A SIMULATION STUDY OF OPERATIONAL PROCEDURES FOR INCREASING THE EFFICIENCY OF INLAND WATERWAYS TRANSPORTATION

Kiran J. Desai
Jerry Prock

ABSTRACT

Inland waterway transportation is an important part of American commerce. Any improvement in the operation of this waterway system could have far reaching effects.

This paper describes a simulation study designed to identify methods of reducing delays at the locks. Factors used in the simulation were: lock utilization, tow mix, distance between locks, and sequencing rules.

Cost estimates are used in conjunction with lock utilization and tow mix to find the total investment and cost of delays under these decision rules. A significant finding was that total costs were lowest for situations in which lock utilization increased as tow mix size increased. Thus, rules for having the lowest delays and rules for having the lowest costs are sometimes contradictory.

INTRODUCTION

Over 25,000 miles of inland waterways in the United States are used for commercial navigation. About one-third of these inland waterways carry the large bulk of freight traffic moving mostly in tows. In the last twenty years the inland waterways have maintained their share of intercity freight traffic. Since 1941 the growth in ton-mile freight traffic has been more than 250 percent. This tremendous growth in freight traffic has put a severe strain on some of the locks on the inland waterways, causing delays in the movements of freight traffic. Several studies have discussed various methods to relieve the congestion at locks; this paper explores the solution of a congestion problem through different sequencing rules, and also the resulting impact on the capital investment in the equipment by the tow operators.

WATERWAY CAPACITY

The factors affecting a waterway capacity is presented here in terms of a queuing problem following Cox and Smith's modification of queuing system [6].

(1) Modification to Arrivals

One way of modifying the arrivals is to modify the mean arrival rate. Carroll, Rao and Wilson, Lave and De Salvo (3, 16) have suggested levying toll charges to the waterway user to reduce congestion at locks. Rao and Bronzini studied the effect of reduction of empty barge movement on inland waterways (19). The reduction of empty barge movement is possible because of the large number of bi-directional empty barge movements on the waterway system. They concluded that "For the particular systems studied, elimination of a great number of empty barge movements allowed the same tonnage to be serviced with significantly lower delays at the key bottlenecks (locks)." In this regard, Carigan and Humphrey (2) also suggest that a system-wide knowledge on equipment availability might be of significant value to the industry.

Davis recognized the effect of use of locks by pleasure craft on the capacity of a lock (7). Hayward (13) studied the effect of different volumes of pleasure craft and commercial tows and found that as volume of pleasure craft increases, the average delay per tow also increases, and this effect is more pronounced at very high levels of tow volume.

(2) Modification to Service Mechanism

Carroll, Davis, and Rao and Bronzini (5, 7,19) examined the restriction of tow mix on capacity of waterway and delays. Their findings show that by limiting the size of tows to a single lockage size, delays could be reduced significantly. Rao and Bronzini (19) also studied the effect of reducing locking time on the waterway system delay. Table 1 shows that as locking time was reduced to 5 percent to 25 percent, total system delays dropped from 3800.92 hours to 3131.37 hours to 1460.68 hours.

(3) Modification of Queue Discipline

Queue discipline is prescribed by the Secretary of the Army for the Ohio River, Mississippi River above Cairo, Illinois, and their tributaries. These regulations require the lockmaster to follow the first come, first served queue discipline, although certain exceptions are made for government vessels, passenger boats and pleasure craft. These regulations also allow a lockmaster to deviate from first come, first served rule to achieve best lock utilization under prevailing conditions. Thus, when tows are waiting on both sides of a lock, the normal procedure has been to serve the opposing queues alternately. The U.S. Army Corps of Engineers has experimented with processing tows with "three-up and three-down" rule. At Vermilion Lock on the Gulf Intracoastal Waterway, tows are sometimes locked five at a time in each direction. The advantage of this rule is that one is substituting a short entry for a long entry at the expense of dummy lockage.

Hayward (13) simulated Lock and Dam 27 on the Upper Mississippi River, with tow mixture of 52:28:20 for single, double and setover lockages, respectively, with varying traffic intensity, and used four different queue disciplines. They are First Come, First Served; Serve Opposing Queues Alternately; Three Up, Three Down; and equalized queue tow choice method. Hayward found that at low traffic intensity one could not statistically differentiate between these four queue disciplines, but at higher intensity the queue disciplines do affect the average delay on tow. Hayward found that the Serve Opposing Queues Alternately gives the lowest amount of delays at higher traffic intensity while First Come, First Served gives the highest delays.

Various approaches, both analytical and seasoned judgment of engineers and planners have been used to determine the capacity of a waterway. Papers by Shultz (21), Davis (7), and Eichhorst and Koch (8) illustrate the diversity of procedures developed for capacity evaluation of a waterway. Closely related to the notion of a capacity analysis, is the prediction of delay costs and tow delays which must enter into the economic evaluation of a waterway system.

