

trials and economic evaluations. Unfortunately, the deadline for the UMRS master plan did not permit this. Once the scenarios were prepared, there was just enough time to evaluate them.

#### CONCLUSIONS

This study provided the imaginative and exhaustive search for improvement measures desired. Knowledge of useful nonstructural measures has been expanded. Certainly these measures should be considered in future navigation planning studies, but planners should be cautious in generalizing the results.

One should not assume hydraulic inefficiencies or approach problems where none exist. Double lockage measures are useless where there are no double-lockage-sized tows. There is no substitute for starting with reliable, quantitative data on performance: PMS, surveys, interviews, and on-site investigations. Solutions must be tailored to the problems. Good combinations of measures must be found. The greatest time and effort should go into developing the best ideas.

*Publication of this paper sponsored by Committee on Inland Water Transportation.*

## Analysis of Lock Capacity by Simulation

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LOKSIM2 is a discrete event simulation model developed to analyze the capacity and delay characteristics of single locks on the U.S. inland waterways. Extending previous single-lock simulation techniques, LOKSIM2 features a highly detailed representation of the components of the locking cycle. The model is directly compatible with data provided by the U.S. Army Corps of Engineers Performance Monitoring System. A preprocessor model, TOWLST1, generates tow traffic inputs so as to match distributions of underlying tow characteristics. The output from LOKSIM2 is used to estimate the parameters of a lock delay function. Delay functions obtained for various lock physical and operating conditions can be used to analyze proposed lock improvements.

This paper describes the development and application of a single-lock simulation model, LOKSIM2, used for lock capacity analysis as part of the Upper Mississippi River Master Plan Study. The LOKSIM2 model was developed in response to the need for a method of analysis that could estimate the physical capacity of a single lock under a variety of structural and nonstructural improvement scenarios. Previous single-lock simulators, including LOKSIM (1), LOCALC (2), the lockage routines in the Waterway Analysis Model (3), and SNGLOK (U.S. Army Corps of Engineers, North Central Division), either could not provide the required level of detail or were too cumbersome to use. They did, however, provide the basis for the LOKSIM2 model, which is basically an extension and refinement of these prior modeling efforts. LOKSIM2 is the most detailed model yet created to simulate the operation of a single lock. All input data can be obtained readily from the U.S. Army Corps of Engineers Performance Monitoring System (PMS). The model was programmed in FORTRAN and GASP, a series of FORTRAN-based subroutines that greatly facilitate programming of simulation models (4).

This paper explains the operation of the model, including the structure of inputs and output, and shows how model results are used to estimate lock capacity.

#### OPERATION OF MODEL

##### Overview of Lock Operations

Before a process can be simulated, it is necessary to become acquainted with the details of that process. If more details are accounted for in the simulation, there is a greater likelihood that the results will be realistic. There is, however, a

