Simulation of Waterway Transportation Reliability

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A microscopic model for simulating barge traffic through a series of locks has been developed and tested with data for a section of the Ohio River. The model was designed primarily to analyze the economic effects of waterway congestion and service reliability. The results indicate that the model is capable of simulating the system performance sufficiently well for analytic purposes. The results also indicate to what extent coal stockouts would increase at a power plant, or alternatively, how safety stocks would have to be increased, as traffic volumes approach capacity.

The reliability of service times on inland waterways significantly influences barge fleet requirements, operating costs, inventory costs, and stock out costs for customers. Therefore, the service reliability influences the competitive position and market share of inland waterway transportation.

To analyze the effects of congestion and service time variability, a simulation model has been developed. In its earliest applications for which results are presented, the model is used to estimate the relations among capacity and service time variance at successive locks, stock-out probabilities and durations, and inventory safety stocks for an electric power plant supplied with coal through the Ohio River. This model will soon be usable for estimating the benefits and costs of alternative plans for maintaining and improving the waterway system.

LITERATURE REVIEW

The research most relevant here regards the economic costs of lock delays, lock delay models, and waterway simulation models. The estimation of economic benefits is essential for selecting and scheduling lock improvement projects. The U.S. Army Corps of Engineers, which is the agency responsible for U.S. waterways, usually estimates the economic benefits of lock improvements from the transport cost differentials between barges and the next cheapest mode (*1–3*). Such evaluation omits some important logistics costs (e.g., for larger inventories and barge fleet sizes) used to hedge against unreliable deliveries.

In systems with unreliable deliveries, stockouts may occur. There are situations in which the on-site stocks are not sufficient to satisfy the demand (*4*). Stock-out costs include duplicate ordering costs from another source or mode and foregone profits (*5,6*). Baumol and Vinod (*7*) indicate that delays can increase the shippers' inventory costs which include on-site carrying costs and stock-out penalties. On the basis of Baumol's model, Nason and Kullman (*8*) developed a total logistics cost model to predict inland diversions from waterways.

Two models based on queueing theory have been found for estimating lock delays. DeSalvo (*9*) models lock operation as a simple single-server queueing process with Poisson distributed arrivals and exponentially distributed service times (i.e., M/M/1 queues). Wilson's model (*10*) extends DeSalvo's by treating the service processes as general distributions (M/G/1 queues). Both models are designed for analyzing single lock delays. However, the assumption of exponentially distributed service times is not consistent with empirical data (*11*) and the Poisson arrivals assumption is also unreliable. Carroll and Desai (*12,13*) studied the arrival processes at 40 locks on the Illinois, Mississippi, and Ohio river systems, and found that 13 of the 40 locks had non-Poisson arrivals at the five percent significance level.

The results for M/M/1 queues in DeSalvo's model (*9*) are derived on the basis of first-in-first-out (FIFO) service discipline although the actual discipline is primarily one-up-one-down. This assumption can still generate reasonable results since delays mainly depend on volume to capacity ratios. Wilson (*10*) modeled the service processes more realistically with a general rather than an exponential distribution. However, arrivals are still assumed to be Poisson distributed at all locks and no exact queueing results are available for locks with two chambers in parallel. Since analytic queueing models must be kept simple to be solvable, the above two models also neglect the interdependence among serial locks and the stalls (i.e., service interruptions at locks). Both of these factors significantly affect service times and reliability.

The system simulation models developed to analyze lock delays and two travel times originated mainly from Howe's microscopic model (*14*). In that model service times are derived from empirically determined frequency distributions. To avoid some troublesome problems and errors associated with the requirement to balance long-run flows in Howe's model, Carroll and Bronzini developed another waterway system simulation model (*15*). It provides detailed outputs on such variables as two traffic volumes, delays, processing times, transit times, averages and standard deviations of delay and transit times, queue lengths, and lock utilization ratios. Both of these models simulate waterway operations in detail but require considerable amounts of data and computer time, which limit their applicability for problems with large networks with numerous combinations of improvement alternatives. Both models assume a Poisson distribution for two trip generations, which is not always realistic. More important for reliability analyses, neither of these models explicitly accounts for stalls, which

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are different in frequency and duration from other events and have significant effects on overall transit time reliability.

Hence a waterway simulation model that explicitly accounts for stalls and estimates the effects of service unreliability of inventory costs is desirable for evaluating and scheduling lock improvement projects.