The classical approach to this problem has been to treat each lock or pool individually, without explicit consideration of its relationships to other parts of the waterway system. The capacity analysis methods of Bottoms (1), and Seifert and Rohrisch (20) are examples of this approach. Lave and DeSalvo (16) have applied analytical queuing theory in their studies of tow delays and lock capacity. They applied a queuing theory to a particular lock rather than to the whole waterway system. Also the simple queuing model used by Lave and DeSalvo does not correspond to the situation at the lock. The queuing model used in their study is that of single sewer with only one queue. On a lock, queues can be formed on both sides of the lock, and a lock service facility is processing both queues. The model also assumes first come, first served queue discipline and homogeneous arrival units, which is not the case for a waterway.

SYSTEM ANALYSIS AND INLAND WATERWAY

The classical method of analysis discussed above may be sufficient for non-congested systems where operations at one point have minimal or no effect on operations at other points in a waterway system. As congestion builds in a waterway, however, system operations become increasingly interdependent; therefore, the system analysis approach should be used to evaluate a waterway system. On a congested waterway, delays throughout the system, rather than local delays, are considered in the analysis. It is likely that when the waterway system is congested, structural improvements or changes in operating rules at a single point may reduce delay costs there but transfer congestion to other parts of the system.

Luce and Sandor (15) and Mackay and Collins (17) have reported the results of application of system analysis to the Welland Canal. Ivanov reported on the potential of applying computers in the control of ship traffic through canals that consist of sequential locks. A study of the Panama Canal reported by Harrison (9) was concerned with the effect of various ship convoy sizes and convoy sequencing on the transit time of individual ships. Nowading researched the problem of methods of assigning ships among essentially parallel facilities in the context of a waterway canal system that contains several locks, offers multiple routing options, and serves bi-directional ship traffic.

Recently a more powerful tool, computer simulation has been used to study an inland waterway system. The first reported application of a computerized Monte Carlo model of a single lock was in connection with a study performed by Carroll (5) with the support of the Tennessee Valley Authority. Carroll's above mentioned work and that of Howe (5, 10-12) on the tow speed function were out together to form an inland waterway system simulation model by Resources for the Future, Incorporated. The RFF model is capable of simulating the movement of shallow draft barge tows through a linear waterway having up to ten locks, twenty ports, and ten delay points. The queue discipline employed in the model is First Come, First Served and the lock chamber selection is based on expected completion time of tow processing. This RFF model was modified at the Pennsylvania State University to accommodate a waterway with a Y configuration (4).

Data required to use this modified RFF model was difficult to prepare and expensive; a new simulation model was developed at the Pennsylvania State University. The Penn State model viewed a waterway as an interconnected network of ports, each of which originates and terminates waterborne freight.

The Penn State model can accommodate 30 ports, 20 delay points, and 75 different lock chambers distributed among 30 locks. Delay points of three types: channel restrictions, external restrictions (e.g., bridges), and system blocks. The waterway itself may have up to five branches as tributaries. The model also allows for 10 of each of the barge types, tow horsepower and flotilla sizes.

THE SIMULATION MODEL

The waterways to be simulated consist of four locks; dual chambers of equal size (110' x 600') with two end posts (Figure 1). The simulation is carried out in two sections. In the first section, a tow generating program (TOWGEN) converts informations concerning commodity Origin-Destination (O-D) tonnages into a set of time-ordered O-D movements of tows having known characteristics. The main procedures used in doing this are minimization of the number of empty barge movements and minimization of the cost. Entering of tows into the waterway follows Poisson Distribution.

In the second section the actual processing of the tows is performed by the waterway simulation model WATSIM, using tows input from TOWGEN. The queue discipline built into this model is - first come, first served, FC-FS. The chamber selection for multichamber locks is based on the expected total processing time for each chamber.

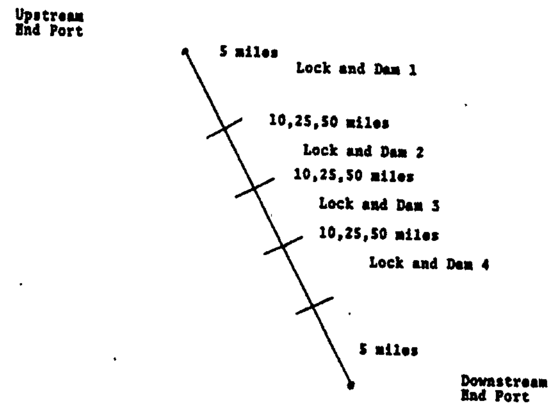


Figure 1. Waterway Simulation Model

The simulation model was written in the FORTRAN-IV language for use on the IBM System 360/67 computer. The model was modified to accommodate two queue disciplines--(1) existing service discipline, EXFCFS, and (2) three up and three down when there are queues. Otherwise, the same as EXFCFS, 3UD--EXFCFS.

SIMULATION RUNS

Data were collected after the steady-state condition was reached. The length of each simulation run was 14,400 minutes (10 days). While many performance measurement variables were recorded, the principle variables were:

1. Average delay for all tows,
2. Average delay for tows delayed,
3. Total number of tows processed,
4. Total number of barges moved through the lock system,
5. Number of barges in transit,
6. Number of tows in transit.