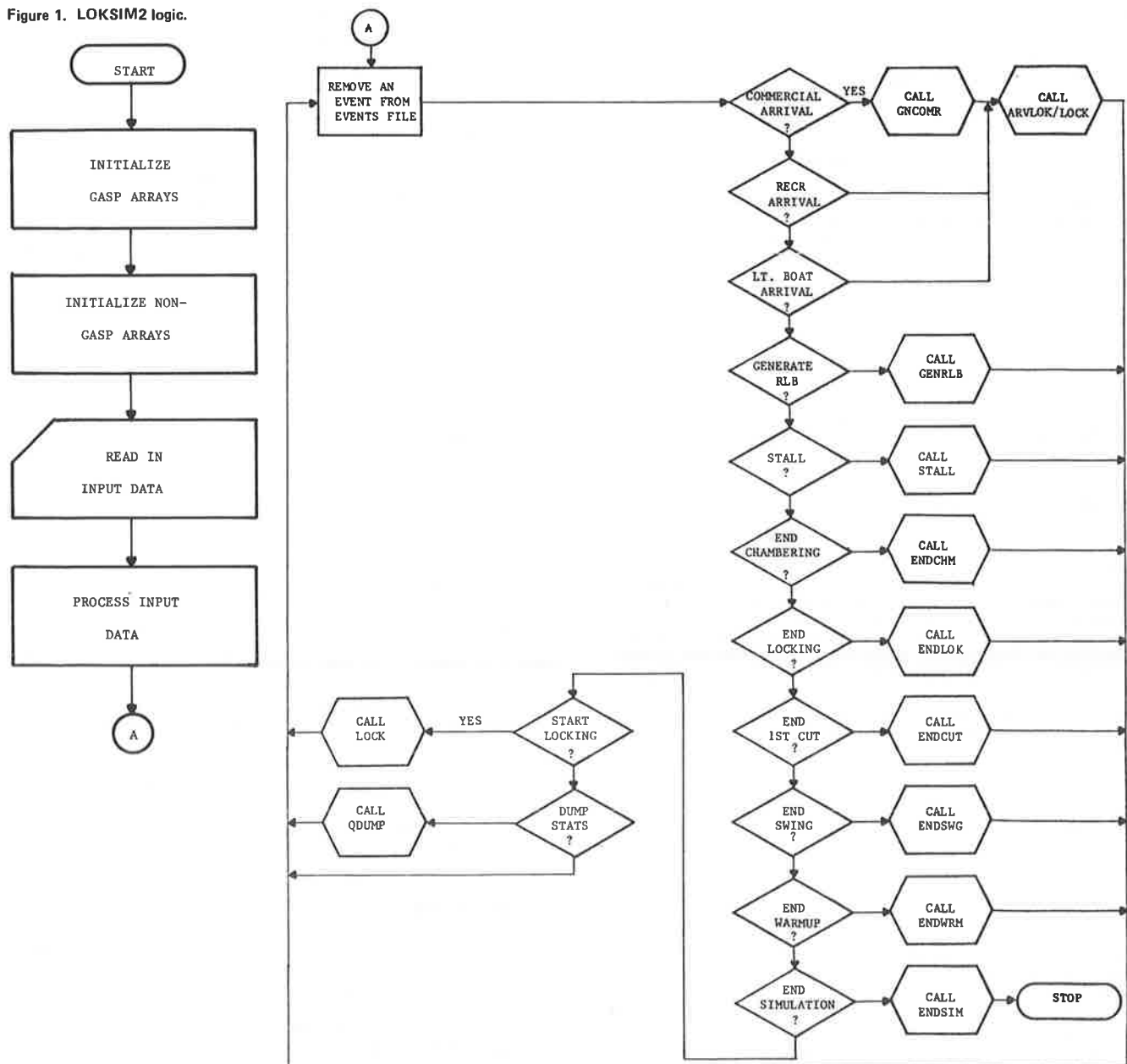
direct relation between amount of detail and cost in terms of development, computer time, and data requirements. Since the objective of this research was to simulate the operation of a single lock, a great degree of complexity could be incorporated into the model. If the purpose had been to simulate an entire system of locks, a less detailed model of lock operations might have been adequate.

Essentially, a lock is a chamber located in or near a dam that can be sealed off and within which the water level can be raised or lowered to meet the water level above or below the dam so that vessels can pass through the dam. Vessels that use locks fall into three categories: (a) commercial tows, which are made up of one or more barges propelled by a towboat; (b) recreational craft, which are noncommercial pleasure boats; (c) light boats, which are towboats traveling without barges. Most lock time is normally devoted to servicing commercial tows.

Because lock chambers and tows come in various sizes and configurations, there are several types of lockages that may occur. A single lockage takes place if the entire tow can fit into the lock as is. A setover lockage occurs if the configuration of a tow must be changed to fit the chamber size but all of it fits into the chamber when it is reassembled (thus, single and setover lockages require only one flooding or evacuation of the chamber). Double lockages occur when the tow is too large to be locked through on one pass; in such a case, some barges go through, the chamber is returned to the starting level, and the remaining barges and towboat are locked through. Recreational craft and light boats (referred to henceforth as RLBs) can be locked through with a tow if there is room left in the chamber, or they can be locked through by themselves or with more RLBs. It is also possible to subdivide single, setover, and double lockages into more specific types if necessary. In addition, on some of the less active waterways, locks can be so limited in size that only a small number of barges (sometimes only one) can be locked through at a time so that triple, quadruple, or quintuple lockages are required. Because this study covered only the Upper Mississippi River system, where all locks (except one) are at least 110 ft wide and 600 ft long, these latter types of lockages did not have to be considered.

