EVALUATION OF ALTERNATIVES FOR MANAGING LOCK TRAFFIC ON THE UPPER MISSISSIPPI RIVER

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1. INRODUCTION AND STATEMENT OF WORK

The Center for Transportation Studies (CTS) at the University of Missouri-St. Louis (UMSL) has been engaged by the St. Louis District of the U.S. Army Corps of Engineers to provide a detailed analysis of how the potential impacts of alternative traffic management policies at locks in the Upper Mississippi River (UMR) Transportation System might vary under different traffic levels. The Corps' Institute for Water Resources, through its Navigation Economic Technologies (NETS) program, had contracted previously with the CTS to design and develop a simulation model for use in evaluating alternative traffic management policies for UMR locks at calendar year 2000 traffic levels. That model and analysis are documented in CTS [2005]. In the prior study, the researchers concluded that, at 2000 traffic levels, the national economic benefits that could be derived from alternative traffic management policies were very small. Further, the benefits would accrue to some users at a cost to others and the barge industry is unsupportive of traffic regulation under current conditions. There remained a question of whether imposition of an alternative scheduling regime might be justified under higher traffic levels or under conditions where operating capacity is curtailed.

In performing the current study to investigate the effects of alternative sequencing policies under higher traffic levels, the CTS has (1) enhanced the previous simulation model, (2) implemented it on a new software platform, (3) examined an expanded set of alternative lock traffic management policies and (4) determined that alternative traffic management practices could significantly benefit users of the Upper Mississippi River transportation system at higher levels of traffic intensity. We also deduced that the alternative traffic management policies evaluated here might significantly benefit system users during periods of congestion that result from navigation restrictions imposed during future new lock construction or from degradation in the performance of the existing UMR locks.

2. LOCATION OF THE STUDY AREA

The UMR Transportation System consists of 29 locks between St. Paul, MN and St. Louis, MO, and extends approximately 670 miles. The transportation system supports commercial traffic patterns far beyond the region contiguous to the Mississippi River and its tributaries. The geographic scope of this study includes model analysis of navigation traffic originating or terminating within a five-lock system on the UMR waterways system, specifically Locks 20-25, as well as traffic originating and terminating outside of the five-lock system utilizing Locks 20-25. Figure 1 presents a map of the locations of the locks and dams of the UMR segment of the inland navigation system. The sub-segment of the UMR system analyzed in this report consists of the portion of the UMR system beginning with Lock 20 to the north and ending with Lock 25 to the south.

Queues of recreational and commercial vessels form periodically upstream and downstream at each of these locks. Each lock is surrounded by different terrain and river conditions that affect the efficiency with which it can process tows of different configurations and each lock has slightly different mixes of vessel traffic with differing arrival patterns.

3. OPERATION OF THE UMR NAVIGATION SYSTEM

Vessels are processed at UMR locks using a first-come, first-served (FCFS or FIFO) policy, but with some priority granted to commercial vessels without barges and to recreational vessels as they can be processed quickly without significantly delaying the processing of commercial vessels with barges. Under extreme operating conditions, the FIFO policy is waived with the agreement of commercial tow operators, and tows are processed through a congested lock in sequences that allow greater local efficiencies to be achieved. There is considerable variation in the arrival, composition and configuration of tows in the UMR. During the winter months, vessel arrivals are relatively infrequent due to ice and other adverse operating conditions on the river and the locks are under-utilized. Traffic levels increase rapidly in March, peak during the summer and fall months, and decline substantially again in December after the completion of southerly movements of seasonal grain shipments. Both commercial and recreational traffic are subject to systematic variation according to day of the week and time-of-day. Unusual events, such as extreme weather conditions, vessel and lock accidents, and equipment malfunctions occasionally prevent or halt lock operations.

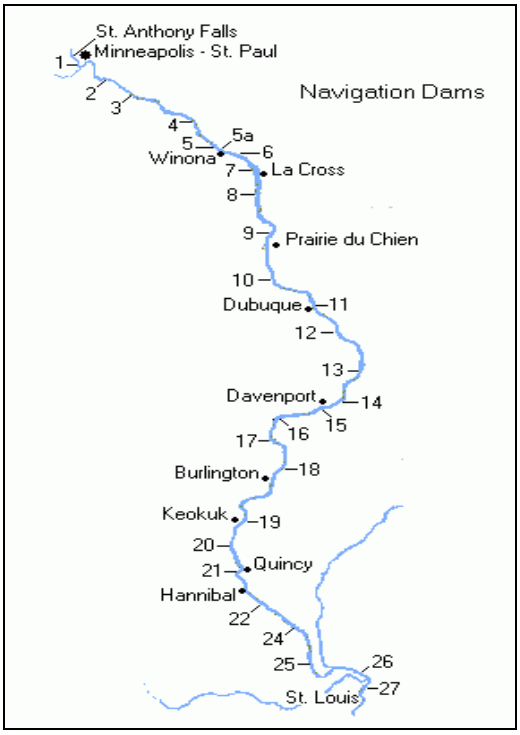

Figure 1 Map of the Upper Mississippi River (UMR) Navigation System
Source: U.S. Army Corps of Engineers

Better utilization of UMR resources and improved services to commercial users might be achieved by employing intelligent scheduling mechanisms for river traffic and lock operations. For example, CTS [2005] proposed that vessels queued at a lock be selected for service in a manner that would be expected to clear the existing queue in the shortest time interval and produced an integer programming formulation of this problem and found an optimal clearing schedule for UMR locks could be derived by complete enumeration. In the optimal solutions, the “most valuable” or “most efficient” vessels are generally placed at the head of the queue.

Recognizing that the sequencing problem is very dynamic and subject to random events (including normal operations with normal operating variance), we investigate how the system might operate under various predefined sequencing rules that exploit this general principal. We judged that a straightforward set of scheduling rules that are transparent to the industry would be better received than an arcane deterministic optimizing model that requires constant updating of data and constant regeneration of solutions as detailed events occur at each lock.

Given the dynamic nature of the system, a realistic simulation model is needed to evaluate the impact of alternative operating rules on the performance of the locks and the likely differential impact on the various users of the UMR navigation system. The model should:

- Accommodate multiple classes of traffic with different arrival patterns, itineraries and service characteristics;
- Provide a queueing and processing structure that can dynamically alter service priorities of queued vessels while conforming to physical realities of upstream and downstream traffic movements to and from the locks;
- Produce detailed measures of system performance that show the mix of vessel traffic movements and waiting times in the vicinity at each lock at different times of the year;
- Facilitate experimentation with alternative sequencing rules under different levels of commercial barge traffic and under different operating characteristics at each lock; and
- Facilitate tests of statistical significance of observed effects on system performance.

In this paper, we describe the construction and application of a discrete-event simulation model with these characteristics. We discuss the several hundred statistical models used to produce the time-varying parameters that drive system performance. We produce statistics that validate the simulated performance against historical data. Finally, we illustrate the use of the model to compare the simulated performance of the UMR navigation system under the alternative operating rules and with increased traffic levels and we share insights derived from the results.