The experimental design consists of the following four factors:

Factor A : lock utilization
- A_1: light utilization (35%)
- A_2: medium utilization (55%)
- A_3: heavy utilization (70%)

Factor B : Tow-Mix, the ratio of single to double lockage size tows.
- B_1: 100/000
- B_2: 75/25
- B_3: 50/50

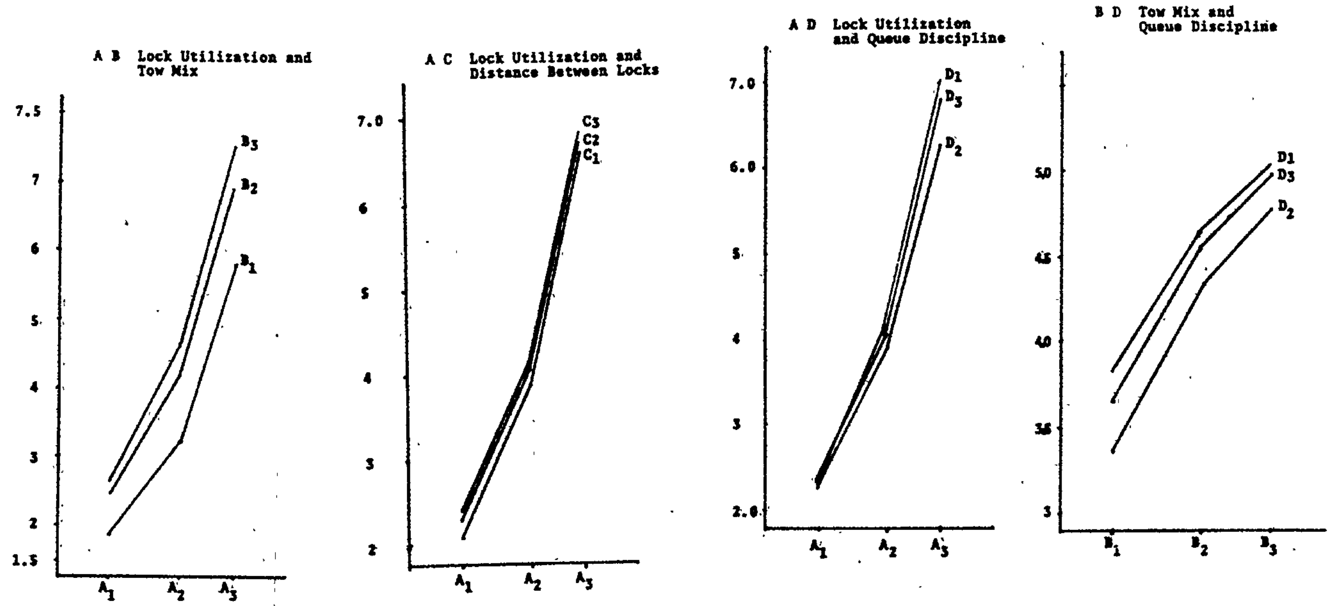
Factor C : Distance between locks.
C_1: 10 miles apart.
C_2: 25 miles apart.
C_3: 50 miles apart.

Factor D : Queue Discipline.
D_1: First come, first served (FCFS)
D_2: Existing service discipline, (EXFCFS)
D_3: Three up and three down, (3UD-EXFCFS)

One replicate computer run is made for each combination of the four factors, yielding a total of 162 computer runs.

ANALYSIS OF RESULTS

The simulation-generated data on each performance measure were analyzed via analysis of variance. For each performance measure, an analysis of variance, four-way classification with interactions, was performed to determine if the main effect (lock utilization, A, tow mix, B, distance between locks, C, and queue discipline, D), the record order interaction (A and B, A and C, A and D, B and C, B and D, C and D), and the third order interaction (A, B and C; A, B and D; B, C and D) had a statistically significant effect on the performance measure in question. However, in order not to invalidate the assumptions underlying the analysis of variance, the square root transformation was used for the variable 1, average delay for all tows, and variable 5, intransit barges; and $\log_e$ transformation was used for the variable 2, average delay for tow delayed.



Grand Mean = 4.35

A_1 = 2.31	A_2 = 4.04	A_3 = 6.7
B_1 = 3.63	B_2 = 4.5	B_3 = 4.92
C_1 = 4.20	C_2 = 4.37	C_3 = 4.47
D_1 = 4.5	D_2 = 4.16	D_3 = 4.39

Source	F Ratio	Sig
D	3.82	5%
C	2.35	10%
B	53.11	1%
A	600.00	1%
DC	0.11	NOT
DB	0.11	NOT
DA	1.63	NOT
CB	0.27	NOT
CA	0.004	NOT
BA	2.02	10%
DCB	0.062	NOT
DCA	0.051	NOT
DBA	0.075	NOT
CBA	0.12	NOT
DCBA	0.04	NOT

Figure 2. Variable 1: Average Delay for all Tows (Square root transformation).