The operation of locks is governed by a set of

Figure 1. LOKSIM2 logic.



preestablished policies designed either to gain better use or to favor one type of craft over another—for example, commercial over RLBs. The so-called "N-up/N-down" policy is the most widely used. This dictates that N tows be served consecutively in one direction and then an equal number in the opposite direction. Other operating policy elements (either stated or followed in practice) include the maximum amount of time the chamber will be held at its current water level in order to service an approaching tow, the maximum amount of time chambering can be delayed in order to fit another vessel in the chamber, the minimum time a recreational craft must wait for lockage, the minimum number of recreational craft that can obtain lockage, and the maximum amount of time that recreational craft must wait for service.

#### Methodology

The LOKSIM2 analytic procedures are outlined in

flowchart form in Figure 1. The figure is incomplete in that the details of all subroutine procedures are not outlined. It does, however, present an overview of the logic of the model. Operations performed by the various program routines are described briefly below.

#### Read in Input Data

LOKSIM2 requires, among other things, a time-ordered listing of tows to be locked through. This list is provided by use of a preprocessor, TOWLST1, specifically developed for this purpose (the operations of TOWLST1 are discussed later in this paper). The characteristics given for each tow on the list include tow number, arrival time, direction, number of loaded and empty barges of each of three types (jumbo, integrated, and mixed), tons of cargo, and generalized lockage type to occur (single, setover, or double). Other inputs to LOKSIM2 include the following:

1. Lengths of the warm-up and simulation periods;
2. Weekly number of RLBs arriving in each direction;
3. Arrival pattern of RLBs, determined by splitting each day of the week into user-specified intervals and designating the percentage of RLBs arriving during these intervals;
4. Number of recreational craft equal in size to a jumbo barge;
5. Operating policies in effect at the lock;
6. Probabilities that certain specialized lockage types (such as multivessel lockages) will actually occur whenever they are possible;
7. Number of jumbo, integrated, and mixed barges that can fit into the lock chamber;
8. Length and width of the lock;
9. Information on stalls (lock down time); and
10. Locking time distributions for 41 components of locking time, input as either constant, uniform, exponential, truncated normal, or empirical distributions.

#### Process Input Data

Information in the data is first checked for reasonableness. If it is unrealistic, an error message is printed and the program is terminated; otherwise, it is stored in the proper arrays. Certain events are also scheduled, including the time the warm-up begins and ends, the time the simulation ends, the first upbound and downbound commercial arrivals, the initial time to generate RLB events, and the first stall event.

#### Remove Event from Events File

For this simulation, events are removed in succession according to their assigned time. Based on what type of event is scheduled, the program takes appropriate action.

#### Call GNCOMR/Call ARVLOK

If the event is a commercial tow arrival, LOKSIM2 first schedules the arrival event for the next tow in the same direction as the current one (subroutine GNCOMR). If the event is an RLB arrival, this step is skipped. Subroutine ARVLOK then determines whether the vessel should be queued or whether it should be assigned to the lock. If it is assigned, the vessel is locked through via subroutine LOCK.

#### Call GENRLB

The GENRLB subroutine is called to generate RLB arrivals for the period that begins one hour after the current simulation time. First, however, it schedules an event signaling the next generation time--i.e., the time in the future at which it is again called.

#### Call STALL

The next stall event is scheduled via a Poisson process, and the length of the current stall is calculated (this is added to the simulation time in the next locking procedure that occurs).

#### Call ENDCHM

Whenever a vessel (recreational or commercial) is beginning the exit process for the last cut of its lockage, ENDCHM is called to determine the type of exit based on (a) whether the lockage was a single, setover, or double and (b) the locking policies. It then schedules an ENDLOK event at the current simu-

lation time plus the sum of the exit times and stores the time at which the lock will be available again.

#### Call ENDLOK

Subroutine ENDLOK is called to examine the queues in both directions to ensure that the specified operating policies are adhered to. If necessary, it will call LOCK to perform any necessary lockages. For example, if any recreational craft have waited the user-specified maximum time, they will be locked through.

#### Call ENDCUT

The ENDCUT subroutine handles the end of the first cut of a double lockage and, if possible and permitted, will process a single lockage or an RLB in the opposite direction of the double between the two cuts. It then schedules an ENDSWG operation.

#### Call ENDSWG

Subroutine ENDSWG is called at the end of each swing operation that takes place between the cuts of a double lockage. It moves the second cut of the double lockage into the lock, checks to see whether there is room left in the chamber for any RLBs, obtains the chambering time for the second cut, and schedules an ENDCHM event at the appropriate time.

