Appointment Systems for Inland Waterway Traffic Control

DRAFT REPORT

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ABSTRACT

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The Upper Mississippi River-Illinois Waterway carries bulk commodities vital to the United States economy. Tows (tow boats pushing groups of barges) utilize 37 locks and dams to navigate this waterway system. Poor asset utilization leads to frequent system delays with potential economic impact.

This study examines scheduling and sequencing options to potentially improve the efficiency of the lockage operations on the Upper Mississippi River-Illinois Waterway (UMR-IW). A discrete, event-based simulation model is presented and evaluated for use in investigating changes to the operational characteristics of an important segment of the Upper Mississippi River inland navigation system. Locks 20-25 provide the basis for the study because of their size, as well as the nature of traffic passing through them, relative to other locks in the UMR-IW system.

The simulation model extends earlier inland navigation simulation models of systems of locks by explicitly incorporating seasonal and interdependent traffic demands for specific origin and destination trips into the model. An analysis of U.S. Army Corps of Engineers OMNI data compiled from the Upper Mississippi River during the period from 2000 through 2003 is presented which indicates that the most heavily utilized locks of the Upper Mississippi River experience periodic traffic congestion, are subject to seasonal changes in demands for service, and operate as a connected system of locks in that they share a large amount of common interrelated commercial tow traffic. The simulation model is calibrated to this historic data and shown to reasonably represent the overall operation of the system including the periodic seasonality of the demand for lock use evident in the Corps OMNI data.

The statistical analysis includes diverse factors, such as night movements, river characteristics, types of vessels, types of lockages, et cetera, to determine their impact on transit times. Equations acquired through the data analysis are used in a simulation model to evaluate the result of implementing scheduling and sequencing rules to minimize queues at locks 20-25. This study examines an array of traffic management alternatives ranging from no action, to the resequencing of tows at a lock or a series of locks, to the complete scheduling of vessels on the waterway similar to how air traffic control governs the movement of aircraft.

1. INTRODUCTION

The purpose of this research is to create and evaluate a discrete, event-based simulation tool for use in investigating changes to the operational characteristics of an important segment of the Upper Mississippi River-Illinois Waterway inland navigation transportation system. The lower five 600 feet long locks of the Upper Mississippi River (UMR) navigation system provide a useful setting for testing such a simulation model as these five locks experience periodic traffic congestion, are subject to seasonal changes in demands for service, operate as a system in that they share a large amount of common interrelated commercial tow traffic, and have been the subject of significant controversy regarding their possible replacement with costly larger sized, lock chambers.

The simulation model developed for the UMR navigation system differs from prior waterways simulation models in two important dimensions. First, the UMR navigation system model explicitly embodies the fact that the demand for use of the UMR is highly seasonal in nature and that the UMR system never achieves or approximates a steady state level of system performance. The lack of steady state performance characteristics is the direct result of annually repeating and readily predictable periods of relatively high and low demands for use of the system. Therefore, the steady state queuing system models used to approximate the operating conditions of the UMR used in existing Corps of Engineers system economic models are not appropriate and may distort the economic evaluation of potential changes to the operating conditions or infrastructure of the system. Second, the UMR navigation system simulation model explicitly incorporates the fact that the production of individual system movements can not be independent of each other as the waterway transportation equipment needed to complete each movement must first be delivered to the origin of the movement from some other waterway location. Hence, the supply of equipment required to complete individual water movements is related to other system movements and the resulting performance of individual locks within the system will be linked by the common tow traffic of the interrelated trips. Therefore, system performance characteristics such as queue sizes and waits for service at system locks will be related and modeling these locks as a sequence of independent servers is not appropriate. Consequently, navigation system economic models that incorporate the assumption that locks operate as independent servers may distort the evaluation of potential changes to the operating conditions or infrastructure of the navigation system.

The interdependency of lock operations created by the service of common tow traffic and the existence of periods of high and low levels of demand for use of the system provide currently untapped sources of efficiency improvements for the implementation of alternative traffic management policies in the operation of the UMR system. Specifically, system efficiencies can be created by scheduling traffic, re-sequencing vessels for processing at the locks or by providing economic incentives for decreasing system use during high demand periods and increasing system use during low demand periods.

2. THE UPPER MISSISSIPPI RIVER NAVIGATION SYSTEM

The Upper Mississippi River is an integral part of a national inland water transportation network. The UMR river navigation system provides an important transportation link both into and out of

America's Midwest. The UMR navigation system extends approximately 663 linear miles from just north of Minneapolis, MN, southward to the confluence of the Mississippi and Missouri Rivers near St. Louis, MO. Reliable navigation conditions are created in the system by a series of 29 lock and dam facilities which maintain a minimum usable channel depth of nine feet for the entire length of the navigable system. Figure 1 presents a map of the UMR portion of the inland navigation system.

The UMR lock and dam system was originally constructed beginning in the 1930's under the authority of the 1930 Rivers and Harbors Act. This legislation directed the U.S. Army Corps of Engineers to construct and maintain a navigation channel with a minimum depth of nine feet. The dams were constructed to retain enough river flow to permit sufficient depth for navigation of commercial tows and other vessels. A series of interconnected water stair steps, called pools, are created by the dams to ensure the desired navigation conditions in the system. The lock chambers were constructed to permit the navigation traffic to pass through the dams and thereby navigate to the next pool in the water staircase. Figure 2 presents a schematic view of the UMR pool system.

The original locks were constructed with main chambers 600 feet in length that were designed to accommodate the largest commercial tows of the 1930's and 1940's. However, over the ensuing decades, towboats on the UMR have become larger and individual flotillas pushed by tows are composed of more and larger barges. Most fully assembled tows on the river today exceed 600 feet in length and require that a group of barges be decoupled from the fully assembled tow in order for the tow to pass through the locks. These segments of tows are termed cuts. These cuts are subsequently re-coupled after passage of the entire tow through the lock as the fully assembled tow continues transiting the system. With rare exceptions, the largest tows operating in the UMR system require two cuts to pass through a 600 foot long lock. These "double lockages" require a relatively lengthy processing time for these tows to pass through UMR locks and contribute to periodic congestion evident at some locks on the lower portion of the Upper Mississippi River. Selected important physical and operational characteristics of the UMR locks are summarized in Table 1.

Agricultural products are the primary commodities transported in the UMR navigation system and account for a majority of the annual volume of commercial shipping activity. The UMR also serves as a major artery for the transport of other bulk commodities such as chemical products, coal, cement, and petroleum products. Most products shipped on the UMR system are intermediate or raw goods destined primarily for use in the ultimate production of other final consumer goods and products.

Commercial navigation on the Upper Mississippi River plays an important role in the national and regional economy. The historic importance of the UMR as a shipping artery is reflected in the increase in tonnage shipped on the system. Tonnage shipped on the system increased from approximately 27 million tons in 1960 to approximately 84 million tons in 2002. At present, there are more than one hundred terminals on the UMR that ship and receive commodities.

Towboats currently moving on the UMR may exceed 5,000 horsepower, push a typical tow composed of up to 16 barges, and routinely exceed 1,100 feet in length when fully assembled.

The four primary types of barges employed on the UMR to carry commodities are open hopper barges, covered hopper barges, deck barges, and tank barges. Open hopper barges are used for moving many types of bulk solid cargo such as coal, raw mineral products, and aggregates and account for some 45 percent of the carrying capacity of all barges operating on the inland waterways. Covered hopper barges carry mainly grain and fertilizer products and account for some 25 percent of the total tonnage capacity nationwide. Tank barges, used for transporting petroleum and chemical products, and deck barges, used for moving a wide variety of products, make up approximately 22 and eight percent of the national barge fleet, respectively. Covered and open hopper barges can transport over 1,500 tons of products per barge, tank barges can transport over 2,000 tons of products per barge, and deck barges vary substantially in their cargo carrying capacity.

Lockage delays in the UMR navigation system occur primarily as a result of the large volume of tonnage shipped through the system at various times of the year. To a lesser and more variable extent, unusual events such as lock malfunctions, tow pilot errors, and adverse vessel or lock operating conditions also contribute to the delays periodically evidenced at these locks. Built beginning in the 1930’s, the lock system was originally designed to readily accommodate tow sizes of up to 600 feet in length. In response to the increased volume of tonnage demand and the economies of larger shipment sizes, tows now routinely push 15 barges with a total length near 1,200 feet. These large tows require lengthy double lockages to pass through the locks and greatly contribute to lockage delays. Also, significant use of the UMR locks by non-commercial vessels, such as privately owned recreation craft, periodically throughout the year contributes to lockage delays in the UMR system.

The five southernmost 600 foot long locks of the UMR navigation system, Locks 20, 21, 22, 24 and 25 (there is no Lock 23) are the most heavily utilized 600 foot long locks and are among the most congested of all locks in the inland navigation system. Table 2, compiled from U.S. Army Corps of Engineers OMNI lock data for calendar years 2000 through 2003, displays by month the mean number of lockages completed and the mean and standard deviation of the time spent by vessels waiting for service at these five locks. Table 2 reveals that a total of 70,180 lockages were completed at these locks during the four year period (an average of 3,509 lockages per lock per year) and that vessels waited an average of 2.4 hours per lockage before beginning processing at a lock. Also clearly evident in Table 2 is the relatively large variability of the distribution of the wait for service time observed throughout the entire four year period.

Of the 70,180 total lockages summarized in Table 2, 58,964 lockages (84% of the total) represent the lockage of commercial tows. These commercial tow lockages were produced by a total of 382 unique tow boats operating at these locks over the four year period with an average of 242 unique tow boats operating at these locks in any given year. These commercial tows waited an average of 2.8 hours per lockage at these five locks. The slightly greater mean wait time of commercial tows compared to the overall mean wait time of 2.4 hours for all vessels reflects the relative priority in the system placed on expeditiously completing non-commercial recreation craft lockages. Corps regulations governing recreational craft lockages state that recreational craft may not be required to wait for more than the completion of three commercial tow lockages. In practice, recreational vessels rarely even wait that long for service. For example, in many cases, recreational vessels are opportunistically locked between successive commercial tow lockages during the lock chamber turnback needed to process the next tow when the commercial tows are moving through the lock in the same direction. Further, multiple recreation vessels may simultaneously utilize the lock chamber in a single lockage operation and are therefore moved out of their arrival sequence in order to fill the chamber with as many waiting recreational vessels traveling in the same direction as possible.

Table 2 further reveals that the monthly distribution of the total number of lockages completed at these five locks is highly seasonal in nature. The demand for lock use annually builds from a very low level in the winter months to a peak level of use in July and August and then gradually declines through the fall months back to a very low level of use by the end of each calendar year. A system is said to be in a steady state when the state of the system is independent of the time of the observation of the system. A characteristic of a steady state system is that its arrival and service rates do not change with time. Clearly, this subsystem of the UMR system never achieves a steady state as the vessel arrival rates change significantly throughout the calendar year. Consequently, this high degree of seasonality evidenced in system usage levels renders steady state models and steady state queuing system approximations as potentially poor indicators of the real operating conditions evidenced at these five locks. A more detailed examination of the operating conditions observed at these locks is presented below in Section 4.