4. MODEL STRUCTURE

We constructed such a refined simulation model using ARENA 10.0 based upon detailed lock operating statistics compiled for calendar year 2000 provided by the USACE and maintained in their Operations and Maintenance of Navigation Infrastructure (OMNI) lock operations database. The OMNI database contained information regarding 18,700 lockages completed by vessels at UMR Locks 20 through 25. Figure 2 presents a screen capture of the Arena 10 UMR simulation model of Locks 20 through 25 in operation with the different colored rectangle representing differing vessel traffic in the system.

The simulation entities that represent UMR vessels are partitioned into six different classes differentiated by barge configurations and related locking characteristics. The classes are designated as follows (in decreasing order of their average times to complete a lockage operation):

1. double tows (tows that require locking in two steps), which take an average of 117 minutes to process at a lock;

2. jackknife tows (tows that must be partly disconnected and pivoted to fit in the locking chamber), which take an average of 82 minutes to process;
3. knockout tows (tows for which the towboat must be disconnected from the barges and reconnected after following the barges through the lock), which take an average of 63 minutes to process;
4. singles (tows that can be locked directly without reconfiguration), which take an average of 33 minutes to process;
5. single commercial vessels without barges (tows that may be proceeding to the next pool to pick up barges, or maintenance vessels), which take an average of 24 minutes to process; and
6. recreation vessels (individual or groups of recreational boats that undergo lockage operations together), which take an average of 14 minutes to process.

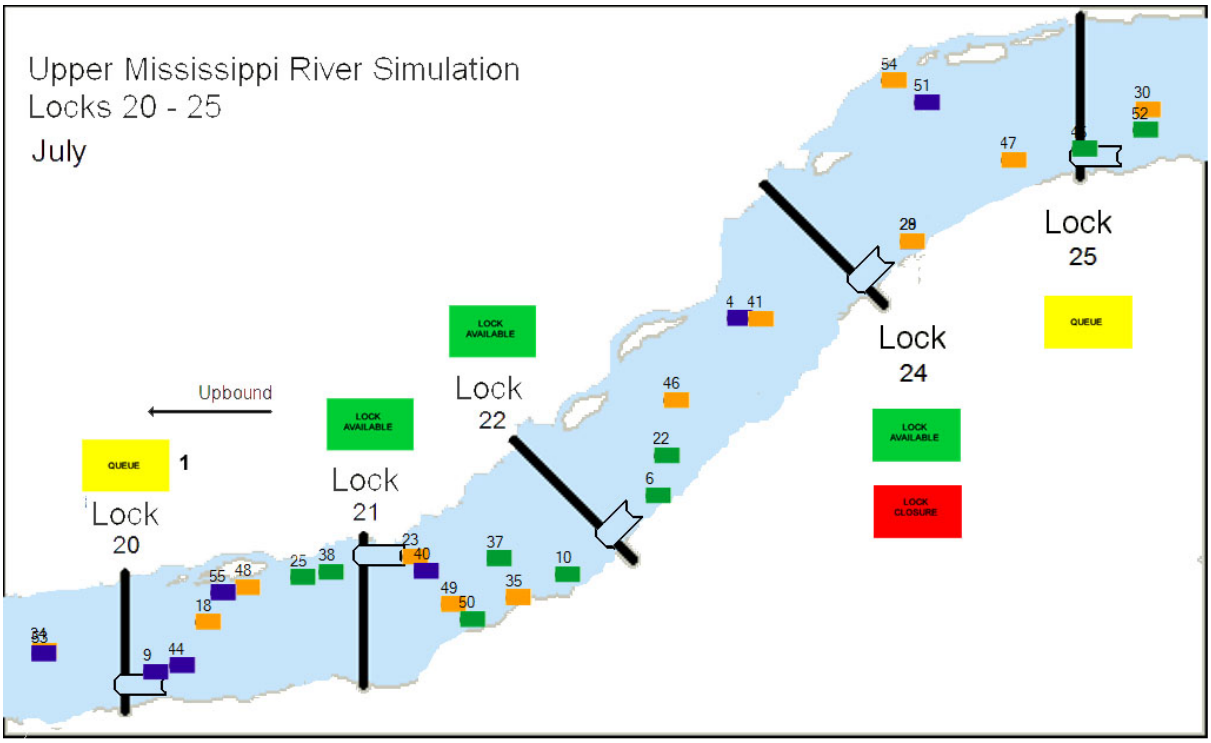

Figure 2. Screen Capture of the Arena 10 Display Diagram for the UMR Simulation

Recreation vessels gather in a designated area (upstream or downstream) when waiting for the lock, so as not to interfere with (or be placed at risk by) commercial tows. Commercial vessels waiting for lockage similarly position themselves to allow traffic to clear the lock from the opposite direction. Vessels wait for a signal from the lockmaster that it is their turn to enter the chamber. Figure 3 is a schematic diagram of the resulting queueing and service system at a lock. At each lock there is a single server (the lock chamber) with four queues from which access may be granted to:

1. a commercial vessel with or without barges, moored for upstream lockage (at UCB, designated as the upstream commercial mooring buoy) waiting for the lock to become available;

2. a commercial vessel, with or without barges, moored for downstream lockage (at DCB) waiting for the lock to become available;
3. a recreational vessel or group of recreational vessels moored for upstream lockage (at URB) waiting for the lock to become available; and
4. a recreational vessel or group of recreational vessels moored for downstream lockage (at DRB).

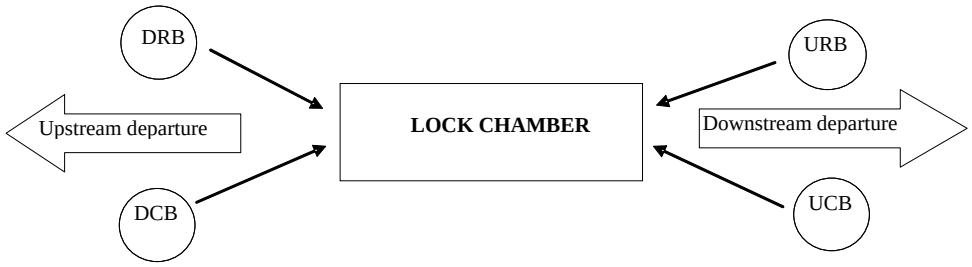

Figure 3. Schematic of a lock service system

A lockage operation is called an "exchange" when a vessel enters the chamber after waiting for the completion of lockage of a vessel traveling in the opposite direction. It is called a "turnback" when a vessel enters the lock after waiting for completion of lockage of a vessel traveling in the same direction and a recycling (turnback) of the lock to bring the water level in the chamber back to the level of the pool in which the vessel is waiting. If vessels arrive from either direction when the lock is empty, the chamber can be configured (turned back, if necessary for the direction of travel) to allow the vessel to enter the chamber without delay. Such lockages, with no waiting time for the vessel, are called "fly" lockages. Different distributions for locking times must be employed for each of the six classes of vessels and they must be adjusted for whether their movement is upstream or downstream at a particular lock, and whether the lockage operation is an exchange, turnback or fly (thus yielding 5x2x6x3 = 180 different service time distributions for the five lock chambers in this section of the UMR).