SIMULATION MODEL

Purpose

A waterway simulation model was developed to analyze the relations between tow trips, travel times, delays, lock operations, coal consumption, and coal inventories while taking account of stochastic effects and seasonal variations. This simulation model enables the estimation of inventory levels and expected stock-out amounts for coal, tow travel times along the waterway, and tow delays under a variety of assumptions about tow trip generation, tow motion, lock service, lock operation discipline, coal inventory level, and coal consumtion. These estimates are useful for estimating economic benefits of lock improvements.

Features

This simulation model is focused on how variations in lock service times affect tow delays and how variations in tow delays affect coal inventories. The output of this model can provide the necessary information to estimate inventory costs, stock-out costs, and expected benefits resulting from lock rehabilitation or lock construction.

This simulation model is microscopic. It traces the motion and records the characteristics of each tow. The characteristics of tows include their number of barges, commodity types, speed, origin and destination, direction of motion, and arrival time at various points. In addition, the model determines cumulative deliveries, cumulative consumption, and actual inventories at various plants.

This is an event-scanning simulation model—the status of which is updated by events. There are five types of events. One is the generation of tow trips, which are generated stochastically on the basis of actually observed traffic distributions. The model uses a table to represent the trip generation pattern and is, therefore, not limited to standard mathematical probability distributions.

A second type of event is the tow entrance in a lock, which is determined by tow arrival time at that lock, the times when chambers become available, and the chamber assignment discipline. If a tow arrives before the lock is available, it needs to wait in the queue storage area. Otherwise, it is served according to the chamber assignment discipline, discussed later. In general, the lock service is presently "first come first serve," subject to the chamber assignment procedure.

A third type of event is a coal tow's arrival at its destination, which increases the cumulative deliveries by the amount of coal that tow is carrying. The cumulative consumption and inventory at the destination are also updated then.

A fourth type of event is the update in the status of cumulative consumptions, inventories, and consumption rates for all coal destinations every unit time. This provides detailed information on inventory levels for all coal destinations.

A fifth type of event is a lock stall. Whenever a stall occurs, the affected chamber becomes unavailable until the end of the stall.

The size of problem that the model can handle is limited by the computer capacity and the storage capacity of the Fortran compiler or linker. There are no restrictions on the number of locks, chambers, cuts, waterway links, tows, utility plants, origin-destination (O-D) pairs, and simulation time periods. This model can simulate two way operation on a mainline waterway.

This model is programmed in Fortran-77, which allows the simulation of relatively complex operations. The following is a more detailed description of how tow trip generation, tow travel times, and coal inventory levels are computed. The overall structure of the simulation model is displayed in Figure 1.

Tow Trip Generation

Tow trips are generated randomly, but the mean of their generating distribution is constant for each O-D pair over each simulation time period. The distribution for tow trip generation is represented by a table. It is assumed that the distribution of trip generation times is similar to the distribution of trip arrival times to locks, (for which data are available).

This model assumes that each tow will maintain its size through its trip. As in trip generation, tow sizes (numbers of barges per tow) are also generated randomly. The distribution of tow sizes is represented by a table and is assumed to be the same for each O-D pair. The tow size table is determined from input data and can represent tow size distribution.

Tow traffic is divided into coal and non-coal traffic. Therefore, for the same O-D pairs, there may be different trip rates

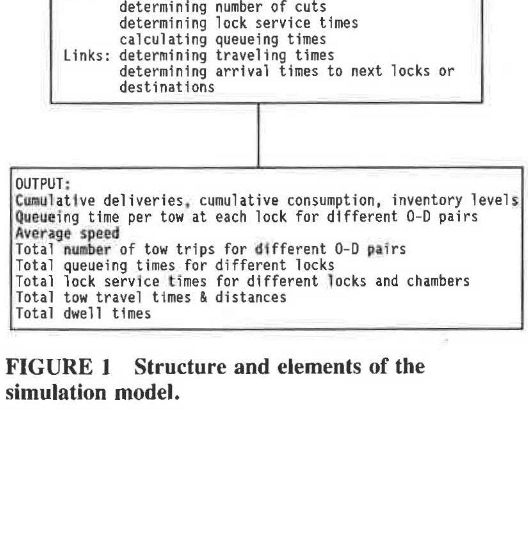

FIGURE 1 Structure and elements of the simulation model.

for coal and non-coal traffic. When coal tows arrive at their destinations, the model updates inventory levels. It is assumed that only a specified fraction of the barges on a coal tow are carrying coal.