3. CHARACTERISTICS OF THE U.S. ARMY CORPS OF ENGINEERS OMNI DATABASE

The Institute for Water Resources (IWR) of the U.S. Army Corps of Engineers (USACE) provided a Microsoft Access database containing tow traffic data recorded by the Corps of Engineers OMNI database system at all Upper Mississippi River locks for calendar years 2000 through 2003. The database consists of several interrelated tables including: a table containing detailed lock traffic and lock performance data recorded from 2000 through 2003; a table containing detailed information regarding the flotilla of barges making up each commercial tow when it passed through a UMR lock; a table containing detailed information regarding the physical characteristics of the towboats operating on the inland navigation system; and a table containing detailed information regarding the physical lock operations associated with each individual UMR lockage.

The subset of records in the original OMNI database related to the tow traffic through Upper Mississippi River Locks 20, 21, 22, 24 and 25 is extracted for analysis and use in the construction of a model designed to simulate the flow of tow traffic through this subsystem of locks. A detailed description of the individual OMNI databases, the procedure employed to identify and extract the data needed for the simulation model, and the subsequent calculations and analyses required to prepare the extracted data into the format required by the simulation model are presented below.

Traffic Table

The OMNI Traffic Table serves as the primary data table for the analysis of system traffic. This table contains a unique record for each transaction completed at each lock represented in the OMNI database. A transaction is the passage of a flotilla (or a portion of a flotilla) through a system lock. Flotillas are composed of commercial tows with barges, government owned vessels, private recreation vessels, light boats (commercial tows without barges) and commercial passenger vessels. These transactions are termed lock operations and each individual record in the Traffic Table is assigned a unique operations ID by the Corps OMNI system. Many flotillas have multiple operations ID's associated with a single lock passage as the lockage of many commercial tows requires multiple "cuts" (the lockage of a portion of a fully assembled tow that is itself too large to pass through the lock in a single lock operation) to complete the transit of the tow through a lock. In contrast, other transactions in the Traffic Table represent the simultaneous passage of multiple vessels through the lock in a single lock operation when the flotilla is composed of multiple recreation craft or multiple light boats processed in a single lockage. Each database record in the Traffic Table contains numerous fields of information regarding the lock, the flotilla associated with the lock operation, and the detailed timing data associated with the lock operation. The important fields in each Traffic Table record are listed below in Table 3 and the asterisks associated with the fields listed in Table 3 indicate data fields that are used to construct the simulation model input database.

Flotilla Table

This OMNI database table contains detailed information regarding the vessels in the flotillas associated with each lock transaction. Unique flotilla numbers are assigned to each vessel or combination of vessels at each lock transited and associated with both the Flotilla Table and Traffic Table records corresponding to each lockage. Unfortunately, however, the flotilla numbers in the original OMNI Traffic Table supplied by the Corps did not correspond with the flotilla numbers included in the associated Traffic Table. Therefore, the Flotilla Table and the characteristics of the individual flotillas were unavailable for use in the construction of the simulation model. Table 4 displays the important data fields contained in the Flotilla Table.

Vessel Table

This OMNI database table contains detailed information regarding the physical characteristics of towboats and other vessels associated with the records in the Traffic Table. Information regarding vessel ownership, vessel type and the vessel horse power are included in this database table. Table 5 below displays the important data fields contained in the Vessel Table.

Operations Table

This OMNI database table contains information regarding the details of the physical operations associated with individual lock operations. This information includes the direction (up-bound or down-bound) of travel of the flotilla associated with the lock operation. Table 6 below displays the important data fields contained in the Operations Table.

4. STATISTICAL MODELING OF OPERATIONS ON THE UPPER MISSISSIPPI RIVER SYSTEM BETWEEN LOCKS 20 AND 25

Purpose of the Statistical Analysis

The UMR statistical analysis was undertaken:

- To produce performance bench marks with OMNI data under historical operating rules and physical conditions
- To create a system for development and maintenance of sets of statistical models to support the enhanced simulation of traffic flows and lockage operations

- To provide comparisons of simulated system performance under alternative operating procedures against historical bench marks.

The statistical analysis has two major thrusts. The first involves the development of descriptive statistics that may be used to validate the transient behavior of the simulation model under historical operating rules and physical conditions. It is important to verify that the simulation model, when run for the base case, gives a proper representation of the system currently in place in order to ensure that a realistic bench mark is employed when assessing the performance of the system under alternative sequencing rules. Historical statistics of waiting times at the bottleneck locks, derived from individual vessel itineraries over the shipping season, can also provide upper bounds on the reductions in waiting time that could be achieved at those facilities under alternative sequencing rules if total vessel and barge movements were to continue at historical levels.

The second thrust of the statistical analysis is to investigate the effects of factors that influence vessel itineraries, tow configurations, expected transit times to the next lock, and expected times required for lock operations. Statistical models from this thrust may be used to moderate the parameters of the simulation model according to the status of the system and system entities (locks, vessels and tows) as the simulation evolves. The models capture seasonal (monthly) effects on average arrival rates, vessel itineraries, lockage times and transit times. They also allow for effects of darkness and river congestion on transit times and lockage times, and for the incidence of impairments to lock operations.

Descriptive Statistics for Waterway Operations and Resource Utilization

Data for waterway lockage operations were extracted from the U.S. Army Corps of Engineers' OMNI database and placed in the SAS datasets. The OMNI data apply to lockage activity, with key events being the arrival at a lock from a specified direction, the start of lockage, and the vessel's departure from the lock into the next river pool. Itineraries of individual vessels are deduced from the time sequence of the vessel's lockages. Attributes of the vessels (type, name, owner, and horsepower) were extracted from the OMNI database and placed into a SAS dataset. These are merged to allow the consideration of vessel attributes in establishing parameters for the simulation model. The merged dataset is also used to create a data stream of movements for each vessel, which was fed to the complementary GPS study to show actual vessel movements. It also enabled the production of detailed vessel movements for individual barge lines to show the impact of scheduling delays on major users of the waterway and to validate OMNI data against any GPS data that may be provided by the barge lines. (In the course of visits with lockmasters, it was mentioned that, in periods of congestion, there seemed to be a tendency for towboats to report themselves as having arrived at a lock and being ready for lockage while actually being still underway to the arrival fix in the river. They may do that to establish their position in the queue and thus distort the measure of transit time from departure at a lock to arrival at the next lock. We would need actual positional data from the barge lines to investigate such irregularities.)

Occasionally, in the OMNI database, vessels appear to present themselves for lockage from a pool other than the pool they were last recorded as entering. This can be due to data-recording errors or to instances where powered vessels without tows pass through a lock together. (In the case of a lockage involving several powered vessels, the lockage information is recorded only for one of the powered vessels.) Consideration must also be given to the elimination of possible outliers when estimating parameters of probability distributions – especially when estimating a vessel's transit times from one lockage to the next.

The following statistics are used for describing the transient state of the system. Time-weighted averages are used in the corresponding summary statistics:

- Number of vessels in queues for lockage at each lock (upbound and downbound)
- Whether or not a vessel is currently involved in a lockage operation at each lock (The time-weighted average of this 0-1 variable is the lock utilization.)
- Number of vessels upbound and downbound in each pool (i.e., in the waterway between two locks).

Summary statistics for system status produced at monthly intervals are:

- Average number of vessels in upbound and downbound queues at each lock
- Average number of vessels upbound and downbound in each pool
- Maximum number of vessels in upbound and downbound queues at each lock
- Maximum number of vessels upbound and downbound in each pool.

Statistical breakdowns are produced according to tow characteristics. We characterize the tow according to the type of lockage operation involved at a 600-foot chamber (i.e., double, single, jackknife, knockout or other) and whether the movement is upstream or downstream. Depending upon the sequencing rule employed, tows with these different characteristics could be differentially affected. Some types of tow may receive improvements in service (reductions in waiting times) while others suffer declines in service (increases in waiting times).

Other statistics are produced to depict the length of time required for lockage operations, the times that vessels and tows spend waiting for lockages, and the times that vessels spend moving from one lock to the next. These represent individual activities or events. Simple averages (rather than time-weighted averages) are used for them. We also describe the frequencies (likelihoods) with which vessels change configuration as they drop off or pick up barges and possibly reverse direction in a pool.

The following descriptive statistics are used to summarize the performance of entities in the UMR navigational system:

- Summaries of times (minimum, 5th percentile, median, mean, 95th percentile, maximum, std. deviation, sum) to complete activities related to operations on the river:
    - Time from departure at one lock to arrival at the next lock (for nonstop commercial movements and for commercial movements involving stops or changes in direction)
    - Waiting time (from time of arrival to start lockage) at locks for commercial tows, broken out by travel direction (upbound or downbound), operation type (fly,

    turnback or exchange) and lockage type (single, double, jackknife, knockout, other commercial, or recreational)
  - Lockage time (from start of lockage to departure) at locks for commercial tows, broken out by travel direction (upbound or downbound), operation type (fly, turnback or exchange) and lockage type (single, double, jackknife, knockout, or other)
  - Total system time at a lock (from arrival to departure) at locks for commercial tows, broken out by travel direction (upbound or downbound), operation type (fly, turnback or exchange) and lockage type (single, double, jackknife, knockout, other commercial, or recreational.)
- Utilization statistics for selected vessel groups and locks over a chosen time interval:
  - Percentage of time that vessels are queued for lockage
  - Percentage of times locks are occupied
- Throughput statistics:
  - Total number of recorded lockages completed in each direction
  - Total number of barges transiting the system in each direction
- Itineraries:
  - Transition matrices, showing the numbers and percentages of vessels that, on entering each pool upstream or downstream, next appear in each of other possible pools upstream or downstream (including infeasible transitions caused by data entry errors or unrecorded multiple lockages).

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A SAS program is written to generate reports that selectively present the summary statistics for lock operations, statistics for vessel itineraries (resetting the times for first recorded events each year when reports include data for multiple years), summary statistics for lockage operations, matrices that show the frequencies of sequential lockages to construct vessel itineraries probabilistically, summaries of the types of movements after entering a pool for the first-order and second-order simplifications of pool transitions, and to generate queuing statistics and pool statistics that reveal the transient state of the system. The program also allows the creation of a data stream giving positional information of each vessel through time (with an event for each arrival, start of lockage and departure). Macro variables allow the analyst to select the beginning date and ending date for statistical summaries and to exclude or include data for lockages of recreational vessels. An option allows the exporting of summary statistics of system status into excel spreadsheets for plotting and word processing.

The SAS programs for generating the descriptive statistics from the OMNI data and a set of resulting reports appear in Appendix A.1.

General Observations from Lock Utilization Statistics and Vessel Itineraries

Calendar year 2003 involved records of 104,730 non-recreational vessel movements with data for lockage and times of movements between locks. Average utilization (the percentage of times that vessels are undergoing lockage operations at the lock) at locks 20 through 25 peaked in summer months at values between 74% and 79%. Maximum queues for lockage ranged between six and eight vessels with tows. Considering activities from the earliest recorded movement of a vessel for the year to the last recorded movement of a vessel for the year, vessels spent an average of 96.8 % of their annual time in the system in river pools away from the locks. They spent 1.5% of their time waiting for lockage (from recorded time of arrivals for lockage to the time at which lockage started) and 1.7% of their time undergoing lockage. The 3.5% of vessel time at locks (waiting for lockage and undergoing lockage) occurred anywhere in the river system – not just at the five locks under study. (See Appendix A.2)

While there were considerable delays in locking vessels in the congested sections of the river, the delays at the five locks obviously constituted a small percentage of the annual operational times for the vessels. At face, this suggests that there may be limited potential of increasing the utilization of towboat resources by using alternative sequencing rules or increasing lock capacity, unless the volumes of river traffic increase substantially above 2003 levels.