To handle interdependencies of tow movements, we employ a Markovian model structure with non-stationary transition probabilities by which a decision for each vessel departing from a lock is made either (1) to continue to the next lock in the same direction without stopping, or (2) to proceed to a destination in the current pool at which the vessel will be reconfigured for its next movement upstream or downstream. In the current implementation of the model, the simulated vessels that do not proceed directly to the next lock are "terminated" after completing lockage and their subsequent activity is handled by regenerating vessels and tow configurations at random in the respective pools for upstream or downstream travel. Vessels that proceed to the next lock without stopping are assigned a transit time in the pool that depends on the tow configuration and time of year, thus allowing for seasonal differences in river flow and traffic conditions.

We employ lognormal distributions for pool-transit times and lockage times. Because of significant differences in their coefficients of variation, we develop separate equations for mean lockage times for double tows, singles (including jackknife and knockout), singles without barges and recreational vessels. For mean pool transit times, we develop equations dependent on the type of tow and the month of pool-transit. Figure 4 presents a schematic diagram of the resulting flow of vessel traffic through the UMR simulation model.

4.1. Lock arrival processes

Commercial vessels are generated randomly and assigned types with probabilities that are adjusted for systematic monthly, day-of-week, and hour-of-day differences in their relative composition upstream and downstream at each lock. We generate all arrivals upstream at Lock 25 and all arrivals downstream at Lock 20 as random arrivals using ARENA's facility for non-stationary exponential distributions, allowing for monthly seasonal variation in vessel traffic. We also employ non-stationary exponential generators for the traffic upstream and downstream at locks 21, 22 and 24 for the traffic that does not proceed directly from the previous lock in the same direction. To impose the time-of-day and day-of-week effects in the arrival of commercial tows – especially for single tows, we generate the commercial arrivals at each lock upstream and

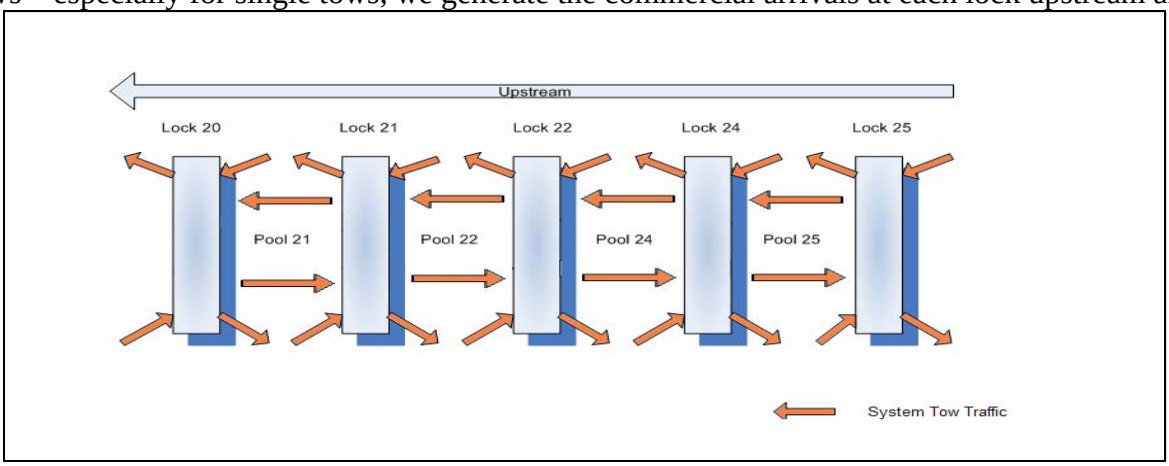

Figure 4. The UMR Simulation Model Schematic Diagram - Tow Traffic

downstream with non-stationary exponential inter-arrival times adjusted on a monthly basis, and with arrival rates inflated by the product of factors for hour-of-day and day-of-week effects so that we generate the arrivals at the maximum average rate for the given time-of-day, day-of-week and month. Then we retain the appropriate proportion of those arrivals for use in the model. For commercial vessels, we use the same proportionate day-of-week and time-of-day effects for aggregate commercial arrival rates in each direction at each lock. The multiplicative adjustments for time-of-day and day-of-week are made as if they are independent of each other. The process for thinning commercial arrivals is depicted mathematically as follows.
Let:

- DAY be the current day of the week (1=Sun, 2=Mon, …,7=Sat);
- HOUR be the current hour of the day (1,2, … ,24);
- MXCHR be the maximum average arrival rate for any hour of day relative to the average arrival rate for all hours of the day;

- MXCDR be the maximum average arrival rate for any day of the week relative to the average arrival rate for all days of the week;
- CHR(HOUR) be the ratio of the average arrival rate for the current hour relative to the average hourly arrival rate over all hours of the day; and
- CDR(DAY) be the ratio of the average arrival rate for the current day of the week relative to the average daily arrival rate over all days of the week.

We thin the commercial arrivals, in aggregate, by admitting the ratio

$$TRC(DAY, HOUR) = \frac{CDR(DAY) * CHR(HOUR)}{MXCHR * MXCDR} \qquad (1)$$

of the generated commercial arrivals into the model. We apply similar ratios, derived for each of the types of commercial vessels, to the equations for the likelihoods that an arrival is of a given type and then normalize them to adjust the vessel-type probabilities for day-of-week and time-of-day effects.

Recreational vessels are generated separately from commercial vessels because their periodic effects are more pronounced and recreational vessels' demands for lockage are subject to different economic influences than commercial users. To impose these periodic effects, we generate recreational arrivals at each lock upstream and downstream with stationary exponential inter-arrival times at the maximum possible rate at any hour of the day in any month of the year and retain the appropriate proportion of those arrivals for use in the model. The process for thinning recreational arrivals for lockage type xxx (where xxx=25U for upstream lockages at lock 25, for example) is therefore more refined and depicted mathematically as follows. Let:

- MONTH be the current month of the year (1,2,…,12);
- RECINTxxx be the smallest average interarrival time (in hours) for any hour of the year at lock xxx;
- TRRxxx be the thinning ratio (percentage of arrivals to be recognized and processed) to apply to RECINTxxx to create recreational arrivals at the proper rate for the current hour;
- MXDARRxxx be the maximum average daily number of arrivals for lockage of type xxx in any month of the year, where xxx=20U etc.;
- MNTHRxxx(MONTH) be the ratio of daily arrival rate for the current month to the maximum daily arrival rate for any month (MXDARRxxx);
- MXDYRxxx be the maximum ratio of the arrival rate for any day to the average hourly arrival rate for all days of the week;
- DAYRxxx(DAY) be the ratio of arrival rate for the current day of the week to the average arrival rate for all days of the week;
- MXHRRxxx be the maximum ratio of the arrival rate for any hour of the day to the average arrival rate for all hours of the day; and
- HRRxxx(HOUR) be the ratio of the arrival rate to the current hour of the day to the average arrival rate for all hours of the day.

Then we have (dropping the xxx extension for brevity)

$$RECINT = 24/(MXDARR * MXDR * MXHRR) \qquad (2)$$

and

$$TRR(MONTH, DAY, HOUR) = \frac{MNTHR(MONTH) * DAYR(DAY) * HRR(HOUR)}{MXDARR * MXDYR * MXHRR}. \quad (3)$$

Applying the thinning ratio, TRRxxx, to arrivals with average inter-arrival time of RECINTxxx generates recreational arrivals for the current hour at the rate of TRRxxx/RECINTxxx per hour.