#### Call ENDWRM

If the chosen event denotes that the end of the warm-up period has been reached, ENDWRM will zero out accumulated statistics, write out summary warm-up queueing statistics, and schedule a queueing statistics dump at the end of each day.

#### Call ENDSIM

Subroutine ENDSIM is called to dump the accumulated queueing statistics at the end of the simulation time. The program is then terminated.

#### Call LOCK

Subroutine LOCK is the core of the LOKSIM2 program. It is called whenever a vessel or vessels require lockage. LOCK distinguishes recreational craft, light boats, and commercial tows as well as single, setover, and double lockages. It will also load into the chamber any other vessels that are in queue or that will arrive within a user-specified amount of time, if there is room. LOCK also performs the valuable function of calculating delay for each vessel as well as cumulative delays. LOCK then schedules either an ENDCHM event if the lockage was single, setover, or RLB or an ENDCUT event if the lockage was double.

#### Call QDUMP

QDUMP is called to dump queueing statistics at the end of each day. It also schedules the next dump in 24 hours from the current simulation time.

#### Example

An example will serve to clarify the steps outlined above. Suppose the event chosen from the events file indicates a commercial tow. First, the next commercial arrival in the same direction is scheduled via GNCOMR. ARVLOK then either assigns the lock to the tow or queues it if the lock is busy. If

assigned, subroutine LOCK is called to process the tow up to its exit. If the lockage is a double, LOCK schedules an ENDCUT event; otherwise, an ENDCHEM event is scheduled (both of these events are scheduled at whatever the simulation time is after LOCK has performed its function). Control is then transferred back to the point where another event is removed from the events list. If the next event shows a vessel arriving during the time the current vessel was being processed, it is queued by the appropriate routines. When the event previously scheduled by LOCK is chosen, if the lockage is a double, control is branched to ENDCUT, where the tow is further processed and an ENDSWG event is scheduled. Control is again returned to the top of the loop and branches to ENDSWG. ENDSWG processes the tow and schedules an ENDCHEM event, and control is returned to the top again (if the lockage was not a double, ENDCUT and ENDSWG would have been bypassed). ENDCHEM then executes and schedules an ENDLCK procedure, and, after another pass through the loop, control is branched to ENDLCK, where operations on this tow are finally completed. All vessels that arrive during the processing of this tow are queued, but some may be locked through with it if conditions permit. However, other nonvessel events (e.g., a stall) can take place during the processing of the tow.

#### Preprocessor Operations

A separate model was constructed to provide LOKSIM2 with a list of tows of varying characteristics to be locked through. This model, in effect a preprocessor, was named TOWLST1. Essentially, it takes aggregate barge, commodity, and tow data and uses them to create the information necessary for LOKSIM2. TOWLST1 is based on the previous modeling efforts, TOWGEN (5) and LOCALC (2), but has features that are unique to each.

TOWLST1 can be broken down into two basic parts. The first restructures input data into lists and distributions, which are then sampled in the second part to create tows of the required characteristics. Tows are created until one of two situations occurs: (a) the simulation time is exceeded by the assigned arrival time at the lock or (b) the total barge matrix is exhausted.

#### Read in Input Data

TOWLST1 currently recognizes three barge and/or tow types: jumbo, integrated, and mixed (these were used to be consistent with PMS data). The information required here is as follows:

1. Percentage tow frequencies for tow sizes of 1-18 barges by direction and type;
2. Probabilities that single, setover, and double lockages will occur for each barge type and tow size;
3. Commodity tonnages to move upstream and downstream (eight commodities are currently recognized: coal, petroleum, chemicals, metallic ores, nonmetallic minerals, stone-clay-cement, grain, and "other");
4. Average loadings of the eight commodities in each barge type;
5. Percentages of commodities allocated to the different barge types; and
6. Dedicated equipment percentages for each commodity by barge type.

#### Convert Tonnages to Loaded Barges

Tonnages are converted to loaded barges as follows:

$$LD_{ibk} = [(ODTONS_{ik} * PCTBRG_{bk}) / TNSBRG_{bk}] + 0.5 \quad (1)$$

where

- $LD_{ibk}$  = loaded barges of commodity k in barge type b to move in direction i,
- $ODTONS_{ik}$  = tons of commodity k to move in direction i,
- $PCTBRG_{bk}$  = percentage allocation of commodity k to barge type b,
- $TNSBRG_{bk}$  = average loading of commodity k in barge type b, and
- 0.5 = term added to correctly round to nearest integer.