Discussion of the OMNI Data

As evidenced in Figure 3, the distribution of lockage times at these five locks is very clearly bi-modal. This bi-modal distribution of lockage times is the result of two very different underlying lockage distributions that characterize lockages at these five locks; one underlying distribution for commercial tows that are over 600 feet in length which require two separate cuts to complete a single lockage and a second underlying distribution for commercial tows and other vessels that are less than 600 feet long which only require a single cut to complete a lockage.

As evidenced in Figure 4, a significant portion of the vessels transiting these five locks, approximately 31 percent, were processed with little or no wait for service after arriving at a lock. Approximately one half of all vessels waited less than one hour for service. The remaining fifty percent of vessels waited for varying durations before being processed through a lock with the vast majority of these vessels waiting for periods of less than 6 hours before receiving service. Finally, a small but significant proportion, approximately 10 percent, of the vessels arriving at the locks waited more than 6 hours or more before service was provided.

Distributions of Lock Specific Wait and Lockage Times

Inspection of individual lock wait and lockage time distributions indicates that there are differences evident in these distributions between locks, so selected summary statistics of wait and lockage time distributions for each individual lock by direction of movement and vessel type are generated and inspected. The direction of movement of a vessel at a lock is defined relative to the natural flow of the river, either upbound or downbound. Three different vessel types are employed to characterize the vessels transiting each of the five locks. The vessel type “multi-cut tows” represents commercial tows requiring multiple cuts to complete a single lockage, the vessel type “single cut tows” represents commercial tows with barges that require only a single cut to complete a lockage, and the vessel type “Other Vessels” represents all other traffic at a lock. The vessel type “Other Vessels” is composed of recreational vessels, commercial passenger vessels, “light” commercial towboats (commercial towboats without barges), and federal government owned vessels.

Selected summary statistics of the wait for lockage time distributions are presented in Table 7 and selected summary statistics of the lockage time distributions are presented in Table 8. As evidenced in Tables 7 and 8, the distributions of wait and lockage times characterized by lock, vessel type, and direction of travel exhibit significantly different summary statistics. For example, Table 7 reveals that the mean wait times for lockage are significantly greater for all vessel types at Locks 22, 24, and 25 than they are at Locks 20 and 21. Also, Table 7 reveals that the wait for lockage times of “other” vessels are significantly less than the wait for lockage times exhibited for multi-cut and single cut commercial tows. This difference reflects the greater priority assigned to completing recreation vessel lockages relative to the priority assigned to completing commercial tow lockages in the queue dispatch policies currently implemented for the locks in the UMR. Further, Table 8 reveals that there are significant differences between mean lockage times characterized by vessel type at all of the locks both individually and collectively. Consequently, these more finely partitioned conditional distributions of lockage times are utilized to represent the processing of traffic at the different locks in the simulation model.

Distributions of Transit Times between Locks for Commercial Tows

The implied transit time for vessels moving through the pools connecting the locks may be estimated as the amount of time observed between the recorded arrival time at a lock for a vessel and the recorded end of lockage time at the previous lock transited by that vessel. These implied travel times often include many different activities undertaken by vessels between consecutive appearances at UMR locks as not all commercial tows move non-stop from one lock in the system to another lock in the system. These implied pool transit times are estimated for all multi-cut and single cut tow lockage sequences observed in the database. Estimates of implied transit times are not computed for other vessel transits because the majority of other vessel lockages in the system involve the lockage of recreation craft where a unique identification of the vessel involved in the lockage is not contained in the data. Also excluded from these implied transit time estimates are tow lockage sequences identified in the data with an implied negative travel time from one lock to another and tow lockage sequences that are physically impossible. For example, an observed tow transit consisting of a downbound lockage at UMR Lock 22 followed sequentially by an upbound lockage at UMR Lock 24 is excluded from the travel time estimates as such a tow movement is physically impossible. Inspection of the data reveals that the anomalous tow lock transitions and negative tow travel times are most likely created by miscoded vessel identification numbers, miscoded lockage and arrival dates, and the fact that not all tow identification numbers are recorded for all light boats moving through a lock together in multiple vessel lockages.

The distributions of implied tow transit times are generated for each possible combination of origin lock, destination lock, lockage type (single cut or multi-cut tow at the destination lock), direction of travel at the origin lock, and direction of travel at the destination lock. The summary statistics of these distributions are displayed in Table 9 for multi-cut and single cut tows.

As evidenced in Table 9 the distributions of implied tow transit times are clearly dependent on the origin lock, the destination lock, the tow type, the direction of travel at the origin lock, and the direction of travel at the destination lock. For example, the mean implied transit time from Lock 21 to Lock 20 (upbound travel of the entire length of Pool 21) for a multi-cut tow is 3.80 hours with a standard deviation of 4.11 hours. In contrast, the mean implied travel time for the same upbound transit of the entire length of Pool 21 for a single cut tow is 5.44 hours with a standard deviation of 16.86 hours. For multi-cut tows completing a downbound transit of the entire length of Pool 21, the mean transit time from Lock 20 to Lock 21 is 2.50 hours with a standard deviation of 3.21 hours. For single cut tows completing the same transit the mean transition time is 10.18 hours with a standard deviation of 93.07 hours. Generally, the mean transit times for upbound tow travel from one lock to another lock are greater than the mean transit times for downbound tow travel for the same lock pair. The summary statistics further demonstrate that single cut tows have substantially greater variability in their transit time distributions and circulate through the system more slowly than do multi-cut tows.

An interesting fact not highlighted in Table 9 is the significantly different manner in which multi-cut tows and single cut tows utilize the system composed of these five locks. Nearly all multi-cut tows transit the entire five lock system before exiting the system either as an upbound lockage at Lock 20 or a downbound lockage at Lock 25 and then ultimately return at some later date to transit the entire five lock system again in the opposite direction. Single cut tows, however, display a significant non-zero probability of changing their direction of travel in some pool between Lock 20 and Lock 25 and, consequently, do not tend to navigate through the entire five lock system in a single direction or single transit.

Evidence of Seasonality in the UMR System

As the UMR is a seasonal navigation system with relatively high usage rates in the summer and relatively low usage rates in the winter, the distributions of selected operating characteristics are partitioned by the calendar month of their occurrence to examine how the operating characteristics of the system change though time. Figure 5, below, presents the number of vessel arrivals by month at each lock during the period from 2000 through 2003. Note that each of the locks exhibits a similar pattern of regular seasonal variability in monthly vessel arrivals. There is very low demand for lockage services in January and February at all five of the locks. Then, beginning in March, the number of vessel arrivals dramatically increases over the very low arrival rates evident in the winter months. The number of vessel arrivals increases again at a somewhat decreased rate though through May and June until the number of arrivals peaks during July and August. Beginning in September, there is a noticeable decrease in vessel arrivals from the summer peak levels to a relatively stable lower rate of arrivals that continues through the late fall months. Finally, in December the arrival rates rapidly decrease to return to the very low levels evidenced in January and February. This seasonal pattern of vessel arrivals is evident in each of the four years of data separately as well as in the aggregated data displayed in Figure 5.

Figure 6 displays the aggregated wait for lockage times characterized by the month of lockage summed over all vessels using each of the locks during the period from 2000 through 2003. As might be anticipated from the seasonal pattern of vessel arrivals observed at the locks, the aggregated wait for lockage times also exhibit a high degree of regular seasonal variability. The aggregated wait for lockage times increase rapidly throughout the spring months, reach their peaks in the summer months, and then gradually decrease throughout the fall months to return to relatively low levels in the winter months. Figure 6 also reveals that Lock 22, Lock 24, and Lock 25 are generally more congested when measured by total vessel wait for lockage time than are Lock 20 and Lock 21.

Figure 7 displays the mean transit times for tows transiting the entire lengths of Pool 21, Pool 22, Pool 23, and Pool 24 by month during the period 2000 through 2003. With the exception of the winter months there does not appear to be significant seasonality evident in the mean transit times of tows moving through the pools between the locks. The northernmost of these pools, Pool 21 and Pool 22, do show some inconclusive evidence of longer mean transit times during the winter months, however, these longer mean transit times are generated by a very small number of observed tow transits. For example, there was a single pool transit observed in Pool 21 and a total of 19 pool transits observed in Pool 22 during the four January months contained in these four years of observations.

Figure 8 displays the mean lockage times for vessels by month for each of the locks during the period from 2000 through 2003. Again, there is some evidence of seasonality present in the monthly distributions of mean vessel lockage times observed at each of the locks. The mean lockage times are lower in the June through September period at each of the locks than the mean lockage times observed during the remainder of the year. This is primarily the result of the greater proportion of local recreation vessels completing lockages at the locks during the high recreation use months of the summer. Recreation vessels typically produce very quick lockages. The distributions of lockage times observed for commercial tows do not exhibit any regular seasonality during the same time period.

There is clear evidence of regular seasonality exhibited in the annual operation of this segment of the UMR. The seasonality through the year appears to be driven primarily by differing levels of system use by vessels rather than by significant differences in the operating characteristics (travel times and lockage times) of the vessels or the locks. To highlight the importance of the differing levels of system use in contributing to the seasonality evidenced in the system, Figure 9 displays by date the total number of commercial tows that have produced their first system lockage of the year and that have not yet produced their final system lockage for that calendar year. Figure 9 clearly shows the seasonality of commercial tow demand for use of the system.

Figure 10 presents details regarding the date of the first annual lockage completed by individual tows at these five UMR locks. As evidenced in the chart, a relatively small number of tows operate in the system during the winter months. As the weather and operating conditions improve in the early spring there is a significant and rapid increase in the number of tows that complete their first annual lockage in the system. As the year progresses, new tows continue to enter the system to complete their initial annual lockage in the system, but at a declining rate. The decline in the number of new arrivals to the system continues throughout the summer months such that by the late fall only a handful of new tows that have not already appeared in the system enter the system for their first annual lockage.

Figure 11 presents details regarding the date of the final annual lockage completed by individual tows at the UMR locks. As evidenced in Figure 11, a relatively small number of tows complete their final system lockage early in the year. As the year progresses, a greater but still relatively small number of tows complete their final system lockage during the late spring and summer months, however, most tows continue to use the UMR system through the entire calendar year with the vast majority of individual tows producing their last annual lockage during the final two months of the year.

To summarize, there is clear evidence of regular seasonality exhibited in the annual operation of this segment of the UMR. The seasonality appears to be driven primarily by regularly differing levels of demand for system use evidenced by both commercial and non-commercial vessels throughout the calendar year rather than by significant differences in the operating characteristics (travel times and lockage times) of the vessels or the locks. The system is characterized by relatively low levels of use in the late winter and early spring months and relatively high levels of use in the mid and late summer months.