4.2. Activity times

Much of the variation in activity times is systematic – caused by differences in sizes and configurations of tows, direction of traffic, type of lockage (fly turnback or exchange) and seasonal conditions. To remove the systematic effects before generating random activity times, we partition the data according to type of tow (double or single) and direction, and construct regression models that give the logarithm of the expected processing time for the particular type of lockage or pool transit. To illustrate the net effect of the adjustments, in Figure 5 we provide plots of lockage times for all vessels at lock 24 upstream, alongside residuals of the logarithms of lockage times from the regression model after the systematic effects are removed (showing the residuals for double lockages in this case).

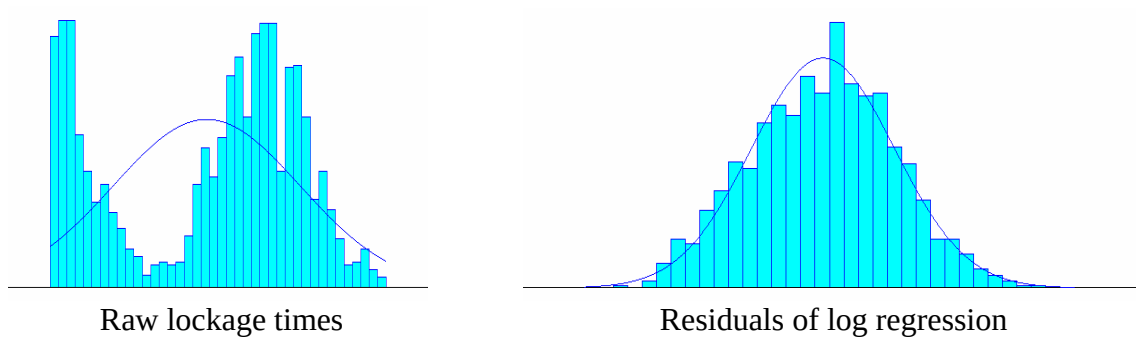

Figure 5. Removing Systematic Variation

With normally distributed residuals of the logarithms of estimated activity times, we may use the expected value of the logarithm of activity times derived from the relevant regression model, together with the standard deviation of the residuals, to calculate the mean and standard deviations of the corresponding lognormal distributions for activity times for each vessel movement. For example, the resulting regression equation in this instance for an upstream double lockage at Lock 24 (including only variables significant at the 0.05 level) was:
ln(lockhrs) = 0.599 - 0.096*feb + .080*jun - .080*jul + 0.040*sep + 0.053*oct - 0.117*turnback.

4.3. System conditions

Periods of impaired lock operating conditions (caused by adverse river conditions or lock or vessel failures that interfere with lock operations) are imposed randomly and independently at each lock at seasonally varying rates. They are imposed in the model by pre-empting the lock for the duration of the impairment. If impairment occurs while a vessel is undergoing lockage, the vessel's lockage time is extended by the duration of the impairment. If impairment occurs while a lock is unoccupied, the lock is made unavailable to process traffic for the duration of the impairment.

4.4. Traffic control at locks

Traffic control at a lock is imposed in the simulation model by having vessels hold, if necessary, at the four mooring buoys (representing positions in the pool from which commercial or recreational vessels are authorized to proceed into the chamber) until the lock is in the proper position for entry from the respective direction. A decision is made with each arrival or departure whether to reconfigure the lock. If there are no vessels queued, the lock is left in its current position, and the next vessel will be able to be processed without delay, because the lock chamber can be repositioned if necessary during that vessel's approach. When there are queues, the selection of the next vessel depends on the queue dispatch priority rule employed. With first in, first out (FIFO), for example, the vessel with earliest arrival time is chosen and the chamber is turned back after a lockage if appropriate. The higher priority vessel at the recreational or commercial mooring buoy in each direction is considered for the turnback decision in a manner that depends on the operational rule in effect.

At the end of each lockage operation, we write to an external file: the specific vessel number (which indicates point of origin and direction), the lockage operation (e.g., 21U for 21 upbound), an indicator of tow-vessel type, the time of arrival, the time of start lockage, the time of departure, whether the lockage was exchange, turnback or fly, and the vessel priority number. This enables us to identify all points in time at which a change in the system's state took place and to perform a complete statistical analysis (including dynamic queueing characteristics) with the same type of data as provided by the USACE in its OMNI database. It also allows multidimensional statistical analyses to be performed on performance statistics for each lock (and the system over-all) as experimental runs are performed under different operating rules.

5. GENERATION OF SIMULATION MODEL PARAMETERS

In addition to the multitude of parameters described above for the Poisson arrival processes, parameters are required for lockage times, likelihoods of continuing to the next lock without stopping, and transit times in the pool when a vessel proceeds from one lock to the next upstream or downstream lock. Parameters are also required for times between lock impairments and for the duration of lock impairments. Equations that determine base-line parameters for the model were derived using statistical models calibrated with year 2000 data from the USACE OMNI database. Among the statistical models are:

- Ten regression models to estimate the logarithms of the mean times to complete lockages of double tows in each direction as a function of month of year and whether lockage is exchange, turnback or fly. The adjusted mean lockage time and standard deviation of the residuals are used to calculate the mean and coefficient of variation of conditional lognormal distributions of lockage times.
- Ten regression models to give the same parameters for single vessels without barges.
- Ten regression models to give the same parameters for singles with barges, using additional indicator variables to distinguish jackknife and knockout tows.
- Ten regression models to give the same parameters for recreational vessels or groups of recreational vessels processed in a single lockage.
- Eight logistic models to estimate the likelihood of continuing on to the next lock instead of stopping for reconfiguration in the current pool. The logistic models use indicator

variables for time of year and type of tow. We generate all vessels for recreational lockages and all singles without barges locally as random arrivals.

- Eight regression models to estimate the logarithm of the mean pool transit time and its standard deviation (for vessels that make the trip without stopping, depending on type of tow and month of year),
- Ten regression models to estimate the likelihood that a randomly generated commercial vessel arriving at a lock in a particular direction will be a double tow, depending on month of the year,
- Ten regression models to estimate the likelihood that a randomly generated commercial vessel arriving at a lock in a particular direction will be a single tow with barges, depending on month of the year,
- Ten complementary regression models to estimate the likelihood that a randomly generated commercial vessel arriving at a lock in a particular direction will be a jackknife tow, depending on month of the year,
- Ten complementary regression models to estimate the likelihood that a randomly generated commercial vessel arriving at a lock in a particular direction will be a knockout tow, depending on month of the year,
- Five regression models to estimate the means for the time between impairments at a lock. These means depend on month of the year and are used as means of exponential distributions for generating impairments.
- Five regression models to estimate the average duration of impairments at each lock, once the impairment has occurred. These are used to produce the means of exponential distributions that determine the duration of impairment.

6. MODEL VALIDATION

Using the aforementioned regression and logistic models for dynamically estimating times and likelihoods for activities and events in the model, we simulated the operation of the five lock system using Arena 10 first under FIFO. We noted that there was excellent correspondence between the average monthly number of lockages simulated upstream and downstream at each lock, and the corresponding numbers of lockages recorded in the OMNI database for year 2000. Indeed, the average numbers of simulated lockages for a specific lock and direction over 100 replications were generally within 2.5% of the actual numbers recorded in year 2000. Simulated monthly seasonal patterns closely approximated the recorded year 2000 patterns. The day-of-week effects (Table 1) and time-of day effects (Table 2) for both commercial and recreational arrivals also nicely matched the year 2000 OMNI data. Our thinning processes for commercial and recreational vessels, in combination with ARENA's treatment of non-stationary exponential distributions for aggregate commercial activity, were thus confirmed to perform properly in imposing the systematic periodic effects on the arrivals.