#### Calculate Number of Required Empty Barge Movements

Given the number of loaded barges that are required to move the given tonnages, the number of empty barges can be calculated by considering the movements of dedicated equipment and then the number of empty movements needed to balance all barges. The number of empty dedicated equipment barges is found by multiplying the number of loaded barges in the opposite direction by the dedicated equipment percentage:

$$DEDMT_{ibk} = LD_{jbk} * DEDPCT_{bk} + 0.5 \quad (2)$$

where

- $DEDMT_{ibk}$  = empty dedicated equipment barges of commodity k and barge type b to move in direction i,
- $LD_{jbk}$  = loaded barges of commodity k and barge type b moving in direction j (opposite of i), and
- $DEDPCT_{bk}$  = dedicated equipment percentage for commodity k in barge type b.

The empty movements required to balance barges are found by

$$BALMT_{ib} = \max [\sum_k (LD_{jbk} + DEDMT_{jkb}) - (LD_{ibk} + DEDMT_{ibk}), 0] \quad (3)$$

where  $BALMT_{ib}$  is the empty balance movements of barge type b in direction i and j is the direction opposite i. When dedicated equipment percentages are 100 percent, there are no corresponding balanced empty movements.

#### Calculate Number of Tows of Each Type

To this point, the numbers of loaded and empty barges of each type that must move in each direction have been calculated. The number of tows needed to move these barges is then determined by using information about average tow sizes. Once average tow sizes are computed, the number of tows is found by dividing the total number of barges by the average tow size:

$$TOWMV_{ib} = (SUBTOT_{ib} / AVTSIZ_{ib}) + 0.5 \quad (4)$$

where

- $TOWMV_{ib}$  = tows of type b to move in direction i,
- $SUBTOT_{ib}$  = total number of barges of type b in direction i
- =  $\sum_k (LD_{ibk} + DEDMT_{ibk}) + BALMT_{ib}$ , and
- $AVTSIZ_{ib}$  = average tow size for barge type b in direction i.

#### Establish Randomized List of Tows of Each Type

The first step in establishing a randomized list of

tows by type is to establish a cumulative matrix of the number of tows of each type to move in each direction. Once this matrix is set up, a random number procedure is used to select a cell in the matrix, which results in a random selection of the tow types to appear consecutively in the tow list. This is done for each direction separately.

#### Establish Cumulative Distribution Function of Tow Sizes

Establishing a cumulative distribution function of tow sizes is a relatively simple procedure that converts tow frequency input data to a cumulative distribution. This is done so that a size can be selected for a tow by sampling with replacement--i.e., by Monte Carlo sampling.

#### Establish Cumulative Distribution Function of Lockage Types to Occur

LOKSIM2 requires that each tow that arrives at a lock be assigned a generalized lockage type: single, setover, or double. This determination is controlled by the nature of the input data previously discussed. The routine discussed here constructs a cumulative distribution function from the input data so that Monte Carlo sampling can later be accomplished.

#### Determine Arrival Time at Lock

Tow arrival times are assigned under the assumption that they occur randomly throughout the simulation period and can thus be modeled as a Poisson process. Specifically, the following equation is used:

$$t = (1/\lambda) \log_e [1/1 - F(t)] \quad (5)$$

for  $0 \leq F(t) < 1$ , where  $F(t)$  is the probability that an interdeparture gap  $< t$ .  $\lambda$  is defined as the mean tow arrival rate at the lock and is found by dividing the total number of tows by the total simulation time.

To determine the departure time of the  $i$ th tow ( $t_i$ ), TOWLST1 obtains a random number from the random number generator, uses Equation 5 to compute the headway, and then assigns the arrival times as

$$T_i = T_{i-1} + t \quad (6)$$

#### Select Direction for Tow

Selecting a direction is a simple matter of determining the probability of obtaining one direction over another based on the number of tows, as follows:

$$\text{Prob(up)} = \text{TOWS}_{up} / (\text{TOWS}_{up} + \text{TOWS}_{down}) \quad (7)$$

Once this is established, a random number between 0 and 1 is chosen. If it is less than or equal to  $\text{Prob(up)}$ , the direction is up; otherwise, it is down.  $\text{Prob(up)}$  is then revised to reflect the fact that a tow of one direction has been removed.