Finally, the nature of the seasonality evident in commercial tow use of the UMR system merits discussion at this point. Commercial towboats that elect to operate on the UMR system forego operating elsewhere in the inland navigation system during the periods that they do operate in the UMR system. These towboats clearly have alternative uses as evidenced by their continuing operations elsewhere in the inland navigation system during periods of adverse operating conditions in the UMR and the fact that when the UMR system is available and operating conditions are favorable some towboats opt to operate on the UMR only for limited periods of time. Consequently, the seasonality evident in system use is driven by not only by the physical operating conditions of the system, but also by the economic returns to operating in the system relative to the economic returns foregone by not operating elsewhere in the inland navigation system.

Effect of the Status of a Lock Chamber at the Arrival Time of a Vessel

Inspection of the detailed lockage time distributions suggests that the state of the lock chamber itself at the time of the arrival of a vessel, either occupied with an upbound lockage, occupied with a downbound lockage, or unoccupied, affects the lockage time of an arriving vessel. To explore this effect, three mutually exclusive lockage types are defined to characterize the status of a lock when a vessel arrives and is then ultimately processed through the lock. A "fly" lockage type for a vessel is defined as a lockage in which the lock is unoccupied when the vessel arrives at the lock and the vessel is the next vessel processed at the lock. A "turnback" lockage type for a vessel is defined as a lockage in which the lock is occupied when the vessel arrives at the lock, the arriving vessel must then wait for service in the lock queue, and when the vessel finally begins its lockage, the immediate prior vessel completing lockage is traveling in the same direction as the vessel beginning its lockage. Finally an "exchange" lockage type for a vessel is defined as a lockage in which the lock is occupied when the vessel arrives at the lock, the arriving vessel must then wait for service in the lock queue, and when the vessel finally begins its lockage, the immediate prior vessel completing lockage is traveling in the opposite direction as the vessel beginning lockage. The definitions of lockage types adopted here differ slightly from lockage type definitions typically adopted in Corps of Engineers publications where the terms fly, turnback, and exchange differentiate lock approaches and exits by vessels rather than differentiate complete types of lockages (see, for example, U.S. Army Corps of Engineers (2004), pages Econ 52-124). Consequently, there are more lockage types typically identified in Corps publications than the three lockage types identified here, however, the definitions adopted here have the virtue of focusing on the state of the lock chamber at the point in time when each vessel arrives at the lock or enters the lock as an individual lockage in a sequence of lockages.

Tables 10, 11, and 12 display selected summary statistics of the distributions of lockage times at the five UMR locks for multi-cut vessels, single cut vessels, and recreational vessels, respectively, characterized by the direction of travel of the vessel completing lockage and the lockage type as defined above. Tables 10 through 12 reveal that there is an important dependency between the observed lockage time of a vessel and the lockage type as defined above at each of these locks. At all locks and in both directions of travel, turnback lockages are on average significantly quicker than exchange lockages for multi-cut tows. This reflects the fact that a large, multi-cut, waiting tow moving in the same direction as the previous vessel completing lockage can begin its approach to the lock while the exiting vessel is still in the lock or exiting the lock. Large, waiting, multi-cut tows moving in the opposite direction as the previous vessel must wait for the exiting vessel to complete its entire exit before approaching the lock resulting in relatively lengthy lockage times. For similar reasons, observed turnback lockages for single cut tows are also significantly faster on average than exchange lockages at all locks in both directions with the sole exception of downbound single cut tow lockages at Lock 22 and Lock 24. For both multi-cut and single cut tows, fly lockage types are on average associated with the longest lockage times at all locks. For local vessel traffic at the locks, turnback lockages are on average quicker than exchange lockages at some locks, exchange lockages are on average the fastest at other locks, and fly lockages are on average the fastest at still other locks.

As a caution, it should be noted that the Corps OMNI database appears to understate somewhat the total quantity of time needed to complete a turnback lockage at these five locks as there is almost always some positive interval of time between the start of lockage time recorded for the second vessel in the turnback sequence and the end of lockage time recorded for the first vessel. In fact, only 2.4 percent of the 23,004 turnback lockages identified in the OMNI data began prior to or at the end of lockage time recorded for the previous lockage. This interval of time averages approximately eight minutes per turnback lockage sequence, is tightly distributed around the mean with a standard deviation of about 10 minutes, and in most cases most likely reflects the time needed to cycle the empty lock chamber from the water level of the exiting tow back to the water level of the entering tow.

Statistical Models to Support Enhanced Simulation of UMR Traffic Movements and Lockages

The initial version of the simulation model (D. Sweeney, December, 2004) was a simplified representation of traffic movements on the UMR. In this model, tows arrived according to seasonal patterns at Lock 25 (as single or double tows) and they cycled through the entire section of the river north of Lock 25. Recreational lockages were generated independently according to seasonal patterns at each lock. Commercial vessels would leave northbound at Lock 20 and return southbound at Lock 20 for their next lockage. The would leave Lock 25 southbound and return for northbound lockage at Lock 25, finally departing southbound from Lock 25 at the end of the shipping season. The vessels never changed tow configuration. Nor did they change direction in the section of the river between Lock 25 and Lock 20. While this model recognized some interdependencies of river movements and lockage activities, it failed to represent the instances revealed in the OMNI database where a substantial portion of vessels (especially single tows) stop in a pool for a change in configuration and may switch direction rather than continuing on to the next lock. The statistical modeling was therefore undertaken to support two levels of enhancement to the simulation level.

Simulation Enhancement – Level 1

In the first level of enhancement to the simulation model, all tows that enter the system northbound at Lock 25 or southbound at Lock 20, and all vessels to be registered for a recreational lockage, are generated randomly according to seasonal patterns. Also generated randomly according to seasonal patterns are the vessels that did not arrive without stopping after departing the previous lock. Alternative tow configurations are (1) double, (2) single, (3) single with jackknife lockage, (4) single with knockout lockage, (5) other commercial, and (6) recreational. At each intermediate lock, a commercial vessel may either (1) continue to the next lock in the same configuration, or (2) be removed from the system and handled through random generation of other vessels that appear for lockage according to seasonal patterns.

Simulation Enhancement – Level 2 (for future implementation)

In the second level of enhancement to the simulation model, we also generate randomly all tows that enter the system northbound at Lock 25 or southbound at lock 20 and all recreational lockages. Under this level of enhancement, fewer arrivals at intermediate locks will be generated independently according to seasonal patterns because movements of commercial vessels are modeled more completely. At each intermediate lock, a vessel may either (1) continue to the next lock in the same configuration, (2) stop for possible change in configuration and proceed in the same direction to the next lock, (3) stop for possible change in configuration and return to the same lock for lockage in the opposite direction, or (4) be removed from the system and handled through random generation of other vessels that appear for lockage according to seasonal patterns. Transit times (including stops for possible reconfiguration of tows and reversal in direction) are generated from distributions with means and standard deviations determined by sets of regression models considering seasonal variation, tow configurations and vessel itineraries.

Both these enhancements are a simplified representation of actual river traffic, as the movements from a lock are treated as independent of the movements prior to arrival at the lock. They should, however, allow the generation of a blend of tows at each lock that correspond properly with seasonal patterns and provide a more reliable test of different sequencing rules at each lock than a model that continually re-cycles the same blend of vessels and tow configurations through the entire system. .

Depending upon the level of enhancement employed, therefore, the vessel itineraries in simulated mode are represented, after each upstream or downstream departure from a lock as:

- Itineraries with Level 1 Enhancement. For departures from a lock, upstream or downstream, the vessel will either
    - Proceed directly (nonstop) to the next lock with the same configuration, or
    - Move to an unknown state (effectively being removed from the system and handled through random generation of new vessels that appear without having been registered as entering their current pool).

- Itineraries with Level 2 Enhancement. For departures from a lock, upstream or downstream, the likelihoods (percentage of occurrences) that the vessel will:
    - Proceed directly (nonstop) to the next lock with the same configuration, or
    - Stop somewhere in the pool, possibly change barge configuration, and proceed in the same direction to the next lock, or

  - Stop somewhere in the pool, possibly change barge configuration, reverse direction, and return to the same lock, or
  - Move to an unknown state (effectively being removed from the system and handled through random generation of new vessels that appear without having been registered as entering their current pool).

Refinement of Vessel Movements and Lockage Activity to Reflect Ambient Conditions (River Conditions and Impairments at Locks)

Lockage times and vessel movements are affected by river conditions, weather, and equipment malfunctions. Much of the variation in system performance might be explained by these phenomena. We wished to include in the simulation model the capability to adjust system performance accordingly. For this purpose, we acquired the following additional data from public sources:

- Times and duration of breakdowns at locks
  - Reasons for impaired performance
    - E.g., fog, equipment malfunction, vessel breakdowns
- Sunrise and sunset for distinguishing night operations.

Impairment data were imported into a SAS dataset. A SAS program is used to create a SAS dataset with a record for each lock, giving start times, end times, and reasons for each impairment at the lock. A SAS macro is invoked to determine the percentage of time in a defined interval (defined by a beginning and ending time) that a lock suffered impairments. A similar macro is invoked to determine the percentage of a time interval that involves darkness. Plots were created that show the considerable correspondence between large lockage queues and intensity of lock impairments. (See Appendix 4.3)

Acquisition of Industry Data for Vessel Movements and Fuel Consumption

A major purpose of this present study was to investigate whether different sequencing rules and coordination of the speeds of tows underway could improve the efficiency of towboat operations. It was thought that good positioning information might be used to alter lock sequences and regulate vessel transit speeds in a manner that reduced overall wait times and lowered total fuel consumption for the industry. In conversations with lockmasters and some industry representatives, it was claimed that the industry itself, through informal radio communications, proper traffic etiquette on the river, and collective action when bottlenecks are severe, already achieves the benefits that might be ascribed to alternative scheduling rules in simulation studies. It was claimed, for example, that vessels do moderate their cruising speeds when delays at the next lock are anticipated. Also, alternative lock sequencing rules (such as N-up, M-down) are used to alleviate congestion when necessary. For reasons stated earlier, the OMNI data do not allow us to validate the claim of fuel savings from adjustments in cruising speeds. They could, however, be used to investigate the extent to which rules other than first-come, first-serve, are used to expedite lockages. Industry data would be highly desirable to ensure that we are using a relevant bench mark for system performance and to ensure that we simulate the traffic movements consistently with actual river operations. The research team was unsuccessful in acquiring historical positioning information from the barge lines to validate OMNI data (especially the times and positions of arriving for lockage).

Seeking industry cooperation and data for the study, our research team met with Chris Brescia, president of Midwest Area River Coalition (MARC) 2000 in the spring of 2004. Mr. Brescia left the meeting essentially agreeing to help our team gain access to industry leaders. Over a month later Mr. Brescia asked for, and received from us, a list of organizations funding the study. After repeated failures to reach Mr. Brescia, another MARC 2000 officer returned our calls and explained that MARC 2000 was putting together a group of three experts to examine the simulation model. Mr. Brescia would contact us to arrange a meeting. Weeks later, Mr. Brescia sent an email stating he was waiting to hear back from a third expert before scheduling a meeting for the review of our simulation model. Our research team never received another email or phone call from Mr. Brescia.