Next in the model validation process we verified that the distribution of lockage times for the different tows and vessels at each lock (upstream and downstream) agreed with reported statistics and we examined the resulting utilization statistics and queueing statistics at each lock. The simulated and actual utilization levels were very close in each case and the queue sizes generally followed seasonal patterns. Over all, relative utilizations and queue sizes among locks also agreed with historical comparisons. The specific values of the average queue sizes determined from the OMNI data were, however, somewhat lower than simulated values for the

FIFO and FIFORECPRIO dispatching rules. This led us to further intensive investigation of the historical data in conjunction with simulation results under alternative dispatching rules, and will be discussed later in that context

Day of Week	Double	Single with Barges	Jackknife	Knockout	Single w/o Barges	Recreation
Sun	63.1 62.9	8.5 7.8	1.6 1.5	1.6 1.6	4.1 4.8	21.1 21.4
Mon	65.3 65.8	11.0 10.7	1.6 1.5	1.9 1.5	7.4 7.4	12.9 13.2
Tue	66.9 66.9	11.9 12.8	2.0 1.7	2.8 2.2	7.5 7.6	8.9 8.8
Wed	64.8 65.0	13.1 14.1	2.0 1.6	2.3 2.0	7.9 7.7	9.9 9.5
Thu	62.6 63.3	14.9 15.1	1.6 1.6	2.4 2.2	7.4 7.1	11.1 10.7
Fri	63.8 62.7	11.5 12.7	1.6 1.4	2.2 2.2	6.1 6.4	14.7 14.5
Sat	59.7 60.3	9.4 8.6	1.6 1.3	2.1 1.9	5.6 6.0	21.5 21.8

Table 1. Actual and Simulated Percentage of Arrivals by Day of Week

Hour of Day	Double	Single with Barges	Jackknife	Knockout	Single w/o Barges	Recreation
00	74.8 75.7	14.1 13.2	2.2 1.9	1.7 2.2	6.6 6.4	0.6 0.6
11	49.2 50.0	12.0 11.0	1.0 1.0	2.4 2.0	6.4 6.3	29.0 29.7
16	57.2 57.2	9.1 10.7	1.7 1.4	1.8 1.8	6.0 6.8	24.1 22.1
20	71.0 71.6	12.1 12.4	1.3 1.6	2.3 2.0	7.5 7.6	5.7 4.8

Table 2. Actual and Simulated Percentage of Arrivals by Selected Times of Day

7. ALTERNATIVE LOCK OPERATING RULES

We examined the performance of the simulated system under six different operating rules:

1. FIFO, the traditional benchmark in the simulation literature.
2. FIFORECPRIO, a variation on FIFO where priority is given to recreational vessels (the policy that closely matches the prevailing USACE guidelines).
3. FIFOFLT, whereby vessels are queued at the upstream and downstream mooring buoys in order of their arrival times, and then selected according to which vessel can complete its lockage most quickly as lockages are completed.
4. SINGPRIO, a grouped priority arrangement whereby commercial vessels that can be accommodated without reconfiguration during lockage (singles without barges and singles) receive priority over commercial vessels that do require reconfiguration (doubles, jackknives and knockouts), and recreational vessels receive priority over

commercial vessels. This is a coarse grouping that reflects relative times to complete lockages.

5. JPRIO, joint priority dispatching whereby vessels are queued hierarchically at the upstream and downstream mooring buoys according to their expected lockage times. Here, the time to turn back the lock is ignored and ties for matched types of vessels in upstream and downstream queues are broken by first-come, first-served selection.
6. FLT, fastest lockage time whereby vessels are queued at the mooring buoys in order of their expected locking times and the next vessel to lock is selected while considering whether the immediate lockage operation can be completed more quickly with a turnback, considering the additional time involved in turning back the lock and the differences in locking times of the best upstream and downstream candidates.

Progressing from FIFO to FLT, additional consideration is given to expected locking times as vessels are queued at and selected from the mooring buoys. We therefore expect that average performance would improve progressively as we proceed through the list. The average lock transit time (including time in queue, maneuvering into and away from the lock, and time in the chamber itself) is used as the key performance statistic affected by the decision rules and the results from 100 replications are in Table 3. In addition to the average lock transit time, we furnish the corresponding waiting times to show the more pronounced effects of the priority rules on vessels' waiting times.

Examining the results in Table 3, we see that the average waiting time under a purely FIFO regime differs a little among vessel categories, but not because the vessel class is given priority. Rather, the differences are attributable to the mix and intensity of traffic that the vessels confront when they arrive for lockage. Recreation vessels, for example, concentrate their activity in the busy summer months. The total lock transit time is the sum of waiting time and the time to complete the lockage for the vessel (i.e., the total time from the vessel's recorded arrival to its departure with sufficient clearance to allow the next lockage to begin). The much longer lock transit times for doubles are attributable to the longer times for the lockage operations of double lockages (approximately 3.9 times greater than for a single lockage).

Under FIFORECPRIO, the waiting times for recreational vessels drop dramatically from the FIFO values and their total lock transit times decrease accordingly, as the recreational vessels receive priority selection. The times for other vessels are affected little because the recreational lockages are completed quickly. Under FIFOFLT, vessels are queued in order of arrival but the vessel chosen for the next lockage is the one that can be locked most quickly (considering the possible differences in lock transit times for turnback versus exchange). It reduces average waiting time by about four minutes, with substantial reductions in waiting times for vessels that can be locked most quickly and increases in locking times for vessels that take longer.

Under SINGPRIO, the waiting times decrease materially for vessels that are accommodated in a single lockage and increase (to a lesser extent) for vessels that require reconfiguration in the locking process. Progressing further to JPRIO, in which vessels are queued in order of the expected processing times for the vessel class, the average queue times drop for the vessels that can be locked most quickly and increase for others. Single commercial tows, for example, experience reductions of 65 minutes (33%) in average lock transit time whereas the double tows

suffer increases of 13 minutes (5%). Further improvements in progressing from JPRIO to FLT are similar in magnitude to the benefit of going from FIFORECPRIO to FIFOFLT.

