transport allocations. If there is a lack of trucks because of mechanical malfunctions, poor maintenance, inspections, etc., logistics officers should immediately find a way to obtain the proper number of trucks to meet the demand of each LVB.

B. RESULTS FROM MODEL-1

For the developed scenario, the optimal amount of logistics materiels to be transported from supply depots to ISPs or combat units is summarized in Table 5. Within this table, the quantities represent the total amount which includes all types of materiels, such as food, oil, and so on: The amount of logistics materiels to be transported from supply depots to ISPs or combat units is summarized. From this table, ISP1 is heavily used and S12 provides a relatively

small amount of materiels. This relationship should clearly exist since transportation costs from supply depots to ISP1 are cheap and all costs from S12 are expensive. From an economic point of view, ISP2 and S12 should not be maintain due to under utilization. We should consider either relocating ISP2 and S12 or removing them completely.

TABLE 5. AMOUNT OF MATERIEL TO TRANSPORT FROM SUPPLY DEPOTS TO ISPs AND COMBAT UNITS.

		SPRING	SUMMER	FALL	WINTER	TOTAL
S12	ISP1	0	0	94	0	94
	ISP2	0	0	6	0	6
	COM1	0	0	0	0	0
	COM2	0	0	0	0	0
	COM3	0	0	0	0	0
S22	ISP1	100	166	132	286	684
	ISP2	0	0	0	0	0
	COM1	0	0	0	0	0
	COM2	0	0	0	0	0
	COM3	0	0	0	0	0
S32	ISP1	228	252	272	158	910
	ISP2	0	0	0	0	0
	COM1	0	0	0	0	0
	COM2	0	0	0	0	0
	COM3	164	206	246	222	838
TOTAL		492	624	750	666	2532

The total amount of logistics materiels to be transported from ISPs to combat units is summarized in

Table 6. From this table, we can see that COM1 and COM2 receive all their supply through ISP1. COM3 receive the bulk of its supply directly from supply depots and only very small amounts through ISP2.

TABLE 6. AMOUNT OF MATERIEL TO TRANSPORT FROM ISPs TO COMBAT UNITS.

		SPRING	SUMMER	FALL	WINTER	TOTAL
ISP1	COM1	164	206	252	222	844
	COM2	164	206	252	222	844
	COM3	0	0	0	0	0
ISP2	COM1	0	0	0	0	0
	COM2	0	0	0	0	0
	COM3	0	0	6	0	6
TOTAL		328	412	510	444	1688

Table 7 contains the amount of logistics materiels which should be stored at supply depots, ISPs, and combat units during specific time periods. Generally, the storage requirements of all supply depots, ISPs and combat units are very low. This is because storage cost is relatively high compare to transportation cost. In addition, it is assumed that the supply of materiels is executed very efficiently, i.e., there is no long supply delays.

TABLE 7. AMOUNT OF MATERIEL TO STORE.

	SPRING	SUMMER	FALL	WINTER	TOTAL
S12	0	0	0	0	0
S22	0	0	0	0	0
S32	0	0	34	0	34
ISP1	0	6	0	0	6
ISP2	0	0	0	0	0
COM1	0	0	0	0	0
COM2	0	0	0	0	0
COM3	0	0	0	0	0
TOTAL	0	6	34	0	40

Table 8 is the summary of total number of trucks required from each LVB to supply depots. These numbers are the same as the units of logistic materiels transported from supply depots to ISPs or combat units.

TABLE 8. NUMBER OF EMPTY TRUCKS TO MOVE FROM LVBs TO SUPPLY DEPOTS.

		SPRING	SUMMER	FALL	WINTER	TOTAL
LVB1	S12	0	0	100	0	100
	S22	0	0	0	0	0
	S32	392	458	400	380	1630
LVB2	S12	0	0	0	0	0
	S22	100	166	132	286	684
	S32	0	0	118	0	118
TOTAL		492	624	750	666	2532

C. RESULTS FROM MODEL-2

MODEL-2 confirms the result of MODEL-1. The summary of result in Table 9 from MODEL-2 is the same as the result in Table 5 and Table 8 from MODEL-1.

TABLE 9. UNITS OF LOGISTIC MATERIEL TO BE TRANSPORTED FROM SUPPLY DEPOTS TO ISPs AND COMBAT UNITS (which is the same as the number of truck that should move from LVBs to supply depots)

	SPRING	SUMMER	FALL	WINTER	TOTAL
S12	0	0	100	0	100
S22	100	166	132	286	684
S32	392	458	518	380	1748
TOTAL	492	624	750	666	2532

D. SENSITIVITY ANALYSIS

1. Limited Access to Some Routes

Sometimes in the summer or winter, transportation routes may be closed because of heavy rain, snow, or frozen ground. When the LSHQ logistics officers decides the most economic transportation routes, they have to consider those seasonal limitations first. In MODEL-1 and MODEL-2, all routes are considered open for transportation. In what follows, we consider a number of scenarios where routes are closed. The results of these cases are summarized is Table 10 through 13.