Considering the difficulty of arranging industry contacts through MARC 2000, we called Worth Hager, president of the National Waterways Conference, asking if the principle investigator on our study could be allowed to speak with industry leaders when they met for the NWC annual convention in St. Louis. Ms. Hager said the schedule was fixed and that our PI would not be allowed to address those at the convention formally or informally.

Since our team was not progressing in its attempts to get industry cooperation through waterway organizations, we contacted Mark Knoy, president of MEMCO Barge Line, at the corporate headquarters in Chesterfield, Missouri. Mr. Knoy met with our researchers, and the meeting seemed productive in that Mr. Knoy expressed a willingness to share data for our research and to provide us with contact information for presidents and CEOs of other major barge companies. MEMCO did share some data, but since the company operates primarily on the Ohio River, it was of limited use for the present study.

We sent letters to the heads of seven leading barge companies operating on the Upper Mississippi River asking for cooperation with the study in the form of operational data including:

- Positional information (Vessel ID with longitude and latitude or river and mileage point) at the smallest time interval available. The data could be at fixed intervals or event driven
- Fuel burn since previous reporting time
- Tow configuration (number of full barges, no of empties, total weight (or draft)
- Other vessel characteristics affecting fuel consumption (power plant and propulsion).

Follow-up phone calls revealed the executives' near unanimous refusal to be associated with the study. A second letter containing a more detailed request for data went to many of the same barge company presidents and CEOs. More follow-up calls yielded no better results. We continue, therefore, to rely on the OMNI data for statistical modeling and developing parameters for the simulation model. We believe, however, that the simulation model, with parameters derived from the OMNI data, can provide a realistic test of the relative performance of different sequencing rules in reducing lock congestion. We would need better positional and operational data from the industry to produce reliable estimates of resulting fuel savings.

Statistical Models for Dynamic Adjustment of Simulation Parameters

Statistical models have been created to support the proposed second level of enhancement to the simulation model. The first level of enhancement simply uses a subset of the equations (namely those pertaining to movements involving commercial vessels that continue in the same direction to the next lock without stopping to reconfigure the tow) and random generation of all other vessels that appear for upbound and downbound lockages from each pool.

The statistical models are used to adjust the parameters of the simulation model that determine vessel itineraries, characteristics of the tow, times to complete lockage, and transit times to the location of the next lockage. A program is used to generate a SAS dataset with individual records for each upstream and downstream lockage involving entry into pools as follows:

- MI20U (entering pool 20 upstream from lock 20 and thus making a northerly departure from the section of the river covered by the simulation)
- MI21D (entering pool 21 downstream from lock 20, thus entering the most northerly section of the river covered by the simulation)
- MI21U (entering pool 21 upstream from lock 22)
- MI22D (entering pool 22 downstream from lock 21)
- MI22U (entering pool 22 upstream from lock 24)
- MI24D (entering pool 24 downstream from lock 22)
- MI24U (entering pool 24 upstream from lock 24)
- MI25D (entering pool 25 downstream from lock 24)
- MI25U (entering pool 25 upstream from lock 26, thus entering the most southerly section of the river covered by the simulation)
- MI26D (entering pool 26 downstream from lock 25, thus making a southerly departure from the section of the river covered by the simulation).

A program is used to fit a series of logistic and regression equations that, given the current tow configuration and pool just entered, estimate:

- the likelihood of continuing nonstop in the same direction for a lockage operation at the next lock (with no change in tow configuration)
- the likelihood of stopping in the pool and continuing in the same direction as a vessel next requiring a double lockage
- the likelihood of stopping in the pool and continuing in the same direction as a vessel next requiring a single lockage
- the likelihood of stopping in the pool and continuing in the same direction as a vessel next requiring a knockout lockage
- the likelihood of stopping in the pool and continuing in the same direction as a vessel next requiring a jackknife lockage
- the likelihood of making a stop in the pool, reversing direction and next reappearing at the same lock as a vessel requiring a double lockage
- the likelihood of making a stop in the pool, reversing direction and next reappearing at the same lock as a vessel requiring a single lockage

- the likelihood of making a stop in the pool, reversing direction and next reappearing at the same lock as a vessel requiring a knockout lockage
- the likelihood of making a stop in the pool, reversing direction and next reappearing at the same lock as a vessel requiring a jackknife lockage
- the likelihood of being removed from the pool to compensate for an instance of next appearing for lockage in another pool.
- the expected time required to complete lockage of the vessel
- the expected transit time to the arrival fix at the next lock if a nonstop trip occurs in the same direction
- the expected time from the departure from this lock to the arrival fix at the next point of lockage if the lock if the vessel stops in the pool with possible change in configuration or direction.

The model-fitting program is constructed to allow the automatic dropping of explanatory variables from the logistic and regression models if they do not meet a chosen level of statistical significance. It also allows for exclusion of observations for fitting the model if individual values of variables are less than a lower percentile threshold or higher than an upper percentile threshold. This is to screen out observations that are likely to have been affected by unusual circumstances (or recording errors) when estimating the mean value of the performance measure. The transition probabilities may be fit using linear forms with truncation (to eliminate values less than zero or greater than one) and normalization (to ensure transition probabilities for all possible succeeding states sum to one), or alternatively, using logistic equations that require normalization only. A keyword parameter guides that selection.

The equations for the transition probabilities are automatically written into files named tprob<*pool*>.sas, where <*pool*> is the entering pool for the lockage. (e.g., for operations involving entry into pool MI21U, the file name would be tprobMI21U.sas). Again, the pool suffix U signifies upstream and the pool suffix D signifies downstream. Similarly, the equations for expected times for lockage are automatically written into files named lock.times<*pool*> (e.g., lock.timesMI21U.sas). The equations for expected times for nonstop transit from the current lock to the next lock are written into files named thru.times <*pool*> (e.g., thru.timesMI21U.sas). The equations for expected times from departure from this lock to the arrival fix at the next lock, for trips involving a stop in the pool and possible change in configuration or direction, are written into files named stop.times <*pool*> (e.g., stop.timesMI21U.sas). Listings of the resulting equations for a fitting of the complete set of models on the unix computer system may be conveniently obtained by executing the command script "prtallc" to obtain a sequential listing of equations for all locks with a single title (saving some paper) or "prtall" to receive separate listings titled for transition probabilities, lockage times and transit times for all locks.

Pending the completion of downloading and merging of data for river levels and flow rates, we constructed equations for transition probabilities and operational times as follows:

Pcontsame = likelihood that the vessel continues nonstop to the next lock in its current configuration = f (month of year, type of tow at current lock)

Pcontdouble = likelihood that the vessel stops for possible reconfiguration and continues in the same direction to the next lock to be locked as a double lockage = f (month of year, type of tow at current lock).

Pcontsingle = likelihood that the vessel stops for possible reconfiguration and continues in the same direction to the next lock to be locked as a single lockage = f (month of year, type of tow at current lock).

Pcontko = likelihood that the vessel stops for possible reconfiguration and continues in the same direction to the next lock to be locked as a knockout lockage = f (month of year, type of tow at current lock).

Pcontjk = likelihood that the vessel stops for possible reconfiguration and continues in the same direction to the next lock to be locked as a jackknife lockage = f (month of year, type of tow at current lock).

Pretdouble = likelihood that the vessel stops for possible reconfiguration and returns in the opposite direction at the same lock to be locked as a double lockage = f (month of year, type of tow at current lock).

Pretsingle = likelihood that the vessel stops for possible reconfiguration and returns in the opposite direction at the same lock to be locked as a single lockage = f (month of year, type of tow at current lock).

Pretko = likelihood that the vessel stops for possible reconfiguration and returns in the opposite direction at the same lock to be locked as a knockout lockage = f (month of year, type of tow at current lock).

Pretjk = likelihood that the vessel stops for possible reconfiguration and returns in the opposite direction at the same lock to be locked as a jackknife lockage = f (month of year, type of tow at current lock).

Pxkill = likelihood that the vessel moves to a condition that would cause it to reappear in another pool for lockage (to be handled in the simulation by destroying the simulated vessel on completion of its current lockage and compensatory random generation of vessels and tows in various pools in consonance with historical monthly frequencies).

Slockhrs = expected number of hours required to complete a single lockage operation for the vessel = f(month of year, towboat configuration, type of lockage, percent of operation performed at night, interaction variables between towboat configuration and percent of operation conducted at night).

Lslckhrs = logarithm of expected number of hours required for a single lockage operation = f(month of year, towboat configuration, type of lockage, percent of operation performed at night, interaction variables between towboat configuration and percent of operation conducted at night). The logarithmic transformation is allowed as an alternative form for possible variance stabilization.

Dlockhrs = expected number of hours required to complete a double lockage operation for the vessel = f(month of year, percent of operation performed at night, interaction variables between towboat configuration and percent of operation conducted at night). Separate estimates were made for single and double lockages because the standard deviations of the lockage times differed materially.

Ldlckhrs = logarithm of expected number of hours required for a double lockage operation = f(month of year, type of lockage, percent of operation performed at night, interaction variables between towboat configuration and percent of operation conducted at night).

The logarithmic transformation is allowed as an alternative form for possible variance stabilization.

Nstransithrs = expected number of hours for nonstop travel from current lock to the next lock in the same direction = f(month of year, towboat configuration, percent of trip occurring at night, interaction between percent of trip occurring at night and towboat configuration, percent of trip during which the next lock to be reached suffers impairment to its operation).

Lognstrnhrs = logarithm of expected number of hours for nonstop travel from current lock to the next lock in the same direction = f(month of year, towboat configuration, percent of trip occurring at night, interaction between percent of trip occurring at night and towboat configuration, percent of tip during which the next lock to be reached suffers impairment to its operation). The logarithmic transformation is allowed as an alternative form for possible variance stabilization.

Transithrs = expected number of hours for travel from current lock to the next lock if the vessel stops for possible change in configuration or change in direction = f (month of year, new towboat configuration, percent of trip occurring at night, interaction between new configuration and whether direction change occurred, percent of trip occurring at night, percent of trip during which the next lock to be reached suffers impairment to its operation).

Logtrnhrs = logarithm of expected number of hours for travel from current lock to the next lock if the vessel stops for possible change in configuration or change in direction = f (month of year, new towboat configuration, percent of trip occurring at night, interaction between new configuration and whether direction change occurred, percent of trip occurring at night, percent of trip during which the next lock to be reached suffers impairment to its operation). The logarithmic transformation is allowed as an alternative form for possible variance stabilization.

In summary, the statistical models that provide parameters for the enhanced simulation model consist of:

- Logistical models for determining next lockage location and tow configuration, considering
  - Month of year
  - Current tow configuration (double, single, jackknife or knockout)

- Regression models for average lockage time and residual standard deviation of lockage time , considering
  - Month of year
  - Tow configuration
  - Proportion of lockage that occurs at night (suppressed in current version of simulation model)
  - Whether exchange or turn-back occurs

- Regression models for average transit time and residual standard deviation of transit time, considering
  - Month of year

  - Changes in tow configuration and location of next lockage
  - Percent of journey occurring at night (suppressed for current version of simulation model)
  - Percent of journey during which impairment is experienced at the next lock (suppressed for current version of the simulation model)

- Distributions of inter-arrival times for generating randomly all vessels that arrive northbound at Lock 25 and southbound at Lock 20, all recreational lockages, and vessels and tows that are removed after lockage for subsequent random generation (i.e., those that do not continue without stopping when working at enhancement level 1).