Lockage Type	FIFO		FIFORECPRIO		FIFOFLT		SINGPRIO		JPRIO		FLT	
	Wait	Transit	Wait	Transit	Wait	Transit	Wait	Transit	Wait	Transit	Wait	Transit
Double	161.1	275.7	162.9	277.5	165.6	279.3	174.1	288.8	175.3	290.1	170.6	284.2
Jackknife	178.9	262.6	183.5	267.2	144.5	226.9	191.6	275.7	112.7	193.4	101.3	183.5
Knockout	169.5	230.7	172.6	233.9	177.4	237.6	184.3	245.6	107.5	167.5	112.4	172.7
Single-Barges	161.0	192.0	163.9	194.9	138.7	169.3	100.8	131.8	99.8	130.1	94.6	125.0
Single-No Barges	155.8	179.3	157.8	181.4	120.3	143.8	91.8	115.4	91.8	115.4	86.1	109.6
Recreation	189.4	202.6	49.1	62.4	48.3	61.6	49.1	62.4	49.3	62.6	48.3	61.5
All Lockages	165.2	247.9	146.7	229.4	142.5	224.4	142.5	225.2	140.4	223.0	136.6	218.6
Replic. Av. & rule effect	A	247.5 +18.2	B	229.3 0	C	224.9 -4.4	C	225.1 -3.8	C	223.0 -5.7	D	219.1 -10.1
Inv Log & rule effect	A	234.3 +15.9	B	218.2 0	C	213.0 -5.2	C	213.8 -4.4	D	212.5 -5.7	E	208.4 -9.8

Table 3. Average waiting and lock transit times (minutes) for 100 simulated years under different operating rules

Because the lockage times and the maneuvering conditions vary according to lock and direction, we performed a two-way ANOVA with the sequencing rule as the experimental factor and lockage (20D through 25U) as a blocking factor. We also performed the ANOVA using a logarithmic transformation of lock transit times to stabilize the variances. In both ANOVA models (raw and logarithmic), the two main effects and the interaction effects were all statistically significant at the 0.0001 level. The impact of using alternative priority rules was thus shown to depend on the lock involved and on the direction of traffic.

The ANOVA results are summarized in the last two rows of Table 3. Note that a strictly FIFO policy would be expected to increase average lock transit times by 16 or 18 minutes (about 8%) relative to the FIFORECPRIO policy. At the other extreme, changing to the FLT policy would reduce expected locking times by 10 minutes (about 4.4%).

Examining the statistical significance of pairwise comparisons of average lock transit times, we concluded that all the decision rules were demonstrably superior to FIFO. The results for FIFORECPRIO and FIFOFLT were statistically distinguishable. SINGPRIO and FIFOFLT were indistinguishable in aggregate performance, but produced quite different waiting times for different classes of vessel. FLT was demonstrably the best at minimizing average lock transit time. Because the upbound and downbound statistics at a lock are necessarily interdependent, we also performed the ANOVA using lock number as the blocking variable. The average lock transit times for individual locks are presented in Table 4 at Year 2000 traffic levels for commercial vessels and at Year 2000 levels plus 10% and plus 20%. The resulting statistical inferences about the relative merits of the decision rules were the same, except that the pairwise differences in performance under JPRIO versus FLT were distinguishable only after the logarithmic transformation.

Average Lock Transit Times (minutes) at Year 2000 Traffic Levels					
	Lock Number				
Sequencing Rule	20	21	22	24	25
FIFO	209.7	186.6	316.1	247.7	277.7
FIFORECPRIO	198.8	177.3	291.7	228.7	250.0
FIFOFLT	197.7	178.0	289.2	227.2	232.2
SINGPRIO	191.7	174.4	289.7	226.1	244.4
JPRIO	192.5	173.9	283.6	224.1	240.7
FLT	192.2	176.5	279.6	223.6	223.1

Table 4. Effects of rules at individual locks

We then evaluated several re-sequencing alternatives with 10% and 20% increases in the level of demand relative to 2000 levels (keeping the same mix of vessel and lockage types) and the resulting average lock transit times (waiting for lockage and lockage time) are presented for the individual locks in Table 4b. It is interesting to see the differential effects of the policies at higher traffic levels and the particularly large increases in transit times with SINGPRIO and FIFORECPRIO at the busiest southernmost locks. At higher traffic levels, using FLT relative to FIFORECPRIO has substantial positive effects at the most congested locks, Locks 22-25, but much smaller and indeterminate effects at the less congested locks, Locks 20 and 21.

Average Lock Transit Times (minutes) at Year 2000 Traffic Levels plus 10%					
	Lock Number				
Sequencing Rule	20	21	22	24	25
FIFORECPRIO	255.3	214.1	500.3	334.6	386.5
SINGPRIO	244.6	208.6	476.8	331,4	370.4
FLT	241.3	213.6	431.5	313.4	307.8

Average Lock Transit Times (minutes) at Year 2000 Traffic Levels plus 20%					
	Lock Number				
Sequencing Rule	20	21	22	24	25
FIFORECPRIO	360.9	282.0	1934.1	760.0	907.0
SINGPRIO	348.4	275.4	1845.6	718.1	913.6
FLT	355.0	282.3	1340.6	635.1	628.5

Table 4b. Effects of rules at individual locks with traffic increases

The time spent in a queue waiting for lockage increases considerably at higher traffic levels. The average times that vessels spend waiting to enter the locks are shown in Table 5 for the higher traffic levels. These results demonstrate the increasing benefits of FLT as demand increases, especially for the single tows. With a 10% increase in demand relative to 2000 traffic, FLT reduces overall average waiting time by about 25 minutes (about 10%) and about 36 minutes (about 14%) versus SINGPRIO and FIFORECPRIO, respectively. With a 20% increase in demand relative to 2000 traffic, FLT reduces overall average waiting time by around 3 hours (about 25%) compared to SINGPRIO and FIFORECPRIO.

Type	FIFORECPRIO		SINGPRIO		FLT	
	+10%	+20%	+10%	+20%	+10%	+20%
Double	288	880	311	1003	287	795
Jackknife	321	904	344	1029	125	158
Knockout	294	808	315	933	140	184
Single	278	797	130	177	119	153
Singles without barges	267	718	121	166	106	133
Recreation	53	69	53	56	52	55
All Lockages	255	757	243	729	219	559

Table 5. Average waiting times (minutes) in study region over 100 simulated years with increased demand

The distribution of waiting times under the different re-sequencing rules is also an important measure of performance. Table 6 provides the median and 95th percentile of waiting times for the rules in Table 5 with a 20% increase in demand relative to 2000 traffic. In general FLT reduces the median waiting time substantially relative to FIFORECPIO and SINGPRIO. For example, with a 20% increase in demand, the median waiting times for double lockages are over 5.5 hours with FIFORECPIO and SINGPRIO, but under 3 hours with FLT. However, the 95th percentile of waiting times for double lockages with all three of these rules is over 60 hours; indicating that some vessels will wait a very long time in such a congested system regardless of the lock operating policy employed to manage traffic.

Type	FIFORECPRIO		SINGPRIO		FLT	
	Median	95%	Median	95%	Median	95%
Double	334	3772	363	4307	148	4055
Jackknife	296	3473	145	475	105	488
Knockout	378	3732	408	4211	110	490
Single	324	3322	351	3922	129	583
Singles without barges	275	3062	130	474	89	441
Recreation	51	125	51	125	50	124

Table 6. Median and ninety-fifth percentile of waiting times (minutes) in study region over 100 simulated years of operation with 20% increase in demand

The expected time savings from the FLT re-sequencing rule can be translated into current National Economic Development (NED) benefits by using the value of approximately $240 per tow hour which is price level adjusted from the year 2000 value of $170 per tow hour reported in CTS [2005]. This value represents the observable average willingness to pay of waterway shippers in 2005 for an hour of tow transportation for tows operating as configured in the UMR. The time savings from FLT, relative to FIFORECPRIO, equate to about $150,000 in increased productive value annually with 2000 levels of traffic, $620,000 annually with a 10% increase in 2000 traffic and $3.7 million annually with a 20% increase in 2000 traffic. Clearly, the expected net NED benefit of FLT increases greater than proportionally with increases in traffic levels and at traffic levels approaching 20 percent greater than those observed in 2000 produces significantly greater expected net NED benefits than FIFORECPRIO or SINGPRIO.