Tow Travel Times

Tow travel times are estimated separately for each waterway section, queue storage area, and lock. Section travel times between locks and/or piers are determined by speeds and distances to be covered. Tow speeds are specified as an input to the model in the form of a probability distribution. The distribution of speeds is assumed to be normal. The model assumes that tows maintain constant speeds between origins and destinations and that backhaul speeds are a constant ratio of linehaul speeds.

To avoid generating extreme speed values, a speed range is specified. If speeds are lower than the 2.5 percentile speed or zero, or higher than the 97.5 percentile speed, the speeds are regenerated.

Queueing times at locks are a major focus of this simulation model. Such queueing delays may occur well before traffic levels approach lock capacity since tow arrivals and lock service times are not uniform. These delay times are computed from the difference between the tow arrival times at the queue storage area and their departure from the queue to enter the lock. The storage area has unlimited capacity and is adjacent to the lock.

Lock service times are generated from a specified distribution table. The distribution table can directly reflect actually observed service times. Therefore, the model can be applied to any type of locks. Lock service times will be affected by lock improvements, which are represented by smaller average lock service times or reduced service time distributions. The average lock service times vary for differentl locks, chambers, and numbers of cuts.

The number of cuts is determined by chamber and tow sizes. The maximum cut size (barges handled simultaneously) is exogenously specified for each chamber. A tow may be divided into different numbers of cuts at different lock chambers.

If a lock has more than one chamber in parallel, (main and auxiliary chambers are usually provided), it is currently assumed that the main chamber will be preferred, unless the additional wait time it requires (compared to the auxiliary chamber) exceeds a specified level. This lock selection bias factor reflects the additional work and delays required to break tows into more (and smaller) cuts, move them separately through the auxiliary chamber and then reassemble them. This bias factor has been estimated separately for various locks from empirical data.

The lock service discipline is currently "first come first serve." It is expected that the "N up-N down" service discipline will be simulated later.

Stalls

Stalls are failure conditions in which chambers are not available to serve tows. Stall characteristics differ among chambers and are defined in terms of durations and frequencies, which depend on weather conditions and lock conditions at each chamber. The model assumes that stalls occur stochastically with an exponential distribution.

Inventory Levels

Inventory levels are represented by the difference between cumulative deliveries and cumulative consumption. Whenever inventory levels drop to negative values, this model computes stock-out amounts and durations for the analysis of total costs. This model updates cumulative deliveries and cumulative consumption whenever coal tows arrive at destinations.

Cumulative deliveries are determined from initial inventory levels, inter-delivery times, and delivery amounts. The initial inventory level is exogenously specified for each destination (utility plant). The interdelivery time is generated by the simulation model. The delivered amount is determined from the barge payload and the number of arriving coal barges. The barge payload is currently assumed to be constant for each tow. The number of coal barges is currently assumed to be a constant fraction of tow size. The coal barge fractions vary for different O-D pairs. Although coal barge fractions are constant throughout the simulated period, the amount delivered by each tow is not constant since tow sizes are randomly generated.

Cumulative consumption is a function of consumption rate and time. The mean consumption rate is constant for each utility plant during each simulation period, although it fluctuates randomly around its mean. However, a constant rate is assumed within each period. The consumption rate is updated every time unit and is, therefore, a step-wise linear distribution over time, whose slopes are consumption rates.

Input Requirements

Generally, the model requires four types of inputs related to (*a*) link and lock characteristics, (*b*) traffic demand between origins and destinations, (*c*) probability distributions, and (*d*) inventories and consumption.

Link and Lock Characteristics

The following kinds of information are needed for each link: (*a*) end nodes, (*b*) link length, (*c*) distances between the end nodes and the lock, (*d*) number of chambers, (*e*) average frequencies and durations of stalls, (*f*) maximum cut sizes of chambers, (*g*) average service times of chambers for cuts of various sizes, (*h*) maximum number of barges for each cut size at each chamber, (*i*) bias time for each auxiliary chamber, and (*j*) random number seeds.

Traffic Demand

Traffic demand in tows per day is expressed in the form of O-D matrices by time periods. The lengths of time periods may be different and need to be specified. Additional information needed includes (*a*) dwell time at origins and destinations (both average and standard deviation); (*b*) average number of barges per tow for each O-D pair; (*c*) fractions of coal barges in a tow for each O-D pair; (*d*) payload in short-tons; (*e*) speed (both average and standard deviation); and (*f*) ratio of backhaul speed to linehaul speed (empty/full or upstream/downstream).