A complete set of program listings, illustrative reports, plots showing the monthly summaries of statistics for status of the system, and illustrative equations for pool transitions and operational times are provided in Appendix A.4. Table 13 contains definitions for additional variables used in the statistical models.

Lock Impairments

Physical impairments of lock operations occur randomly, with varying frequency throughout the year. A SAS program creates datasets giving the time between and duration of impairments of locks. The resulting datasets were exported into an Excel file for use by the academic version of the JMP software (JMP IN 5.1) for determining the best forms of distributions to be used for random variables (choosing from exponential, lognormal, gamma, and Weibull distributions, for example). Residuals for the regression models may be subjected to similar distributional tests.

Goodness of fit testing was performed on the impairment data for the distribution of the interval between stoppages and the duration of a stoppage. Times between impairments and duration of impairments are subject to seasonal influence. In the simulation model, intervals between impairments are represented by an exponential distribution with time-varying mean. Durations of impairments were best represented by a lognormal distribution with seasonally adjusted means and standard deviations.

Plots of the distributions of monthly impairment statistics and tables of average rates of occurrence, average time between incidents, and average duration of impairments are provided in Appendix A.5.

Water Conditions

Data from the Rock Island District's website were retrieved for stage levels and flows on the Mississippi River at locks 20 through 22. The St. Louis District provided data for the stage levels at locks 24 and 25. Flow readings were not taken at locks 24 and 25. Using all available data, these variables were added as explanatory variables for possible use in the model. Unfortunately, water-level data and flow rates were not complete for all pools and the data that we did use failed to enhance the statistical models. We decided to rely on the monthly seasonal indicator variables to convey information about typical water conditions.

Birth of Tows in Pools

Recall that, depending on the level of enhancement used in the simulation model, tows of various configurations have to be generated as random arrivals for upstream or downstream lockage at each lock. We determined that seasonally adjusted exponential distributions (nonstationary Poisson processes) represent this behavior quite well. Reports of the average inter-arrival times and the percentage of different tow configurations (also subject to monthly variation) appear in Appendix A.6.

In summary, the incorporation of information re ambient river conditions and lock impairments stands as follows:

- Seasonal distributions of times between breakdowns at locks and duration of breakdowns at locks
  - incorporated into the simulation model as independent events at each lock according to seasonal data

- Consideration of sunrise and sunset times in determining the percentage of time that an activity occurs in daylight (or conversely, at night)
  - allowed in some statistical models but yet not incorporated into the simulation model

- Consideration of the percentage of vessel transit time that occurred during an impairment at the succeeding lock
  - allowed in some statistical models but yet not incorporated into the simulation model

- Water level data and flow rates did not seem to enhance the statistical models and were not complete for all pools.

5. TRAFFIC MANAGEMENT ALTERNATIVES IDENTIFIED FOR STUDY

An array of traffic management policy alternatives is outlined below. Any of these traffic management policies can be implemented for managing traffic congestion in the Upper Mississippi River navigation system. These alternatives are described below in order from least intrusive to most intrusive with respect to their effect in altering the current operating practices evident in the water transportation markets served by the UMR system.

A. Existing Traffic Management

The US Army Corps of Engineers currently manages vessel traffic at the locks by processing vessels on a first-come, first-served basis. Exceptions to this first-come, first served policy do exist. The first exception is that recreation vessels receive priority processing at the locks in that they wait no longer than three commercial lockages before receiving service. In actuality, they rarely wait even three lockages and are usually processed as soon as practicable after their arrival at a lock. The second exception to the first-come, first-served policy is when excessively large queues form at a lock, the Corps and representatives from industry may coordinate in deciding the best order of lockage in order to clear the unusually lengthy queues. Typically, excessive queues are not the result of high traffic levels but are more commonly the result of periods of lock unavailability or impaired lock performance. As the market currently operates under this basic first-come, first-served lock policy, leaving the system traffic management as it exists is the least intrusive traffic management policy.

B. Managing Traffic by Scheduling Vessel Appointments at Locks

The next least intrusive traffic management policy is to schedule appointments for vessels at the locks during periods when the locks are congested. Vessels would be given an appointment time at each lock as they progress through the system. Vessels could be informed of their likely lockage time as the progress towards a lock. The appointment time for the vessel can be updated as the state of the lock or larger system changes either using already available information in the Corps OMNI system or supplemented by additional information provided by a vessel tracking system. The economic value of such an appointment system is that vessels can alter their speeds or operations to attempt to conserve fuel or undertake other productive activities knowing that their appointment at the lock is secure..

C. Managing Traffic by Re-sequencing Vessels in Lock Queues Locally

When queues do form at a lock, vessels could re-sequenced according to an optimization model designed to produce a better traffic management solution for clearing the queues than the first-come, first served policy. The re-sequencing of vessels in lock queues can be designed to take advantage of possible efficiencies available from locking vessels in a certain sequence and also to take advantage of the potential differential economic value of completing individual vessel lockages. In such a re-sequencing lock traffic management policy the "most valuable" or "most efficient" vessels would typically go to the head of the queue for early processing relative to their arrival time thereby passing less valuable vessels who are relegated to waiting for the more valuable traffic to pass. Section 6 below presents the details of a algorithm designed to implement such a policy.

D. Managing Traffic by Re-sequencing Vessels in Extended Lock Queues

This traffic management alternative is nearly identical to the policy entitled Managing Traffic by Re-sequencing Vessels in Lock Queues Locally except that it broadens the scope of vessels considered for re-sequencing to include not only vessels currently in queue at a lock but also vessels traversing pools upstream and downstream headed to that lock. Again, the "most valuable" or "most efficient" vessels would typically go to the head of the queue, if they are able to arrive in time for processing before lower valued or less efficient vessels. The re-sequencing algorithm could be updated as the state of the system changes either using already available information in the Corps OMNI system or supplemented by information provided by a vessel tracking system

E. Managing Traffic by Re-sequencing Vessels in Multiple Lock Queues Simulateneously

This traffic management policy extends the two previously discussed re-sequencing policies by further broadening the scope of vessels managed by considering vessels traversing pools upstream and downstream and in queues at multiple system locks simultaneously. Once again, the “most valuable” or “most efficient” vessels would typically receive expedited lock service at multiple system locks, especially if they are able to arrive in time and if they are headed to another relatively un-congested lock, relative to less valuable vessels. The vessel sequencing algorithm could be updated as the state of the system changes either using already available information in the Corps OMNI system or supplemented by information provided by a vessel tracking system

F. System-wide Traffic Management Using Vessel Tracking

This traffic management alternative continually monitors and manages the location and direction of all river traffic. A system, operating similar to Air Traffic Control, coordinates all vessel movements and lockages at all locks. This is a very intrusive traffic management policy and would essentially control all movements of all tows through the system.

6. A LOCALLY OPTIMIZED VESSEL SEQUENCING ALOGITHM FOR EFFICIENTLY CLEARING A LOCK QUEUE

If queues form at a lock, an optimization model can determine what lockage sequence of tow/barges (hereafter abbreviated as TB’s) should be invoked in order to clear the queues as quickly as possible. Generally we endeavor to either minimize the total elapsed time until the queue has been eliminated (often referred to as “makespan time” in the production scheduling literature), or we may wish to minimize some weighted (or unweighted) function of total (or average) cycle time. (In this case total and average cycle times are equivalent since average cycle time is found by dividing total cycle time by a constant—the number of TB’s processed). For our purposes, cycle time is the sum of queue time plus lockage time for a TB.

In order to see the difference between these two objectives, we consider two TB’s. One, TB1, has fifteen barges with an estimated lockage time of 90 minutes heading upstream. The second, TB2, has fifteen barges with an estimated lockage time of 105 minutes heading downstream. There are two possible set up times associated with this “exchange situation.” If TB1 (heading upstream) is processed first, there is a delay of 10 minutes until TB2 (heading downstream) may enter the lock. If TB2 is processed first, there is a delay of 5 minutes until TB1 may enter the lock. Armed with these estimates, we compare the two sequences as follows:

	Est. Lockage Time	Est. Lockage Start Time	Est. Lockage Completion Time
TB1	90	0	90
TB2	105	90+10	**205**
Or			
TB2	105	0	105
TB1	90	105+5	**200**

In this example, the queue is cleared in **205** minutes using a TB1:TB2 sequence or in **200** minutes using a TB2:TB1 sequence. Thus the TB2:TB1 sequence is preferred if we wish to clear the queue as soon as possible.

However, if a weighting scheme were used based simply on the number of barges associated with a TB, we see that the TB1:TB2 sequence would be preferred when calculating a total weighted completion time (see table below where **4425** < **4575**).

	Weighting	ELT	ELST	ELCT	Weighted Compl. Time
TB1	15	90	0	90	90*15=1350
TB2	15	105	90+10	205	205*15=3075
			Total Wgt. Compl. Time		**4425**
Or					
TB2	15	105	0	105	105*15=1575
TB1	15	90	105+5	200	200*15=3000
			Total Wgt. Compl. Time		**4575**

Given this behavior, we seek to find a "best" sequence of TB's through a lock. At this point we appeal to results from the production scheduling literature.

Consider a 1-machine production line where three jobs are to be processed with each job having an expected processing time. This is known as the "classical job shop scheduling problem." For example,

Job	Processing time
A	5
B	3
C	6

Now for the job processing sequence A,B,C we calculate the completion time (or cycle time) for each job to get:

Job	Processing time	Completion or cycle time
A	5	5
B	3	5+3=8
C	6	8+6=14

Then the average cycle time (or completion time) for sequence A,B,C is (5+8+14)/3 = 9. Note of course that this is different from the average processing time which of course is not a function of the job sequence in this example. Now consider a job sequence of B,A,C. We get:

Job	Processing time	Completion or cycle time
B	3	3
A	5	3+5=8
C	6	8+6=14

In this case the average cycle time for sequence B,A,C is (3+8+14)/3=8.33

Thus we see that a simple ordering by shortest processing time (SPT) minimizes average (or total) completion (or cycle) time for jobs being processed by one machine.

Unfortunately, our particular sequencing application also incorporates set up times for exchange and turnback situations. Therefore, a simple rule such as SPT may or may not result in the "best" sequence.

We devise an optimization model that formalizes various approaches and objectives for generating "optimal" sequences. We consider three unique ordering protocols, any of which may be utilized in the optimization model.

The first is a first come, first served (FCFS) protocol. Here we order TB's separately on each side of the lock according to FCFS. Then we have an FCFS order for all TB's headed downstream and another FCFS order for all TB's headed upstream. Since set up times for turnback situations are often smaller than set up times for exchange situations, it is easy to see that the industry-favored N up/M down protocol serves to reduce the total set up time when clearing a queue. The use of N up/M down also serves to reduce the delay for a TB over and above a *strict* FCFS protocol where TB's were processed through the lock regardless of which side of the lock they were on. A *strict* FCFS protocol simply sequences the TB's in the overall order in which they arrived at the lock.