Table 5 also shows the significantly increasing wait times expected in a congested system like the UMR as traffic demand increases. Figure 6 presents the interpolated relationship between

expected lock wait times for the FIFORECPRIO, SINGPRIO, and FLT policies and differing levels of expected system lockages. The nine data points displayed in Figure 6 correspond to the expected values of waiting times at each system lock as a function of the expected number of total lockages associated with 2000 traffic levels, a 10 percent increase in 2000 traffic levels and a 20 percent increase in 2000 traffic levels for each of three alternative lock operating policies. With a 20% increase in 2000 traffic, even under FLT, the average waiting times exceed nine hours. However, Figure 6 also clearly indicates the relatively increasing effectiveness of the FLT policy as traffic increases. With increased levels of traffic, even more sophisticated traffic and intrusive traffic management policies such as simultaneous lock queue management or systemic traffic management might provide some additional economic benefits, though in such a congested system, there may be little that can be done operationally to prevent waiting times from far exceeding current levels.

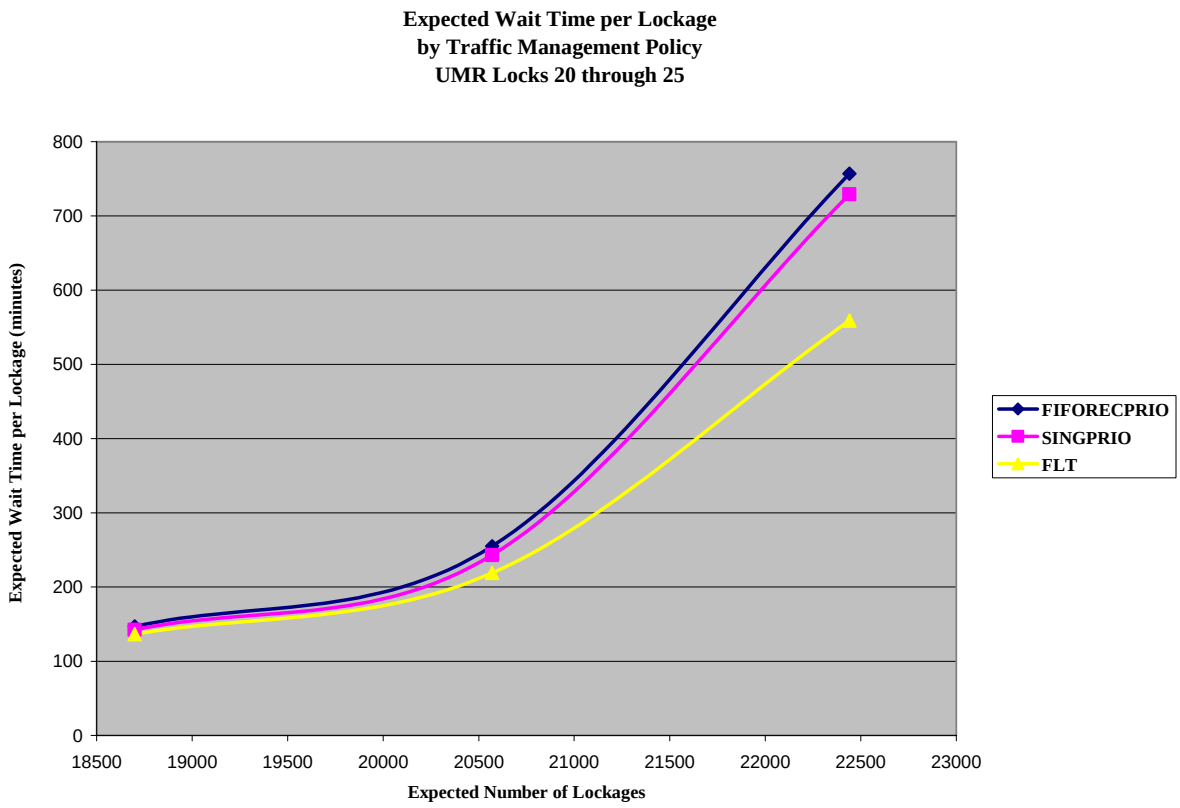

Figure 6. Expected Wait Time per Lockage by Traffic management Policy for Increased Levels of Traffic

7.1. Seasonal variation in lock utilization

The utilization of a lock (percentage of time that the lock is engaged in serving a vessel) is determined by the intensity of arrivals and the time to serve the mix of traffic. Because the amount and blend of traffic vary throughout the year (and to some extent vary among the locks), there is considerable seasonal variation in the utilization of the locks – especially at the beginning and end of the shipping season. To illustrate this, in Table 7, we show the percentage

utilization of locks 20, 22 and 25 in the months of April, August, October and December as inferred from the simulation results.

The implied lock utilizations are consistent with our conclusion that, if commercial traffic levels should increase to 20% above the volumes of year 2000, the system becomes strained in the peak shipping season. October arrivals will spill into December and utilizations at Lock 25 and Lock 22 exceed 90% in April through October. Impairments in those months will almost inevitably lead to prolonged delays under those circumstances. Some method of reducing locking times would be required to achieve higher throughput.

Lock	**Month**	**FIFORECPRIO**			**SINGPRIO**			**FLT**		
		Yr 2000	Plus 10%	Plus 20%	Yr 2000	Plus 10%	Plus 20%	Yr 2000	Plus 10%	Plus 20%
25	Apr	80	86	91	81	86	90	79	85	88
	Aug	79	86	91	79	86	91	79	85	91
	Oct	79	85	92	79	85	91	79	84	91
	Dec	40	45	51	40	45	54	41	45	54
22	Apr	84	90	94	85	90	94	83	89	92
	Aug	81	88	95	81	88	95	81	87	93
	Oct	77	83	91	77	83	90	77	83	88
	Dec	38	41	47	37	42	48	37	41	47
20	Apr	73	79	85	73	79	85	72	79	85
	Aug	70	77	82	71	77	82	70	75	82
	Oct	73	80	86	73	79	85	72	78	83
	Dec	24	27	30	24	27	30	24	27	29

Table 7. Percentage utilization of locks (after impairments) in selected months

8. DISCUSSION AND CONCLUSION

In our analysis of the detailed simulation results, we noticed that the sum of the four queue sizes at a lock under FIFORECPRIO (the nominal rule being employed) was generally higher than actual queue sizes by 0.5 to 1.5 vessels during periods of peak seasonal activity. On closer examination of historical data, we observed a noticeable tendency for recreational vessels and single vessels without barges to be locked very shortly after their recorded arrivals. This suggests that there may be some systematic bias in the recording of arrival times for recreational vessels (e.g., using the time for the last vessel that arrived when groups of recreational vessels were locked together) and there may be some priority given to commercial vessels without barges, as would certainly be the case, for example, for Coast-Guard vessels dispatched to assist with some problem on the river. Other possible explanations are informal actions by lockmasters to increase the efficiency of operations when queues are building and that vessels time their own arrivals to avoid congestion or conserve fuel when faced with significant lock congestion. In other words, there is evidence of self-regulating behavior in the operation of the UMR system, by which operational rules are “bent” to conform to the needs of the moment and by which vessel traffic responds to the conditions in the immediate vicinity and adjacent pools. This self-regulation will tend to mute the beneficial effects of alternative traffic management policies

The purpose of this study was to see if efficiencies might be achieved in lockage operations by implementing alternative sequencing rules for lockage operations that consider only the vessels queued at the local lock and the expected times of processing them in different sequences. It appears, from our results, that the current expected yield from such vessel re-sequencing would be less than 5% of the time that vessels spend at locks in this section of the river. New priority rules raise questions of equity by differentially altering the expected waiting times for different classes of vessel traffic. At current traffic levels, which are approximately ten percent less than 2000 traffic levels, there is insufficient justification to introduce changes of this nature.