Probability Distributions

Probability distributions are specified in this model for (*a*) lock service timers, (*b*) trip generation, (*c*) tow composition (barges per tow), and (*d*) coal consumption at power plants.

The probability distribution tables represent cumulative distribution curves, wherein the abscissas are cumulative frequency, and the ordinates represent the ratio of the tabulated variable to its mean. To reduce the input complexity and specify only ordinates, a specified number of equal intervals is currently used for any cumulative frequency distribution.

Inventories and Consumption

Initial inventory levels in short-tons for different nodes (utility plants) must be specified. In addition, consumption rates in short-tons per day are expressed in the form of node matrices by time period. The information on cumulative deliveries, cumulative consumption, and inventory levels, is provided for intervals whose duration in days must be specified.

Model Output

This model prints out the following results: (*a*) total tow travel time (not including the queueing time, lockage time, and dwell time) in days; (*b*) total tow travel distances in 1,000 mi; (*c*) total dwell times at origins and destinations in days; (*d*) total queueing times in days for different locks and chambers; (*e*) total lock service times in days for different locks, chambers and cuts; (*f*) total number of tow trips for different O-D pairs; (*g*) average speed in mi per day; (*h*) queueing time (both average and standard deviation) in days per tow at each lock for different O-D pairs; (*i*) monthly cumulative deliveries, cumulative consumption, and inventory levels tables in 1,000 short-tons for different utility plants; (*j*) cumulative deliveries, cumulative consumption, and inventory levels tables for specified intervals in 1,000 short-tons for different utility companies; (*k*) graphs of cumulative deliveries and cumulative consumption by specified time intervals for different utility plants; and (*l*) graphs of inventory level by specified time interval for different utility plants.

CASE STUDY

A five-lock section of the Ohio River, centered on the Gallipolis Lock was selected for a case study because that lock constitutes a relative bottleneck in the water capacity. Compared with the four locks nearest to it, (Belleville, Racine, Greenup, and Meldahl), Gallipolis is the oldest and its two chambers are the smallest. A new Gallipolis lock chamber is under construction. The physical characteristics of these six locks are given in Table 1.

In general, a new lock will provide better service quality by reducing service time and improving reliability. The prior expectation is that electric utility plants served by a waterway may be able to reduce the required inventory levels and the expected stock-out costs if the service reliability on the waterway is improved.

The objective of this case study is to compare the inventory levels and expected stock-out amounts of a utility plant downstream of Gallipolis for cases with and without a new Gallipolis lock.

The Stuart utility plant, which belongs to Dayton Power and Light Co., was chosen for this case study. It is located between the Greenup and Meldahl locks. It is 63.5 mi downstream from Greenup and 31.7 mi upstream from Meldahl.

Model Application

This case study focuses on the Ohio river between the Belleville and Greenup locks. Although the model can simulate multiple plants, only one utility plant was analyzed. It included O-D pairs. The simulation period is 1 year.

Link and Lock Characteristics

To simulate the operation between Belleville and Greenup, five nodes and four links are used. The link characteristics are shown in Table 2. The lock characteristics are shown in Table 3.

It is noted that except for Node 5, which represents the Stuart utility plant, all nodes are null nodes that are used as the origins and destinations of non-coal traffic to generate equivalent volumes and congestion levels.

For existing locks, the average lock service times are determined according to the 1984 lock data. Because the new Gallipolis Lock is still under construction, its service times were not available and had to be estimated. The estimated values are slightly smaller than those of the four older locks, which have similar chamber sizes, because the newer lock is assumed to improve service.

TABLE 1 PHYSICAL CHARACTERISTICS OF LOCKS

	Chambers			
Lock Name	Year Opened	Width (ft)	Length (ft)	Lift (ft)
Belleville	1968	110	1200	22
	1968	110	600	22
Racine	1971	110	1200	22
	1971	110	600	22
Gallipolis	1937	110	600	23
	1937	110	360	23
Gallipolis (new)	1991	110	1200	23
	1991	110	600	23
Greenup	1959	110	1200	30
	1959	110	600	30
Meldahl	1962	110	1200	30
	1962	110	600	30