The second protocol is to order all TB's on one side of a lock by non-decreasing estimated lockage times. A similar ordering is effected for all TB's on the other side of the lock. This is akin to the SPT job shop scheduling algorithm described above.

The third protocol is to order all TB's on one side of a lock by non-decreasing weighted estimated lockage times. A similar ordering is effected for all TB's on the other side of the lock.

It is important to note in all three protocols described above, that TB's on one side of the lock will be processed through the lock in the order generated. However, the actual sequence of TB's through the lock may intersperse upstream and downstream TB's while still maintaining the order of TB's on each side of the lock.

Description of the Optimization Model

Assumptions:

Let N be the total number of TB's in queue.
Let N_D be the total number of TB's in queue on the downstream side of the lock.
Let N_U be the total number of TB's in queue on the upstream side of the lock.

For i =1, ..., N_D (N_U) generate an expected lockage time, $t_{Di}(t_{Ui})$, for each TB. Note that this time may depend on whether the TB is on the downstream (D) or upstream (U) side of the lock. For i = 1,..., N_D (N_U) generate a weight, w_{Di} (w_{Ui}), for each TB. This may be generated from the number of barges or some weighted combination of tows and barges, or the barges may have different weights depending on whether they are loaded or empty, etc. Other weighting or priority schemes may be used as well. We assume that w_i's increase with the "importance" or "weight" of a TB. For protocols 1 and 2 we set $w_{Di}=w_{Ui}=1$.

We then order the downstream TB's as 1,... N_D, and the upstream TB's as 1,…N_U where $(N_D+N_U=N)$ according to one of the three protocols described above.

Define the following data elements: Let $SAME_U$ ($SAME_D$) denote the setup time required for two upstream (downstream) TB's passing through the lock in sequence. This is also referred to as a turnback situation. Let OPP_U (OPP_D) denote the set up time required for an upstream (downstream) TB passing through the lock followed by a downstream (upstream) TB. This is also referred to as an exchange situation. (Generally $OPP > SAME$).

Define a maximum delay constant, D, to be the maximum delay time allowed for any TB over and above the *strict* FCFS protocol for sequencing queued TB's through the lock. Further, calculate $FCFSx_i$ for i=1,…,N_D and $FCFSy_i$ for i=1,…,N_U. These are the estimated lockage completion times using the *strict* FCFS protocol.

Now define the following decision variables. Let $ENDLOCK_N$ be the end lockage time for the *N*th TB and define $ENDLOCK_0$ to be the starting lockage time for the first TB through the lock.

For j =1,... *N*-1 define:

$$Z_{jUU} = \begin{Bmatrix} 1 \text{ if tow/barge sequence j and j+1 are on the upstream side of the lock} \\ 0 \text{ if not} \end{Bmatrix}$$

$$Z_{jDD} = \begin{Bmatrix} 1 \text{ if tow/barge sequence j and j+1 are on the downstream side of the lock} \\ 0 \text{ if not} \end{Bmatrix}$$

$$Z_{jUD} = \begin{Bmatrix} 1 \text{ if tow/barge sequence j and j+1 are on the upstream side and then the downstream side} \\ 0 \text{ if not} \end{Bmatrix}$$

$$Z_{jDU} = \begin{Bmatrix} 1 \text{ if tow/barge sequence j and j+1 are on the downstream side and then upstream side} \\ 0 \text{ if not} \end{Bmatrix}$$

For i =1, ...N_D and $j=i,...,(N_U+i)$ define:

$$x_{ij} = \begin{Bmatrix} 1 \text{ if downstream TB } i \text{ is the } j\text{th overall TB to pass through the lock} \\ 0 \text{ if not} \end{Bmatrix}$$

For i =1, ...N_U and $j= i,...,(N_D+i)$ define::

$$y_{ij} = \begin{cases} 1 \text{ if upstream TB } i \text{ is the } j\text{th overall TB to pass through the lock} \\ 0 \text{ if not} \end{cases}$$

Note that x_{ij} and y_{ij} are only defined for $j \geq i$. This is because in each of the protocols we require TB's on each side of the lock to be processed in that order.

Let $0 \leq p \leq 1$ be a user specified objective function weighting parameter. If p is equal to 0, we minimize makespan time ($ENDLOCK_N$) regardless of weighting, but maintain the chosen protocol ordering. If p is equal to 1, we minimize the total weighted cycle (lockage and queue) time.

Then we have the following sequencing integer program:

(1)

$$MINIMIZE\ p\left[\sum_{i=1}^{N_D}\sum_{j=i}^{N_U+i} w_{Di}x_{ij}(ENDLOCK_j) + \sum_{i=1}^{N_U}\sum_{j=i}^{N_D+i} w_{Ui}y_{ij}(ENDLOCK_j)\right] + (1-p)ENDLOCK_N$$

subject to:

(2) $$\sum_{j=i}^{N_U+i} x_{ij} = 1 \quad \forall i = 1 \ldots N_D$$

(3) $$\sum_{j=i}^{N_D+i} y_{ij} = 1 \quad \forall i = 1 \ldots N_U$$

(4) $$Z_{jUU} + Z_{jDD} + Z_{jDU} + Z_{jUD} = 1 \quad \forall j = 1, \ldots N-1$$

(5) $ENDLOCK_0 = 0$

(6a) $$ENDLOCK_0 + \sum_{i=1}^{N_D} t_{Di}x_{i1} + \sum_{i=1}^{N_U} t_{Ui}y_{i1} = ENDLOCK_1$$

(6b)

$$ENDLOCK_{(j-1)} + \sum_{i=1}^{N_D} t_{Di}x_{ij} + \sum_{i=1}^{N_U} t_{Ui}y_{ij} + SAME_U Z_{(j-1)UU} + SAME_D Z_{(j-1)DD} + OPP_U Z_{(j-1)UD}$$

$$+ OPP_D Z_{(j-1)DU} = ENDLOCK_j \text{ for } j = 2, \ldots N$$

(7) $x_{ij} + x_{i+1,j+1} \le 1 + Z_{jDD} \quad \forall i = 1,...N_D - 1; \forall j = i,...N_U + i$

(8) $y_{ij} + y_{i+1,j+1} \le 1 + Z_{jUU} \quad \forall i = 1,...N_U - 1; \forall j = i,..., N_D + i$

(9) $x_{ij} + y_{j-i+1,j+1} \le 1 + Z_{jDU} \quad \forall i = 1,...N_D; \forall j = i,...N_U + i - 1$

(10) $y_{ij} + x_{j-i+1,j+1} \le 1 + Z_{jUD} \quad \forall i = 1,...N_U; \forall j = i,..., N_D + i - 1$

(11) $x_{ik} \le \sum_{j=k+1}^{N_D+N_U-1} x_{i+1,j} \quad \forall i = 1,..., N_D - 1; \forall k = i,..., MIN(N_D + N_U - i, N_U + i)$

(12) $y_{ik} \le \sum_{j=k+1}^{N_D+N_U-1} y_{i+1,j} \quad \forall \mathrm{i} = 1,..., \mathrm{N}_\mathrm{U} - 1; \forall k = i,..., MIN(N_D + N_U - i, N_D + i)$

(13) $\sum_{\substack{i \le MIN(j,N_D) \\ i \ge MAX(1,j-N_U)}} x_{ij} + \sum_{\substack{i \le MIN(j,N_U) \\ i \ge MAX(1,j-N_D)}} \mathrm{y}_{\mathrm{ij}} = 1 \quad \forall j = 1,...N$

(14) $\sum_{j=i}^{N_U+i} x_{ij}(ENDLOCK_j) \le FCFSx_i + D \quad \forall i = 1,...N_D$

(15) $\sum_{j=i}^{N_D+i} y_{ij}(ENDLOCK_j) \le FCFSy_i + D \quad \forall i = 1,...N_U$

$x_{ij} = 0 \text{ or } 1 \quad i = 1,...N_D; j = i,..., N_U + i$

$y_{ij} = 0 \text{ or } 1 \quad i = 1,...N_U; j = i,..., N_D + i$

(16) $Z_{jDD} = 0 \text{ or } 1 \quad \forall j = 1,...N - 1$

$Z_{jUU} = 0 \text{ or } 1 \quad \forall j = 1,...N - 1$

$Z_{jDU} = 0 \text{ or } 1 \quad \forall j = 1,...N - 1$

$Z_{jUD} = 0 \text{ or } 1 \quad \forall j = 1,...N - 1$

From the above formulation we see that constraints (2) and (3) force each TB to be assigned a sequence number through the lock. Constraint (4) requires that each pair of contiguous passages through the lock are either (up, up), (down, down), (up, down), or (down, up). Constraints (6a) and (6b) keep track of the end lock times for each TB in sequence. Constraints (7) through (10) force the corresponding *Z* variable to 1 when two particular TBs are sequenced through the lock thus incurring one of the four setup times. Constraints (11) and (12) ensure that the TB's on each side of the lock are processed in the order 1, 2,….$N_D(N_U)$. Constraint (13) ensures that either an upstream or downstream TB is processed through the lock as the jth TB. Constraints (14) and (15) ensure that no TB is delayed by more than D units of time over and above a *strict* FCFS protocol.

Additional constraints for limiting the number of consecutive same-direction TBs passing through the lock may be modeled are as follows.

Suppose we wish to allow no more than 3 consecutive same-direction lockages.

Then we may add the constraints (for the case where N = 20):

$$Z_{1UU} + Z_{2UU} + Z_{3UU} + Z_{4UU} \le 3$$
$$Z_{2UU} + Z_{3UU} + Z_{4UU} + Z_{5UU} \le 3$$
$$\vdots$$
$$Z_{16,UU} + Z_{17UU} + Z_{18UU} + Z_{19UU} \le 3$$
$$Z_{1DD} + Z_{2DD} + Z_{3DD} + Z_{4DD} \le 3$$
$$Z_{2DD} + Z_{3DD} + Z_{4DD} + Z_{5DD} \le 3$$
$$\vdots$$
$$Z_{16DD} + Z_{17DD} + Z_{18DD} + Z_{19DD} \le 3$$

Throughout this section we have invoked a protocol ordering on each side of the lock. That is, we require that for TB's on one side of the lock, the ordering invoked will be the ordering used to process TB's through the lock (although TB's from the other side of the lock may be interspersed). We now prove a result that shows that such an ordering cannot be violated in an optimal solution to the nonlinear integer program (1)-(13) and (16). We consider protocols 2 and 3 since protocol 1 is, by definition, first come, first served.

Let p=1. Consider protocol ordering 2 of non-decreasing unweighted lockage times for each side of the lock. We claim this ordering must hold in an optimal solution to (1)-(13) and (16). We prove this result by contradiction. Let TB1 and TB2 approach the lock from the same side. Let TB1 have an unweighted lockage time of A units and TB2 have an unweighted lockage time of A+B units where B>0. Then according to protocol 2, TB1 should be processed through the lock before TB2. We would then have ENDLOCK(TB1) < ENDLOCK(TB2) and we let ENDLOCK(TB2) = ENDLOCK(TB1) +S+ A +B where S > 0 denotes the setup and processing time for TB's from the other side of the lock that are processed between TB1 and TB2 (if any—if none, then S denotes the setup time required to process TB2 directly after TB1).