Variable 1. Average delay for all tows.

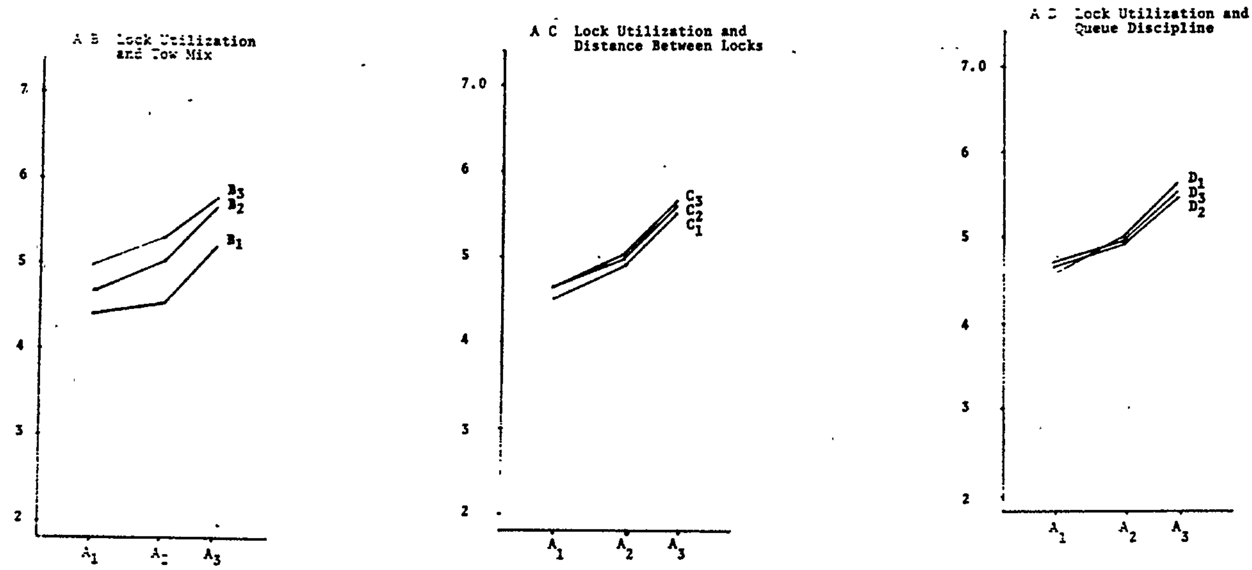
Summary results of the analysis of variance for variable 1 are given in Figure 2. The average delay for all computer runs for the raw data is 22.79 minutes. Factor D, the priority rules, has a significant effect on this variable. The EXFCFS rules gave the lowest delay per tow and the FCFS rules gave the highest delay per tow. None of the first order interacting involving factor D is significant. The plot of factor D with factor A shows that at all levels of lock utilization the queue discipline EXFCFS gives the lowest delays per tow.

The plot of factor D with factor B shows that at all levels of tow mix, the queue discipline EXFCFS gives the lowest delays. The plot of factor A with factor B shows the delays are lowest for tow mix of 100/000, single to double lockage size. The plot of factor C with factor A shows that the delays are lowest when locks are 10 miles apart. Here the study of the arrival patterns shows that the tow arrivals at locks are non random, i.e., the locks which are 10 miles apart are in actuality regulating the flow of tows in the waterways.

Variable 2: Average delay for tows delayed.

The summary results of the analysis of variance for variable 2, average delay for tow delayed, are given in Figure 3. Factors A, B and C are found to be significant at the 1 percent level and factor D and interaction of factor D and factor A are significant at 10 percent level.

The plot of the interaction of factor D and factor A shows that at higher utilization, queue discipline EXFCFS gives the lowest delays for tows delayed; whereas FCFS gives the highest delays.



Source	F Ratio	Sig
D	2.5	10%
C	6.072	1%
B	306.6	1%
A	590.58	1%
DC	0.23	NOT
DB	0.39	NOT
DA	2.212	10%
CB	0.335	NOT
CA	0.127	NOT
BA	1.953	NOT
DCB	0.22	NOT
DCA	0.084	NOT
DBA	0.14	NOT
CBA	0.36	NOT
DCBA	0.107	NOT

Grand Mean = 5.05013

A_1 = 4.611	A_2 = 4.986	A_3 = 5.55
B_1 = 4.67	B_2 = 5.13	B_3 = 5.33
C_1 = 4.99	C_2 = 5.07	C_3 = 5.09
D_1 = 5.07	D_2 = 5.01	D_3 = 5.07

Figure 3. Variable 2: Average Delay for Tows Delayed (Log_e transformation).

The interaction plot of factors A and C shows that when locks are 10 miles apart, the delays for tows delayed is lowest while there is not much difference in delays when locks are either 25 or 50 miles apart.