TABLE 2 LINK CHARACTERISTICS

Link	Lock Name	Node In	Node Out	Length (mi)	Distance Between In Node & lock (mi)
1	Belleville	1	2	37.9	21.1
2	Racine	2	3	37.6	16.8
3	Gallipolis	3	4	51.8	20.9
4	Greenup	4	5	94.4	30.9

TABLE 3 LOCK CHARACTERISTICS

Lock Name	Average Service time (in days per cut) 1 cut	2 cuts	Upper Limit of Cut size (in barges per cut)
Belleville	.03512	.09823	18*
	.02389	.07682	8*
Racine	.03425	.09579	18*
	.02427	.07805	8*
Gallipolis	.03563	.07840	6*
	.02088	.06173	3*
Gallipolis	.03000	.09000	18**
(new)	.01600	.07000	9**
Greenup	.03267	.09213	18*
	.02027	.08108	8*

* : based on PMS data
**: based on chamber dimensions

Traffic Demand and Consumption

There were five O-D pairs in this case study. O-D Pair 1 represents coal traffic for the Stuart plant. The other five O-D pairs are non-coal traffic or coal traffic for other utility plants.

The baseline values for average trip rates and tow sizes are determined from 1984 data, and are shown in Tables 4 and 5. The average consumption rates over 12 mo for the Stuart power plant were determined from 1984 coal consumption data and are shown in Table 6.

Other Parameters

The mean and standard deviation of downstream tow speeds are 9.02 and 2.82 mph (216.48 and 67.68 mi/day), respectively. The ratio of upstream speeds to downstream speeds is 0.83. These values were developed on the basis of 1983 statistical data of vessel performance on inland waterways. The barge payload was assumed to be 1,400 long tons or 1568 short tons. (One long ton = 2,240 lbs whereas a short ton = 2,000 lbs.)

Model Validation

The ability of the model to realistically simulate actual operating conditions may be assessed by comparing predictions with actual data. Tables 7 through 9 show such comparisons between results of simulation runs of one year and actual data from 1984. Table 7 shows that traffic volumes are predicted quite accurately by the model, with an average deviation of 1.53 percent. Table 8 shows that the waiting time in queues

TABLE 4 AVERAGE TRIP RATES

Month	Trip Rate (tows/day) O-D pair 1-5	1-2	2-3	3-4	4-5
Jan.	1.98	3.06	3.23	3.36	4.88
Feb.	1.97	3.48	3.46	3.76	5.65
Mar.	1.36	4.43	4.77	4.43	6.06
Apr.	1.57	4.68	4.63	3.74	6.31
May	2.27	4.31	4.39	4.33	5.52
June	1.91	6.31	5.76	5.91	10.44
July	2.20	5.55	5.20	5.15	9.10
Aug.	1.98	5.63	5.84	5.54	8.36
Sep.	2.08	5.07	5.61	5.42	8.71
Oct.	2.40	2.44	3.24	3.37	6.55
Nov.	2.13	2.43	2.92	2.95	5.82
Dec.	1.22	2.77	3.14	3.96	6.30

TABLE 5 AVERAGE TOW SIZES

O-D Pair	Tow Size (barges/tow)
1-5	6.8
1-2	9.1
2-3	9.4
3-4	8.4
4-5	6.7

TABLE 6 AVERAGE CONSUMPTION RATES AT THE STUART POWER PLANT

Month	Consumption Rate (1000 short-tons/day)
Jan.	17.23
Feb.	18.03
Mar.	15.26
Apr.	14.90
May	18.35
June	16.70
July	17.32
Aug.	18.52
Sep.	18.80
Oct.	16.29
Nov.	15.33
Dec.	16.48

TABLE 7 TRAFFIC VOLUME COMPARISON

Lock	Volume (tows/year) Data	Model	Deviation (%)
Belleville	4466	4292	3.90
Racine	4591	4580	0.24
Gallipolis	4575	4622	1.03
Greenup	6511	6450	0.94

TABLE 8 WAITING TIME COMPARISON

Lock	Wait Time(min/tow)		Deviation (%)
	Data	Model	
Belleville	21.45	21.81	1.68
Racine	17.26	15.22	11.82
Gallipolis	200.53	137.33	31.52
Greenup	14.46	13.31	7.95

TABLE 9 RELATIVE UTILIZATION OF LOCK CHAMBERS (VOLUMES ARE GIVEN IN TOWS/YEAR)