#### Determine Tow Type

Tow type is determined by using the randomized lists described above. Given the direction, the appropriate list is pointed to and the entries are taken off it in succession. Near the end of the simulation period, one list may become exhausted. In this event the list is reused, starting at the top.

#### Determine Tow Size

Given direction and type, tow size is selected by

randomly sampling the cumulative distribution function established previously. Near the end of the simulation period, a tow size may be selected that exceeds the available number of barges. In this case, tow size is set equal to the number of remaining barges.

#### Determine Number of Loaded and Empty Barges

TOWLST1 uses the binomial probability distribution to determine the number of loaded and empty barges. This is a discrete distribution suitable for modeling phenomena with two possible outcomes, usually denoted as "success" and "failure". The distribution function is simply a summation of consecutive terms; i.e.,

$$F(x) = \sum_0^x b(n, p) \quad (8)$$

where  $b(n, p) = \binom{n}{x} p^x (1-p)^{n-x}$ .

Given direction and type, TOWLST1 calculates the probability of a "success" (obtaining a loaded barge) as

$$p = \sum_k LD_{ibk} / (\sum_k LD_{ibk} + \text{TOTLMT}_{ib}) \quad (9)$$

where TOTLMT is the sum of dedicated equipment and balance empty barges and where direction  $i$  and barge type  $b$  have been previously determined by the program.

Next, TOWLST1 samples from  $b(n, p)$ , where  $n$  is equal to the tow size, to determine the number of loaded barges. Empty barges are found by subtraction. The terms in Equation 9 are then revised to reflect the number of loaded and empty barges that remain.

#### Determine Lockage Type to Occur

TOWLST1 samples the cumulative distribution functions set up previously. Lockage types are found as either single, setover, or double. This determination is based solely on the nature of the input data, which in turn is a function of tow size and type.

#### Write Tow Characteristics to Tow List for Input to LOKSIM2

As the characteristics of each tow are completed, they are written to a file that is eventually used by LOKSIM2.

#### Select Characteristics of Next Tow

After writing tow characteristics to the tow list, TOWLST1 loops back to determine the arrival time of the next tow. This loop is continued until one of the two stopping criteria is met.

#### LOKSIM2 Output

The following statistics are included in the LOKSIM2 output: number of lockages, lockages with hazardous cargo, loaded barges, empty barges, tow size (mean, minimum, maximum), commercial cargo tonnage, and processing time (mean, standard deviation, minimum, maximum). Information on the distribution of delay time is also provided. These outputs are presented separately by direction (up, down, and total) and lockage category (commercial, recreational-light, mixed, and total). A separate table reports the current, mean, standard deviation, and maximum queue length at the end of each day, by direction and lockage category. This is quite useful for identifying infinite queuing situations with unstable traffic and delay statistics.

## ESTIMATION OF LOCK CAPACITY

Application of Model to Upper Mississippi River System Locks

For the purposes of this study, the Upper Mississippi system was defined as being those locks on the Mississippi River from Locks and Dam 27 just north of St. Louis, Missouri, upstream to Locks and Dam 1 just south of St. Paul, Minnesota, plus all the locks on the Illinois River. Because it was deemed impractical to analyze the effects of all alternatives at each lock, a series of representative locks was chosen for each river. It was felt that these locks were indicative of the systems at different points. These were Locks and Dams 2, 10, 16, 19, 25, 26, and 27 on the Mississippi and Brandon Road, Starved Rock, and Peoria on the Illinois. The results from these locks were then applied to neighboring locks.

Calibration of the model was carried out first. This basically involved matching generated empty-barge movements to 1976 and 1977 PMS data. Integrated barges were assumed to be 100 percent dedicated--i.e., each loaded-barge movement generates an opposite direction empty-barge movement. Dedicated equipment percentages of the other two barge types were varied until the total empty barges generated produced a ratio of total barges to total kilotons of commodity traffic that matched the ratio shown in PMS (1.00 to 1.10 at most locks). This calibration was performed individually for each lock, and the resulting dedicated equipment percentages were used for all subsequent model runs.

Distributions of lockage component time were estimated by analyzing PMS data for 1976 and 1977. Uniform distributions were used in all cases except for gate operating time and RLB entry and exit times, where constants were used.