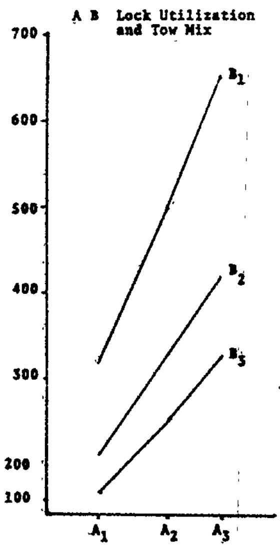
The analysis on arrival pattern of tows shows that when locks are 10 miles apart, the arrival patterns are non Poisson, i.e., locks are interdependent (23). This explains why delays are smaller when locks are 10 miles apart.

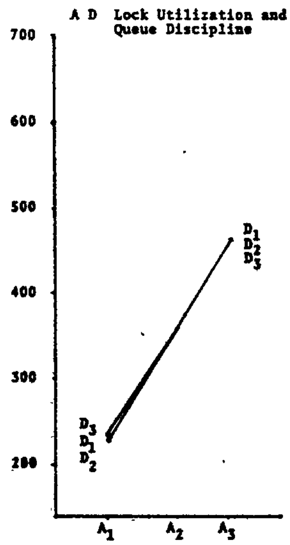
The interaction of factors A and B is consistent with the variable average delay for all tows. That is, the lowest delay occurs when tow size is limited to the single lockage size.

Variable 3: Total number of tows.

The analysis of variable 3 is shown in Figure 4. Here only factor A and factor B have significant effect on the total number of tows processed through the system. The queue disciplines have no effect on the variable at any utilization level.

The plot of the interaction of factor A and factor B indicates that the maximum number of tows passed through the waterway was of single lockage size at all utilization levels. This implies that under this condition a maximum number of towboats were needed to move the freight. Hence, the investment in the towboat and cost of manpower are highest on all single lockage size tows.[1]





Source	F Ratio	Sig
D	0.09	NOT
C	0.22	NOT
B	1264.36	1%
A	1156.17	1%
DC	0.076	NOT
DB	0.08	NOT
DA	0.09	NOT
CB	0.18	NOT
CA	0.20	NOT
BA	48.05	1%
DCB	0.11	NOT
DCA	0.11	NOT
DBA	0.10	NOT
CBA	0.46	NOT
DCBA	0.09	NOT

Grand Mean = 353

$A_1 = 229$	$A_2 = 362$	$A_3 = 467$
$B_1 = 450$	$B_2 = 321$	$B_3 = 247$
$C_1 = 353$	$C_2 = 351$	$C_3 = 354$
$D_1 = 352$	$D_2 = 352$	$D_3 = 353$

Figure 4. Variable 3: Total Number of Tows.

Variable 4: Total number of barges moved through the system.

The analysis of variable 4 is shown in Figure 5. The EXFCFS priority rule allows the lowest number of barges, 3162 as compared to the FCFS priority rule, which allows 3457 barges over a 10-day period. This relationship holds for all levels of utilization as shown in the plot of factor A versus factor D.

The plot of factor A with factor B shows that the tow mix of 100/000, single to double lockage size, allows the maximum number of barges through the system; whereas the tow mix of 50/50, single to double lockage size, allows the lowest number of barges through the system.

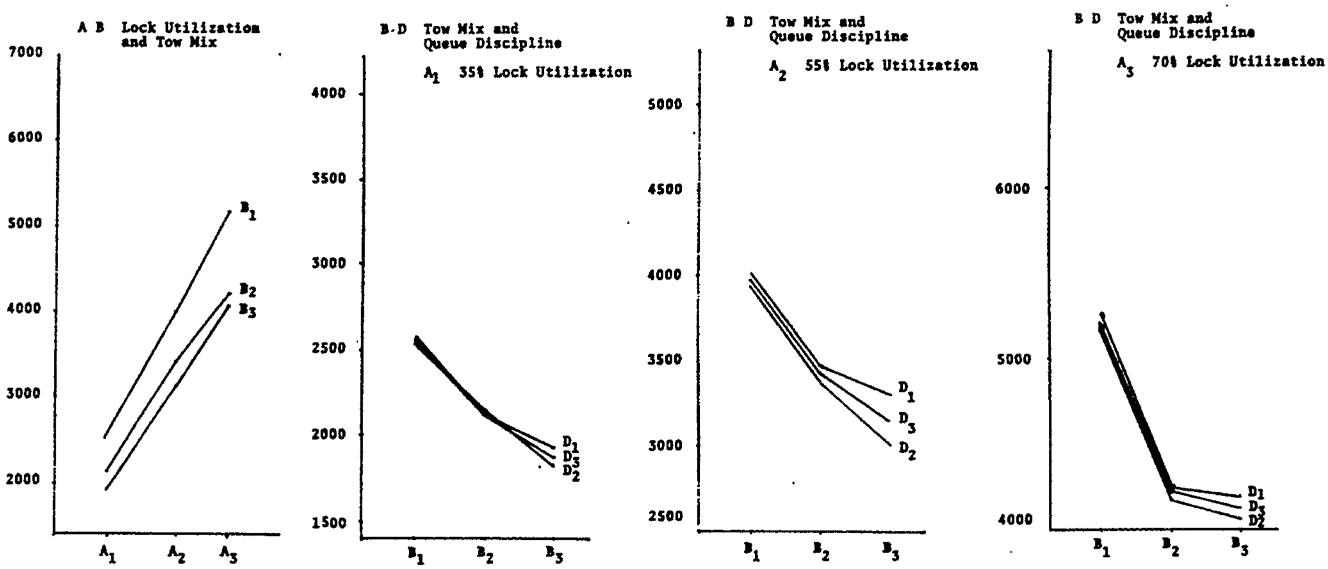
The plot of the interaction of factors A, B and D show that at 35 percent utilization, the number of barges moving through the system is not affected by the priority rule used, but all single lockage size tows moved the highest number of tows through the waterway. At the higher utilization A_2 and A_3, the priority rule FCFS, allowed the largest number of barges through the waterway.