Lock	Data			Model			Deviation (%)
	Main Chamber	Total Lock	%Main	Main Chamber	Total Lock	%Main	
Belleville	3332	4466	74.61	3134	4292	73.02	2.13
Racine	3848	4591	83.82	3851	4580	84.08	0.31
Gallipolis	3656	4575	79.91	3488	4622	75.47	5.56
Greenup	4500	6511	69.11	4891	6450	75.83	9.72

is predicted reasonably well by the model, although the model significantly underestimates the delays at the Gallipolis Lock. That lock has unusual operating characteristics because it requires disassembly of tows into exceptionally small and oddly composed cuts. A more detailed analysis of operations at Gallipolis may be required to more accurately model its peculiarities. Table 9 shows that the model can satisfactorily estimate the relative utilization of the two chambers at each lock, with an average deviation of 4.43 percent. It should be noted that the model predictions are not only close to actual observation, but are also not systematically biased in any particular direction.

System Congestion and Reliability

In waterways, as in other transportation systems, delays increase much faster than volumes as the capacity is approached and tend toward infinite values. Moreover, the relative variance of service times (e.g., the coefficient of variation = standard deviation divided by the mean) is expected to increase faster than the average service times, with unfavorable effects on system reliability. In a linear network such as that in our case study, the capacity of the entire system is limited by the capacity of the most constrictive element in the series, namely the Gallipolis Lock. Because a new lock will be opened in 1991, which will match the capacity of Gallipolis to that of the other locks in the series, we present simulation results for both the old and new locks.

Table 10 shows the effects of traffic volumes and safety stocks on expected stock-out amounts. It is evident that as volumes (both coal traffic and non-coal traffic) increase from baseline levels (1.0) to levels 50 and 100 percent higher (i.e., volume ratios of 1.5 and 2.0, respectively), the stock-out amounts increase more than proportionately. As safety stock levels are increased from 0 to 150,000 and 300,000 tons, the stock-out amounts consistently decrease. The rate of decrease tapers off (to zero, eventually) as safety stocks are increased.

The effect on stock outs of the new higher capacity Gallipolis Lock is nearly negligible at current volumes (volume ratio = 1.0). However as volumes double, its effect becomes quite significant, since the old lock would reach a utilization rate of 82.85 percent (i.e., 83 percent of capacity). In this case, the decrease in stock-outs ranges from 60,850 tons/day (= 363, 010 − 302,160) or 16.76 percent at zero safety stock to 54,790 tons/day or 40.73 percent at a safety stock of 300,000 tons.

Table 11 shows the effects on stock outs of stalls (failures) at locks. The stalls column indicates stall frequency. Thus 1 indicates baseline conditions (i.e., frequency based on 1980–1987 data), whereas 2 and 3 indicate that frequency is doubled and tripled, respectively. The predicted stock-out amounts are given for both the old and new Gallipolis Locks in the format old/new. The results show that stall duration and frequencies have relatively slight effects on stock outs when volumes are low, that is, when comparing Case 2 or Case 4 with the baseline Case 1. However at high volumes (Cases 9–12), when the system operates closer to its capacity, the effects of stalls become significant and the advantage of the higher capacity of the new Gallipolis Lock is quite substantial.

Total System Costs

The results of this work show how expected stock-out levels increase disproportionately with congestion levels (i.e., volume to capacity ratios) and decrease (with diminishing returns) as safety stocks are increased. Figure 2 shows how the total system costs depend on holding costs and stock-out costs. Holding costs, which include storage costs and interest charges on the safety stock are indicated by the linear function H in the Figure 2. The holding cost is assumed to be $0.10/ton-

TABLE 10 EXPECTED STOCK-OUT AMOUNTS FOR VARIOUS SAFETY STOCK LEVELS AND VOLUMES

Gallipolis Lock	Volume Ratio	Utilization of Gallipolis lock %	Expected Stock-Out Amount (1000 short-tons/day)		
			Safety Stock(1000 short-tons) 0	150	300
Old	1.0	38.19	220.88	91.41	7.28
	1.5	59.19	258.58	125.33	29.23
	2.0	82.85	363.01	236.17	134.52
New	1.0	18.73	219.74	90.50	6.97
	1.5	27.42	254.04	121.26	26.73
	2.0	35.92	302.16	176.38	79.73

TABLE 11 EXPECTED STOCK-OUT AMOUNTS (IN 1,000 TONS/DAY)