Our results suggest that at current traffic levels the savings from re-sequencing queues of vessels on the UMR would be rather small (less than $150,000 annually), and these benefits would be distributed quite unevenly, with some users disadvantaged by new policies. Furthermore, vessels will likely adapt to traffic dynamics and changed locking operations and the unscheduled lockage impairments that will certainly continue to occur (as in the past). These factors will tend to reduce the actual benefits below the levels that we have found. Considering the equity tradeoffs involved and the fact that the time that vessels spend in this section of the river constitutes a very small portion of their overall annual operating times, we conclude that there is insufficient justification to introduce new sequencing rules at current traffic levels.

With greater traffic levels, the benefits from re-sequencing increase substantially, as do expected lock waiting times. Our results suggest that with a 33% increase in demand relative to 2005 traffic levels, annual cost savings of $3.7 million are possible from better sequencing of vessels in queues – but also that long queues will remain with this increased level of demand. If traffic levels dramatically increase or existing lock performance degrades substantially, then implementing new traffic and lockage management policies such as FLT could yield significant economic benefits that significantly outweigh the differential impacts to existing FIFORECPRIO lock operations in the UMR. Further, even more sophisticated traffic and lockage management systems and policies could be implemented (analogous to the traffic control system for air traffic), though implementation would be a daunting task – perhaps more from a legal and organizational perspective, than from a technological perspective. Such systems with real time vessel tracking and control could lead to additional efficiencies in operations, as well as contribute to improved safety, security, and environmental protection.

Since either substantial increases in traffic, or reduced service capacity at a lock will amplify the potential benefits of alternative traffic management policies, we would expect that interference in normal lock operations for major maintenance or construction activities would create a situation where the use of alternative rules could also enhance system performance. The model could be readily modified to reflect the operational effects of anticipated navigation restrictions required during construction or maintenance activities and used to develop good sequencing rules to cope with the operating restrictions.

The ARENA 10 simulation model provides a robust and accurate tool that can be used to explore other options for improving system performance. New rules that increase the priorities for vessels that have experienced long waits and coordinated policies that manage multiple lock queues together can be tested. The model can be modified to investigate the potential system performance with new 1200 foot lock chambers, the effects of new operating policies that shift

the mix of vessels to decrease the number of double lockages, and to study other ways that the system could be modified to cope with higher levels of demand.

In sum, the ARENA 10 simulation model presented in this paper has proven to be an effective tool for examining the potential impact of implementing the different operating rules. With minor modifications, it may be used to explore further options in increasing efficiency of the UMR navigation system that may have even higher payoffs

9. REFERENCES

Carroll, J. L. (1972), “Analysis of Waterway Systems”, Final Report, U.S. Army Corps of Engineers, North Central Division, Chicago, IL.

Carroll, J. L. and Bronzini M. S. (1973), “Waterway Transportation Simulation Models: Development and Application”, Waterway Resources Research, pp. 51-63.

Center for Transportation Studies, University of Missouri-St. Louis (2005), “Management Systems for Inland Waterway Traffic Control Final Report”, The Institute for Water Resources, U.S. Army Corps of Engineers.

Dai, M.D.M. and Schonfeld, P. (1994), “Metamodeling Approach for Approximating Series of G/G/1 Queues on Congested Waterways”, Proceedings of the First ASCE Congress on Computing in Civil Engineering.

Dai, M.D.M. and Schonfeld, P. (1992), "Approximation Methods for Queuing Delays in Waterway Networks", Proceedings of the World Transportation Research Conference, Lyon, France, June.

Dai, M. D.M. and Schonfeld, P. (1991) "Simulation of Waterway Transportation Reliability", Transportation Research Record 1313, pp. 98-105.

Kim, Y. M., and P. Schonfeld (1995), “Neural Network Estimation of Waterway Lock Service Times”, Transportation Research Record 1497, pp. 36-43.

Martinelli, D. and Schonfeld, P. (1995), "Approximating Delays at Interdependent Locks," Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, November/December, pp. 300-307.

Ramanathan, V. and Schonfeld, P. (1994), "Approximate Delays Caused by Lock Service Interruptions," Transportation Research Record 1430, January, pp. 41-49.

Sweeney, D. C. (2003), “Recent Trends in Output, Industrial Organization, and the Willingness to Pay in the United States Inland Waterborne Commercial Transportation Industry”, Center for Transportation Studies, University of Missouri-St. Louis and the U.S. Army Corps of Engineers.

Sweeney, D. C. (2004), “A Discrete Event Simulation Model of a Congested Segment of the Upper Mississippi River Inland Navigation System”, Center for Transportation Studies, University of Missouri-St. Louis and the U.S. Army Corps of Engineers.

Ting, C. J. and Schonfeld, P. (2001a), "Efficiency versus Fairness in Priority Control: Waterway Lock Case, " Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, March/April, pp. 82-88.

Ting, C.J. and Schonfeld P. (2001b), “Control Alternatives at a Waterway Lock”, Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, March/April, pp. 89-96.

Ting, C. J. and Schonfeld, P. (1999), "Effects of Speed Control on Tow Travel Costs," Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, July/August, pp. 203-206.

Ting, C. J. and Schonfeld, P. (1998a), “Optimization through Simulation of Waterway Transportation Investments,” Transportation Research Record 1620, pp. 11-16.

Ting, C. J., and P. Schonfeld. (1998b), “Integrated Control for Series of Waterway Locks”, Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, July/August, pp. 199-206.

Ting, C.J. and Schonfeld, P. (1996), "Effects of Tow Sequencing on Capacity and Delay at a Waterway Lock”, Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, January/February, pp. 16-26.

U. S. Army Corps of Engineers (2004), Integrated Feasibility Report and Programmatic Environmental Impact Statement for the UMR-IWW System Navigation Feasibility Study, U.S. Army Corps of Engineers, Rock Island District, September.

Wang, S. L. and Schonfeld, P. (2002), “Development of Generalized Waterway Simulation Model for Waterway Operation”, Transportation Research Board 2002 Annual Meeting, Transportation Research Board.

Wei, C.H., Dai, M.D.M. and Schonfeld, P. (1992), “Computational Characteristics of a Numerical Model for Series of Waterway Queues," Transportation Research Record 1333, pp. 45-54.

Zhu, L, Schonfeld, P., Kim, Y. M. Flood, I. and Ting C. J. (1999), "Queuing Network Analysis for Waterways with Artificial Neural Networks", Artificial Intelligence for Engineering Design, Analysis and Manufacturing, pp. 365-375.