Variable 5: Number of Intransit Barges

The analysis of number of barges intransit at the end of ten days of simulation is summarized in Figure 6. The plot of interaction between factor A and factor D illustrates the queue discipline has no significant effect on the number of barges intransit.

The interaction plot of factor A and factor C shows that as distance between locks increases, more barges are in transit. This is due to the fact that with more distance to cover, the tows are going to be in transit for a longer time.

At 35% (low) utilization, the number



Grand Mean = 3410

A_1 = 2185.6	A_2 = 3522.6	A_3 = 4521.7
B_1 = 3918.7	B_2 = 3259.7	B_3 = 3051.4
C_1 = 3419	C_2 = 3399	C_3 = 3411
D_1 = 3457	D_2 = 3362	D_3 = 3410

Source	F Ratio	Sig
D	4.064	5%
C	0.18	NOT
B	365.84	1%
A	2452.00	1%
DC	22.50	1%
DB	0.83	NOT
DA	0.505	NOT
CB	0.067	NOT
CA	0.238	NOT
BA	14.32	1%
DCB	2.817	5%
DCA	3.47	5%
DBA	0.099	NOT
CBA	0.665	NOT
DCBA	0.585	NOT

Figure 5. Variable 4: Total Number of Barges Moved Through the System.

of barges in transit at any one time is highly variable. That is, at any given moment the system could be either empty or highly congested. By chance the simulation runs ended when the system had a considerable number of barges in transit.

At the 55 and 70 percent lock utilization, the interaction plot of factor A and factor B shows that at all single lockage tow sizes have the highest number of barges in transit while 50/50 single, double lockage size tow mix has the lowest number of barges in transit.

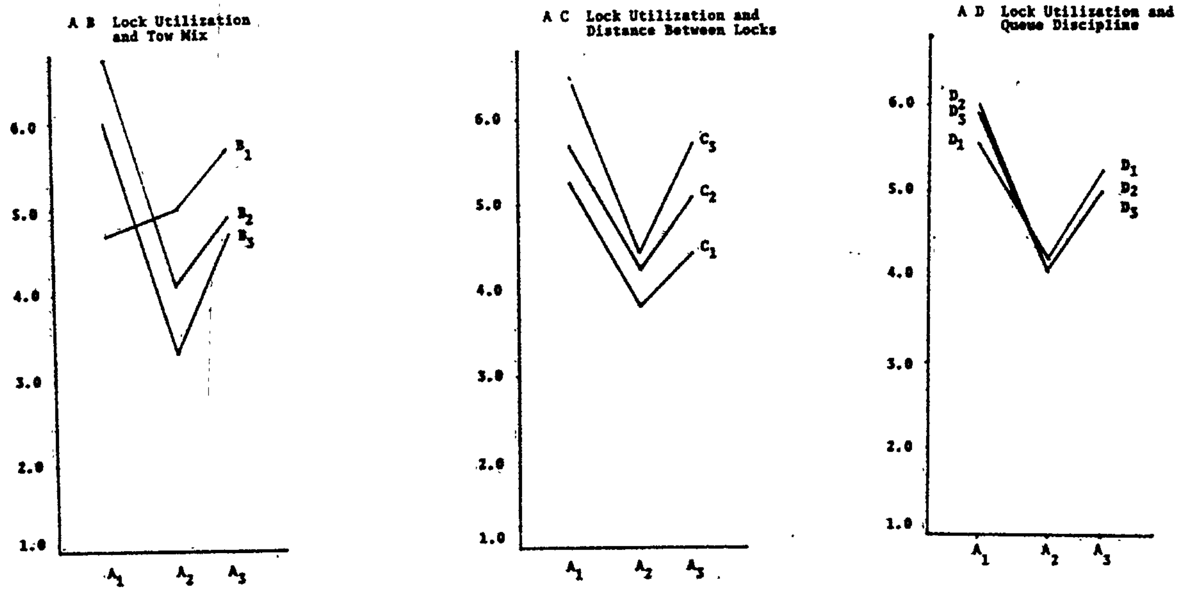
Variable 6: Number of Tows Intransit

The analysis of intransit tows is given in Figure 7. The only significant factors are A and B. The interpretation of the analysis of this variable is the same as that of the intransit barges variable. The only difference is that here tow size will refer to the size of the towboat used for the tows. The single lockage size tow requires a smaller towboat than the towboat used in double lockage size tow. The smaller towboat is cheaper than the larger towboat.