Forecasts of upbound and downbound tonnage by commodity group at each lock for the years 1977, 1990, 2000, 2010, and 2040 were made by the Corps of Engineers. Forecasts for years between these dates were made by using linear interpolation. Since the objective of the analysis was to produce a complete delay curve that captures the relation between average tow delay and annual commodity tonnage throughput, the exact year in which a particular tonnage level is achieved is relatively unimportant. The main use of the forecasts is to preserve the commodity mix expected at the lock at various traffic levels.

The commodity mix also affects the seasonality of traffic demand, which greatly influences capacity and delay. To incorporate the effect of seasonality, each lock was simulated for each of four seasonal months: January, April, July, and October. Each such month represents conditions for an entire season (winter, spring, summer, and fall, respectively), composed of the seasonal month plus the preceding and following months. The portion of the annual tonnage that would appear at the lock during the seasonal month was calculated as follows:

$$\text{Seasonal month tons} = (\text{tons in season/days in season}) \times \text{days in seasonal month} \quad (10)$$

Data for this calculation, which consist of monthly tonnage by commodity group, were taken from PMS observations for 1976 and 1977. This method has the advantage of capturing seasonality without giving undue weight to an individual seasonal month. Later in the analysis it was discovered that two periods, peak (April to October) and off-peak (November to January), would work as well as four seasonal months. Peak also assumed a July recreational traffic level, whereas off-peak assumed no

recreational traffic. Expansion factors for peak and off-peak periods were calculated in much the same way as those for seasonal months.

Given the above, the model was run under existing conditions for 1977 and 1990. Capacity was estimated for the representative locks by using the method of formulating delay curves presented in the next section of this paper.

It is important to recognize that lock capacity is very sensitive to tow size. Therefore, in this study results were produced at each lock under two tow-size assumptions: (a) the existing tow-size distribution would be maintained and (b) tow sizes would increase significantly over the next 30-50 years.

Formulation of Lock Delay Curves

On completion of the model runs, estimates of annual traffic were made, and estimates of annual delay were obtained by weighting the delay in each period by the ratio of tows in that period to total tows. The example given in Table 1 clarifies these procedures. From Table 1, annual traffic = 14 944 kilotons and annual delay =  $107 \times (2010/2451) + 31 \times (441/2451) = 93$  min.

The traffic and delay estimates thus arrived at were expressed in the form of the following hyperbolic delay function:

$$d = Dq/(Q - q) \quad (11)$$

where

$d$  = average tow delay at flow  $q$ ,  
 $D$  = average delay at flow  $Q/2$ ,  
 $q$  = annual lock commodity traffic, and  
 $Q$  = physical capacity of the lock.

This functional form was selected when sensitivity tests revealed that it produced an excellent fit to the simulation data in the region where flows exceed 50 percent of capacity (i.e., the high-delay region) and an acceptable fit in the low-flow region. This curve also has the essential properties that delay is zero at zero flow and infinite at 100 percent of capacity use and the desirable feature that one of its parameters is the estimated physical lock capacity.

Delay curve parameters  $Q$  and  $D$  were computed from two data points  $(q_1, d_1)$  and  $(q_2, d_2)$ . It was found that the best results were obtained when  $(q_1, d_1)$  was at a traffic level that produced about 50 percent use of the lock and  $(q_2, d_2)$  at a traffic level that yielded about 95 percent use. Use, which is defined as the time the lock is busy divided by the total time in the month, is one of the output items from the model. In some cases, interpolation was necessary to find traffic levels that produced 50 and 95 percent use. The equations used to calculate  $Q$  and  $D$  are