In order to prevent trucks and supplies from being assigned by the models to those seasonally limited routes,

each was assigned a cost ($1000) higher than any other route. From the result of this change, values of all variables shift. As is evident from this result, no transportation will now exist between blocked routes.

[Key: S--Supply depot, I--ISP, C--Combat Unit, TSJ--Quantity of stored materiels at supply depot, TSK--Quantity of stored materiels at ISP, TSC--Quantity of stored materiels at combat unit, $ -- cost]

TABLE 10. BLOCKAGE BETWEEN ROUTE S12 AND ISP1.

	TRANSPORTATION AND STORAGE QUANTITY					$	COMMENT
	SPR	SUM	FALL	WIN	TOTAL		
S-I	328	437.5	578.5	473	1817	16259.199	No transportations S12 - ISP1
S-C	164	206	152	193	715		
I-C	328	412	604	473	1817		
TSJ	0	4.5	10	0	14.5	196.33	
TSK	0	25.5	0	0	25.5		
TSC	0	0	0	0	0		

TABLE 11. BLOCKAGE BETWEEN ROUTE ISP2 AND COM1.

	TRANSPORTATION AND STORAGE QUANTITY					$	COMMENT
	SPR	SUM	FALL	WIN	TOTAL		
S-I	328	437.5	514	464	1743.5	16258.758	No transportations
S-C	164	206	216.5	202	788.5		
I-C	328	412	539.5	464	1743.5		
TSJ	0	4.5	10	0	14.5	196.33	ISP2 - COM1
TSK	0	25.5	0	0	25.5		
TSC	0	0	0	0	0		

TABLE 12. BLOCKAGE BETWEEN ROUTE S32 AND COM3

	TRANSPORTATION AND STORAGE QUANTITY					$	COMMENT
	SPR	SUM	FALL	WIN	TOTAL		
S-I	328	437.5	514	464	1743.5	16258.758	No transportations
S-C	164	206	216.5	202	788.5		
I-C	328	412	539.5	464	1743.5		
TSJ	0	4.5	10	0	14.5	196.33	S32 - COM3
TSK	0	25.5	0	0	25.5		
TSC	0	0	0	0	0		

TABLE 13. BLOCKAGE OF TWO ROUTES: S12-ISP1 AND S32-COM3.

	TRANSPORTATION AND STORAGE QUANTITY					$	COMMENT
	SPR	SUM	FALL	WIN	TOTAL		
S-I	328	437.5	578.5	437	1817	16259.199	No transportations
S-C	164	206	152	193	715		
I-C	328	412	604	437	1781		
TSJ	0	4.5	10	0	14.5	196.33	S12 - ISP1, S32 - COM3
TSK	0	25.5	0	0	25.5		
TSC	0	0	o	0	0		

From the above tables, it can be seen that the quantities of stored materiels and the storage costs are always the same for the different set of routes being blocked. However, the amount of transported materiels and the costs of transportation slightly varies.

2. Storage Cost Changes

The storage costs of supply depots, ISPs, and combat units are expected to vary. Let us assume that, in the case of food, cement, exchange-items, and repair-parts, storage costs for the fall at S32 are raised by one dollar, and the summer storage costs at ISP1 for cement, exchange-items, and repair-parts are also raised by one dollar. The results of these changes are summarized in Table 14.

TABLE.14. CHANGES IN STORAGE COSTS.

	TRANSPORTATION AND STORAGE QUANTITY					$	COMMENT
	SPR	SUM	FALL	WIN	TOTAL		
S-I	328	412	514	464	1718	16244.325	No storage at ISP1
S-C	164	206	242	202	814		
I-C	328	412	514	464	1718		
TSJ	0	30	10	0	40	209.50	
TSK	0	0	0	0	0		
TSC	0	0	0	0	0		

From Table 14 above it can be seen that the quantities of materiels to be transported and to be stored at specific supply depots and ISPs vary from the values obtained from the blocked-route data discussed in Section D. 1. above. When the storage cost increased for some materiels mentioned above, the amount of storage at each depot is changed as well.

V. CONCLUSIONS

Optimization efforts are applied to many issues in modern society. Especially in the military, optimizing the usage of limited resources is essential during peacetime. In this thesis the optimization approach is applied to military transportation operations. The focus is from the point of view of the logistics officers who control logistics materiels stored at supply depots, and vehicles within Light Vehicle Battalions (LVBs). These officers select the most economical transportation routes and the distribution of logistics materiels in order to minimize total costs.

Two models are developed for this research. The first model searches for the most economical transportation routes and the optimal amount of logistics materiels transported by LVBs using those routes; the other model calculates the number of vehicles needed by LVBs to perform the requested transportation orders effectively. In the case where access to some routes is limited, or some storage costs are changes, these factors are considered for analysis within the programs.

The approach of this thesis provides logistics officers a scientific and economical method of deciding which transportation routes to use, and the quantity of materiels to be carried by each route. The linear programming models developed in this thesis can be an effective aid to the logistics officer.

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