DISCUSSION OF RESULTS

Each combination of variables in the simulation run of this study results in a different combination of towboats, barges and delay time in the waterway system. These three factors are the determinants of the cost to the users of the waterways.

Thus far, this study has derived a



Grand Mean = 5.035

A_1 = 5.1	A_2 = 4.17	A_3 = 5.82
B_1 = 4.69	B_2 = 5.25	B_3 = 5.15
C_1 = 5.57	C_2 = 5.024	C_3 = 4.5
D_1 = 5.03	D_2 = 5.05	D_3 = 5.01

Source	F Ratio	Sig
D	0.01	NOT
C	7.294	.1%
B	2.237	NOT
A	17.85	.1%
DC	0.005	NOT
DB	0.003	NOT
DA	0.272	NOT
CB	0.38	NOT
BA	7.97	.1%
DCB	0.004	NOT
DCA	0.228	NOT
DBA	0.02	NOT
CBA	1.06	NOT
DCBA	0.022	NOT

Figure 6. Variable 5: Number of Intransit Barges (Square root transformation).

number of variables based on simulation runs. The concern now is to translate these variables into dollar terms. The numerical results presented will give an indication of the order of potential costs due to combinations of variables, but the procedures demonstrated are more important than the dollar results presented.

In all instances the cost figures are based on the results of the interaction of variables A and B.

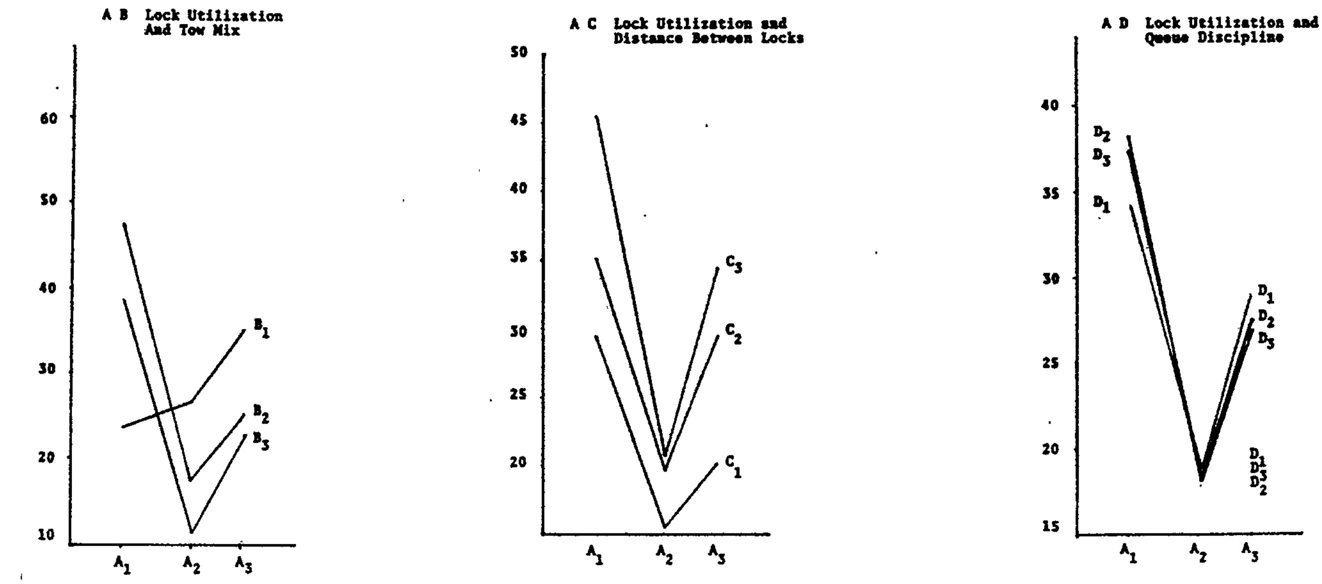
According to a study published by the Bureau of Business and Economic Research at Memphis State University the cost of towboats is approximately $250 per horsepower.[2] Single lockage tows would use towboats of 1800 Hp and double lockage tows would use towboats of 3500 Hp. This results in a towboat cost of $450,000 and $875,000 respectively.

The cost of the barges must be added to the cost of the towboat in each situation in order to calculate the total capital investment under each combination of variables. Based on data from the Memphis State University study the cost per barge is estimated to be $174,863.38.[3]

Total Capital Investment

	A_1	A_2	A_3
B_1	48,745,353	60,762,019	83,771,854
B_2	58,350,271	52,854,028	88,048,323
B_3	51,017,826	58,660,380	72,905,461

As utilization(s) increases, the effect of using double lockage tows in reducing total investment also increases. In contrast, the reverse is not true; as the proportion of double lockage tows increases, investment does not necessarily tend to decline with higher utilization.