Case	Multiplier			Starting Inventory (1000 tons)		
	Volume	Stalls	Stall Duration	0	150	300
1	1	1	1	220.1/219.7	91.41/90.50	7.28/6.97
2	1	1	2	221.1/220.0	91.56/90.71	7.29/7.01
3	1	1	3	222.4/220.5	97.69/91.29	7.54/7.10
4	1	2	1	221.2/220.0	91.66/90.73	7.37/7.00
5	1	3	1	221.5/220.2	91.86/90.89	7.49/7.13
6	1.5	1	1	257.2/254.0	124.1/121.3	28.30/26.73
7	1.5	2	1	259.1/254.6	125.9/121.8	29.14/26.89
8	1.5	3	1	261.6/255.8	128.3/122.9	30.89/27.64
9	2	1	1	363.0/302.2	236.2/176.4	134.5/79.73
10	2	2	1	416.4/302.8	282.0/177.0	174.9/83.10
11	2	3	1	579.6/306.2	435.8/180.0	311.7/82.54
12	2	3	2	823.1/320.8	678.5/193.7	553.0/92.80

Key: Expected stock-out amounts given with OLD/NEW Gallipolis Lock. Multipliers are ratios of ASSUMED/BASELINE values. Case 1 represents baseline values.

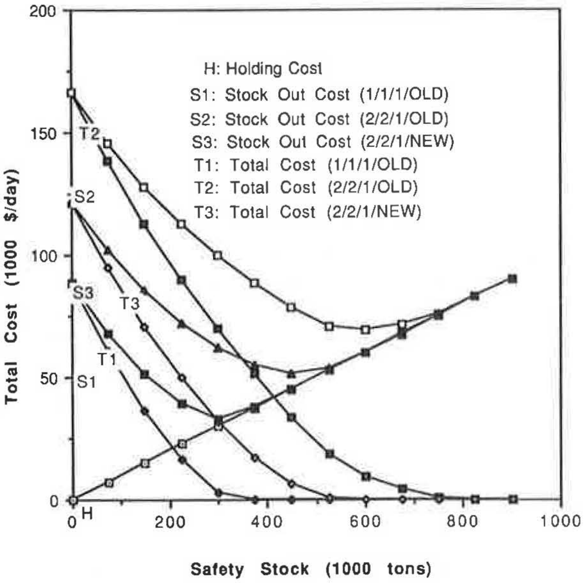

FIGURE 2 Effect of holding costs and stock-out costs on total system costs.

day. If that holding cost were doubled, the slope of the function H would double.

Figure 2 shows the stock out costs for three combinations of parameters, using the key VOLUME/STALL FREQUENCY/STALL DURATION/GALLIPOLIS LOCK. Thus, according to this key, 2/2/1/OLD means that volumes and stall frequencies are twice the baseline values, stall durations are equal to baseline values, and the old Gallipolis lock is being simulated. It should be remembered that our baseline volumes represent 1984 data. A cost of $0.40/ton is assumed in computing the stock out cost curves of Figure 2.

The total system cost is obtained by adding the holding cost to the stock out costs. Because the holding cost is the same for all cases in Figure 2, we obtain one total system cost function for each of the three stock out cost functions. The total cost curves show that as volumes and stall frequencies double (from 1/1/1/OLD to 2/2/1/OLD) the optimal safety stock levels should approximately double from 300,000 to 600,000 tons and that total system costs would more than double from approximately $33,000/day to $69,000/day. If, however, the new Gallipolis Lock was operational, the optimal safety stock level would only be approximately 450,000 tons and the system cost would be approximately $51,000/day, despite doubled volumes and stall frequencies. The curves in Figure 2 show quite clearly the tradeoffs between increased safety locks and increased stock out costs.

Figures 3 through 5 repeat the analysis of Figure 2 with various assumptions about the cost of holding safety stock and the cost of stocking out. They show that as stock out costs increase relative to holding costs, the optimal amounts of safety stocks should increase.

It should be noted that the only sources of delivery unreliability modeled so far are lock operations and lock failures. Safety stock policies of utilities might also be affected by other factors such as probabilistic expectations of coal mine strikes, frozen waterways and coal price changes. It is possible that such factors may dominate the effects of lock performance analyzed to date.