$$Q = \{ (1 - d_1/d_2) / [1 - (d_1 q_2)/(d_2 q_1)] \} q_2 \quad (12)$$

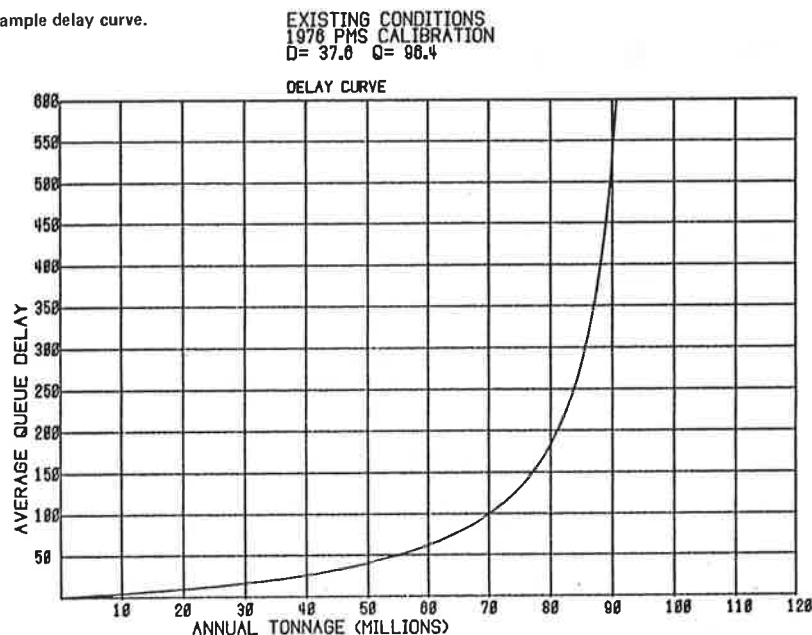
$$D = d_1(Q - q_1)/q_1 = d_2(Q - q_2)/q_2 \quad (13)$$

Table 1. Procedure for determining annual traffic and annual delay.

Period	No. of Tows	Delay (min)	Kilotons	Expansion Factor	Adjusted Kilotons
Peak	2010	107	2573	5.18	13 328
Off-peak	441	31	592	2.73	1 616
Total	2451				14 944

Note: Expansion factor = days in period ÷ days in seasonal month.

Figure 2. Sample delay curve.



A sample delay curve plot for existing conditions at the new 1200-ft chamber under construction at Locks and Dam 26 is shown in Figure 2. The physical capacity (Q) is 96.4 million tons/year and represents the maximum traffic level that can be supported by the lock, given existing tow sizes and ideal conditions. Because ideal conditions cannot be attained, it is necessary to define operational capacity to be at a level somewhat less than physical capacity. During the course of the study it was found that operational capacity can be estimated by selecting a point on the delay curve beyond which the rise in the curve is essentially vertical. In most cases, this occurs when the flow is 90-95 percent of capacity and average delay is in the range of 7-10 h. This implies that the operational capacity of Locks and Dam 26 under existing conditions (with the existing tow-size distribution) is approximately 92 million tons (95 percent of physical capacity). Of course, other criteria could be used to select operational capacities. The delay curve itself is the important result presented here.

The delay curve method of estimating capacity proved to be an efficient procedure. After calibration verified the applicability of the method, all that was required was to run the model at different traffic levels so that peak runs produced levels of lock use of 50 and 95 percent. Off-peak runs were then made with the same annual commodity flows. Thus, only two points were necessary, each of which consisted of extrapolations that used peak and off-peak runs.

#### SUMMARY AND CONCLUSIONS

The purpose of this research was to develop and apply methods of estimating the capacity of navigation locks on inland waterways. A detailed simulation model with a variety of user-specified parameters was developed, tested, and applied to locks in the Upper Mississippi River system. Input data can be easily obtained from the Corps of Engineers PMS. Output from this model was then used to generate delay curves from which operational capacities were derived for existing conditions.

A variety of system improvement scenarios were also formulated. These were necessary because future demand for waterway transportation on the Upper Mississippi was projected to be higher than the current system can support. Since the effects

of the improvements accrue to various input components of the model, simulation of them was a straightforward process. Delay curves were then developed for each alternative. The curves can be used to estimate the physical and operational capacities and can also be used to determine at what point in time operational capacities are reached, if commodity forecasts are trustworthy. In this way future bottlenecks in the system can be identified so that waterway planners can be provided with the information needed to formulate and analyze various improvement plans.

#### ACKNOWLEDGMENT

The work reported in this paper was carried out by the University of Tennessee Transportation Center under contract to the North Central Division (NCD) of the U.S. Army Corps of Engineers. Greg Kandl and Don Ward of NCD programmed the LOKSIM2 model and performed numerous analyses of PMS data files to generate model input. Harvey Kurzon of NCD was the technical monitor of the work performed. The assistance of numerous other Corps personnel, particularly in the St. Louis District and the NCD, is gratefully acknowledged.

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*Publication of this paper sponsored by Committee on Inland Water Transportation.*