Grand Mean = 27.7

A_1 = 36.6	A_2 = 18.6	A_3 = 27.8
B_1 = 28.5	B_2 = 30.3	B_3 = 24.3
C_1 = 21.5	C_2 = 27.8	C_3 = 33.7
D_1 = 27.4	D_2 = 27.9	D_3 = 27.7

Source	F Ratio	Sig
D	0.0165	NOT
C	7.944	1%
B	2.01	NOT
A	17.458	1%
DC	0.005	NOT
DB	0.002	NOT
DA	0.17	NOT
CB	0.09	NOT
CA	0.71	NOT
BA	7.886	1%
DCB	0.004	NOT
DCA	0.13	NOT
DBA	0.01	NOT
CBA	1.129	NOT
DCBA	0.013	NOT

Figure 7. Variable 6: Number of Tows Intransit.

A method for computing the average costs of delays was suggested by Rao and Bronzini.[4] The operating costs per towboat, both single and double lockage size, was estimated to be $1,625 per day for each towboat and $25 per day per barge.

The costs just mentioned are assumed to be based on 1971 data. Since that time the American economy has experienced considerable inflation. Adjusting these cost figures in accordance with movements in the consumer price index[5] and applying this to the simulated tow size results in a cost of $1.897 and $2.132 per minute respectively for single and double lockage tows. The final cost of delays would be found by multiplying the delays on all tows times total tows times 36.5 (the number of ten day periods in a year) times the appropriate cost per minute factor.

The totals of the costs, investments and delays are presented in the following table.

Total Costs

	A_1	A_2	A_3
B_1	48,822,902	61,131,714	85,291,046
B_2	58,438,717	53,273,656	89,481,024
B_3	51,101,472	59,080,805	74,266,708

As can be seen, as utilization increases desirability (in terms of cost) tends to move toward more double lockage size tows.

CONCLUSION

Other studies on inland waterway problems have used number of tows per day to study the effect of tow mix on the capacity of inland waterway. In such studies, direct comparison of the effect of tow mix on the capacity of a waterway can be difficult because in order to carry the same amount of traffic it would require fewer number of tows to pass through a lock if larger tows are permitted on an inland waterway. To alleviate this difficulty in this study lock utilization rather than number tows per day variable was used.

This study shows that as utilization of locks increases, the tow delays for all tows as well as for the tows which were delayed increases. This confirms the findings of others as well as what one would expect from queuing theory. This study also shows that if a tow larger than single lockage size were permitted, the average delay for all tows as well as for the tows delayed would increase. This is true at any utilization level of locks. The implication of this finding is that if one wishes to minimize delays on inland waterways, the tow sizes must be restricted to single lockage size only.

Another finding of this study is that distance between the locks also affects delays on the waterway. As the distance between the locks increases, so do the delays. Also the finding of this study is that under certain set of conditions one can decompose a waterway system into series of independent subsystems. At 70 percent lock utilization, tow mix of all single lockage size tows, locks act as independent of each other under the following conditions.

(1) First Come First Served, FCFS, queue discipline and distance between locks equal to or greater than 25 miles up to 50 miles.

(2) 3 UD, EXFCFS, queue discipline and distance between locks equal to or greater than 10 miles up to 50 miles.

For 70 percent lock utilization and tow sizes of single lockage, the locks are interdependent for the following conditions.

(1) Existing first come first served, EXFCFS, queue discipline and distance between locks varying from 10 to 50 miles.

(2) First come first served, FCFS, queue discipline and when locks are 10 miles apart.

The observation of this study conducted also indicates the level of average delay for all tows are lower for the queue discipline, EXFCFS, than both queue disciplines, FCFS and 3 UD, EXFCFS.

In order to move the maximum number of barges the tow size should be restricted to the single lockage size and the queue discipline FCFS should be employed. To minimize the equipment intransit the tow size should be restricted to 50/50 single to double size, and EXFCFS queue discipline should be employed.

The cost estimates are used in conjunction with lock utilization and tow mix to find the total investment and cost of delays under these decision rules. A significant finding is that total cost was lowest for cases in which lock utilization increased as tow mix size increased. Thus rules for having the lowest delays and rules for having the lowest costs are not the same.

FOOTNOTES

[1]Here one must recognize that for double lockage-size tows, the towboat needed is larger in size--horsepower--hence costs more, but the cost increases at decreasing rate (22).

[2]Impacts of A Waterways User Charge on the Economy of Tennessee, Bureau of Business and Economic Research, Memphis State University, Memphis, Tennessee, May, 1978, p. 71.

[3]Ibid.

[4]S. Rao and M. S. Bronzini, "A Simulation Study of Methods for Increasing Capacity Utilization on the Inland Waterways," Technical Note 71, Pennsylvania Transportation & Traffic Safety Center, 1972.

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