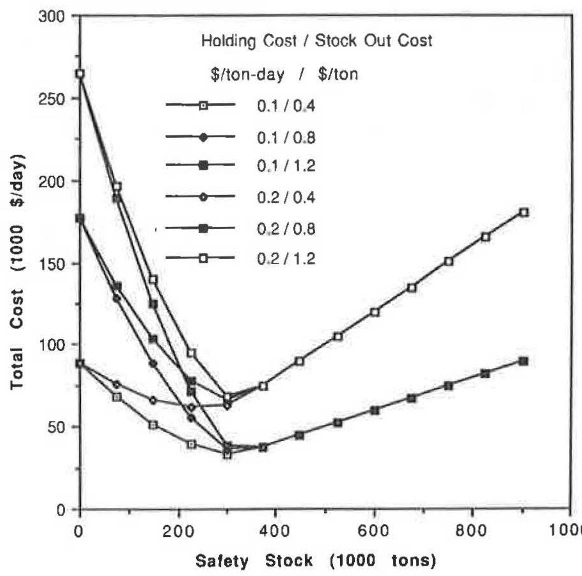

FIGURE 3 Total system costs (1/1/1/OLD).

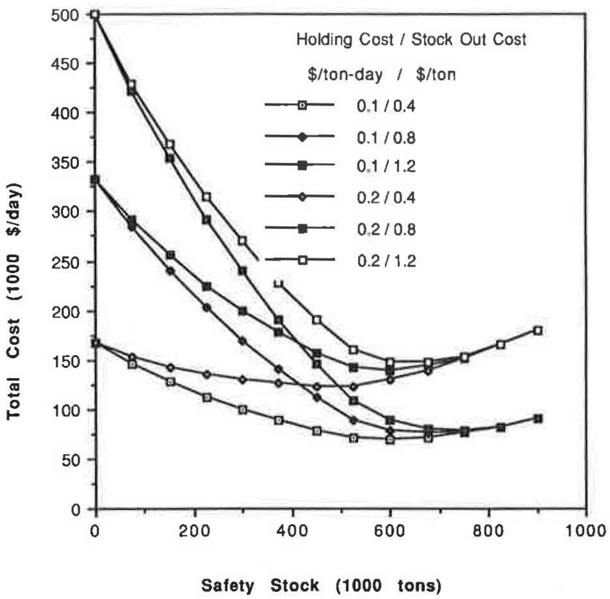

FIGURE 4 Total system costs (2/2/1/OLD).

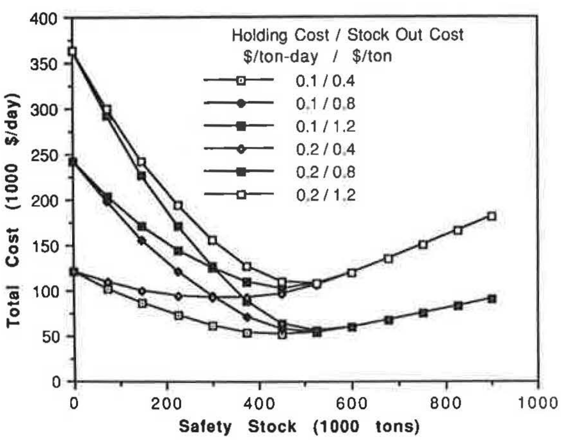

FIGURE 5 Total system costs (2/2/1/NEW).

CONCLUSIONS

Waterway Congestion and Reliability

The results of this work show how expected stock-out levels increase disproportionately with congestion levels (i.e., volume to capacity ratios) and decrese (with diminishing returns) as safety stocks are increased. Such results provide the basis for tradeoffs between inventory holding costs and stock-out costs. The optimized safety stocks resulting from such tradeoffs, and hence their holding costs, would increase as congestion increases and transit time reliability decreases in the system. Such effects are relatively slight when volume to capacity ratios are small. If and when volumes increase substantially above present levels, reliability benefits can justify capacity improvements such as the new Gallipolis Lock.

Model Capability

The simulation model provides estimates of system performance that are sufficiently detailed and accurate for analytic purposes, although its computer requirements are quite modest for a microscopic simulation model. The model's accuracy might be improved by improvements in traffic generation, tow composition, lock selection, and failure generation functions. These improvements might be developed on the basis of a more extensive analysis of empirical data and, possibly, on lock maintenance and failure research. The model may also be extended to translate physical performance measures such as fleet requirements, delays, safety stocks, and stock outs into monetary costs and benefits. Finally, more macroscopic versions of the model are being developed to efficiently analyze alternative investment and maintenance strategies for the national waterway system.

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