Now assume that in an optimal solution TB2 precedes TB1. Since TB2 is processed before TB1, we have ENDLOCK(TB2) < ENDLOCK(TB1) and ENDLOCK(TB2) = ENDLOCK(TB1) + B. Also ENDLOCK(TB1) = ENDLOCK(TB2) +S + A.

Compare the objective values.

For the TB1:TB2 ordering our objective function is:
ENDLOCK(TB1)+ENDLOCK(TB2)= ENDLOCK(TB1) + ENDLOCK(TB1) +S +A + B = 2*ENDLOCK(TB1)+ S +A + B.

For the TB2:TB1 ordering our objective function is: ENDLOCK(TB2) + ENDLOCK(TB1) = ENDLOCK(TB1)+B + ENDLOCK(TB1) +B + S + A = 2*ENDLOCK(TB1) + S + A + 2B.

The latter total is clearly larger than the former implying that the ordering must be TB1:TB2.

The proof for protocol 3 is analogous.

Finally, this result enables a search on the order of 2^N rather than a search on the order of N. For N=20, 2^{20}~10^6 while 20! ~ 2*10^{18}.

If p = 0, we have an integer linear program (as long as constraints [14] and [15] are not invoked) that will minimize the makespan (or elapsed time) for all TB's in queue to pass through the lock according to the given protocol. Such a problem may be solved using commercially available integer programming software. However if p > 0, a nonlinearity in the first term is introduced (and is present in constraints (14) and (15) as well). Thus, in the case where p > 0, we address the problem using a complete enumeration approach. A complete enumeration approach may also be utilized when p = 0. Fortunately, it appears that the potential size of the queues (observed from historical data) is such that complete enumeration is indeed possible. We describe such an approach next.

For queues ranging in the area of 12 or fewer TB's downstream of a lock and a similar number upstream of a lock, it is feasible to use complete enumeration under a wider variety of constraints, rules, etc. (Note that in the year 2003 for locks 19-26, it appears that the maximum in queue upstream or downstream of a lock is less than 10 with the sum being less than 20). For queues larger than 24, we arbitrarily drop those in excess (say S TB's) having the largest weighted times or the latest in terms of FCFS. Once S TB's have passed through the locks we reoptimize with the S TB's that were dropped initially.

Suppose the first TB upstream is to be sent through the lock. Then there are the following possibilities for the second TB through the lock: either the next TB passing through the lock is from the same side or it is from the opposite side. Similarly, we have a like number for the first TB through the lock being downstream. Then we have on the order less than $4^{(N/2)}$ combinations of actual sequences through the locks given the invocation of the protocol for orderings in non-decreasing order of weighted times or in terms of FCFS. A figure of less than $4^{(N/2)}$ holds since there is only one remaining sequence whenever the downstream (upstream) queue has been processed.

Some Observations on Operational Issues

TB's are tied up on the shore farther and farther away from the lock as the queue grows longer. Once an "optimal sequence" is generated, it is clear that the next TB to be locked through on one side of the lock may not be the TB that is closest to the lock. If, for example, a TB had the "best" weighting but was tied up a long distance from the lock, it would take some time to get into position. However, if our policy was one of the following two, it seems that we can avoid such a long set up time. These policies in effect create a "buffer/staging" area for the next TB to enter the lock from upstream (downstream).

Policy 1: Always leave the nearest tie up to the lock vacant when queues start. Then order the TB's for passage by the weighting scheme and the next scheduled TB is then directed to tie up at the nearest tie up while waiting for passage through the lock.

Or Policy 2: When a queue forms, the TB that is at the nearest tie up to the lock is directed to make passage through the lock first. At this point, the nearest tie up is vacant and we direct the next scheduled TB to that tie up location to await entry through the lock

Such policies eliminate the extra set up time to approach a lock from a far tie up location.

7. THE UMR SIMULATION MODEL

There is a growing body of literature concerning the use of simulation models in analyzing waterway transportation networks that has its beginning with a report by Carroll (1972) and an article by Carroll and Bronzini (1973). These two early efforts laid the foundation for the use of simulation models in modeling inland waterway system operations. The authors demonstrate that simulation models are useful in analyzing waterway operations because inland navigation systems exhibit a sufficient degree of interdependent performance characteristics to limit the use of queuing theory tools or other related analyses in faithfully capturing the behavior of such systems.

Later, beginning in the early 1990's, a series of articles documents the development of a sequence of increasingly complex inland waterway simulation models designed to explore and evaluate an increasingly large range of operating issues and management policies (for examples, see Dai and Schonfeld (1991), (1992), and (1994); Kim and Schonfeld (1995); Martinelli and Schonfeld (1995): Ramanathan and Schonfeld (1994); Ting and Schonfeld (1996), (1998a), (1998b), (1999), (2001a), (2001b); Wang and Schonfeld (2002); Wei et al. (1992); Zhu et al. (1999)). These articles create and utilize many different simulation models to analyze various methods of scheduling and sequencing tows in attempts to reduce overall lock delay times and reduce water transportation costs.

However, all of the waterways simulation models created in this series of articles invoke two related simplifying assumptions that create important distortions when attempting to model the operation of the UMR navigation system. The first of these assumptions is that the navigation system approximates a steady state level of performance. As the detailed examination of the

Corps OMNI data described above makes clear, the UMR navigation system never achieves or even approximates a steady state level of system performance. In the winter months, nearly all of the floating equipment operating north of Lock 25 exits that portion of the UMR system to operate elsewhere until the system "reopens" in the spring for the next navigation system. Consequently, waterway transportation equipment must initially enter the UMR system each year with an upbound lockage at Lock 25 and again ultimately exit the UMR system each year with a downbound lockage at Lock 25. The lack of steady state performance of the UMR system is primarily the direct consequence of the fact that the demands for both commercial and non-commercial use of the system vary significantly over time throughout each annual navigation season.

The second of the simplifying assumptions invoked by prior waterway simulation models is that the demands for service of tows at the individual locks comprising the system are independent of each other. The UMR navigation system segment north of Lock 25 is a closed loop system with only a single connection through Lock 25 to the remainder of the inland waterway system. Therefore, to complete a specific origin to destination movement, the needed waterway equipment must either first move from some other location in the UMR to the origin of the movement or the equipment must enter the UMR system as an upbound lockage through Lock 25 and then proceed to the origin of the movement. Consequently, specific movements of tows are not completely independent of each other as the towboats and barges required to complete each movement must move through the system at some earlier point in time either as new entrants to the system or from the destination of a previously completed movement. Hence, individual tow movements are often dependent on the completion of prior movements and the demands for service of tows at the individual locks cannot be modeled as independent of each other.

Based on the results of the analysis of the Corps OMNI data described above, a simulation model is formulated and constructed that simulates vessel and lock operations of the UMR navigation system segment extending from Lock 20 to Lock 25. The model simulates individual vessel movements at and between these locks for an entire calendar year. The model incorporates exogenous variables that influence vessel movement through the system such as total system traffic levels, differential operating characteristics of vessels, inter-dependence of lock processing times for vessels, and, most importantly, intra-seasonal variability of demands for system use.

The logic underlying the simulation model is founded on the observed operation of the UMR system as recorded in the Corps OMNI data. The model begins the simulation year with a "cold start" in that very few tows are desirous of entering and using the system during the winter months. In the early spring, system use rapidly increases as more and more tows begin entering and circulating through the system. During the summer months the number of new tows entering and using the system is roughly balanced by the number of tows that exit the system. In the fall months the number of system exits begins to gradually outweigh the system entrances and, finally, in the winter months the number of system exits greatly outnumbers the number of system entrances culminating with nearly all tows exiting the system sometime during December.

A commercially available product of Micro Analysis and Design, Micro Saint Sharp, Version 1.2, is employed to create the discrete-event UMR simulation model. Micro Saint Sharp is a software product designed to facilitate the production of discrete event simulation models using a Microsoft Windows based graphic user interface. The Micro Saint Sharp software also permits the simulation model to utilize an embedded animation feature to graphically present the movements of the vessels through the system on a scaled map on a personal computer display as the model executes. This visual feedback helps audiences unfamiliar with simulation models to literally watch the simulated system operate during model execution and to observe changes in the system as they occur in simulation time. Figure 12 presents the scaled map created for the on-screen presentation of the UMR Simulation Model.

UMR Simulation Model Components

Micro Saint Sharp based simulation models are formed of "model components" that are related through a network diagram termed a "task network". The two most important types of model components that comprise a task network are tasks and entities. Tasks represent related network activities. Entities "travel" through the network of related tasks. The paths that individual entities follow as they move through the network are determined by supplementary model components. The critical components of the waterway simulation model are described in more detail below. Detailed descriptions of the role and use of all model components may be found in Micro Analysis and Design, Inc.'s Micro Saint 4.0 User Guide (2004).

Entities

An entity is an object that travels through a network of tasks and indicates by its location in the network when each task is executing or waiting to execute. Each entity defined in the UMR simulation model represents a unique waterway flotilla or vessel. There are three distinct broad categories of flotilla defined in the simulation model: recreation vessels; small tows; and large tows. Recreation vessels represent local traffic at individual system locks that do not utilize any other system lock, small tows represent commercial tows that may move through the entire system and that pass through each of the system locks in a single cut lockage, and large tows represent commercial tows that may move through the entire system and that require a multi-cut lockage to pass through each of the system locks. The three groups of entities in the UMR simulation model are described in detail below.

- Recreation Vessels

This group of vessels includes recreational boats, passenger boats, and government boats. Unlike commercial tows, these vessels arrive at a given lock in the system, lock through that lock in a given direction, and then do not reappear at that lock or any other system lock for relatively long and uncertain periods of time. Further, these vessels can and do lock through system locks in multiple vessel lockages. In the simulation model, these vessels (or groups of these vessels each comprising a single lockage) are independently generated by separate tasks for each combination of lock and direction of travel and then these vessels are terminated in the system after completing their one and only lockage at the lock where they were generated. Recreation

Vessel arrivals are treated in the model as independent Poisson random variables characterized by direction of travel, arrival lock, and by month of arrival. Consequently, the time between recreation vessel arrivals (the inter-arrival time) by lock, direction of travel, and month of arrival are represented by independent exponential distributions whose means are extracted from the Corps OMNI database and entered as parametric inputs into the simulation model. Table 14 displays the mean number of local vessel arrivals by lock and direction for each month of the simulation.

- Small Tows

This group of vessels represents commercial tows that are small enough (less than 600 feet in length) to fit completely in the 600 foot long chambers of each of the five locks. These vessels are processed through each of the locks in single cut lockages. These tows are introduced periodically into the system as independent Poisson random variables characterized by direction of travel, arrival lock, and by month of arrival. Consequently, the time between small tow arrivals (the inter-arrival time) by lock, direction of travel, and month of arrival are represented by independent exponential distributions whose means are extracted from the Corps OMNI database and entered as parametric inputs into the simulation model. These tows then complete their initial lockage and make a probability based decision on whether to terminate their trip after that initial lockage or to continue on to the next lock in the same direction of travel without stopping or reconfiguring their flotilla. The probability of continuing to the next lock varies monthly by lock, direction of travel and tow type. In this manner some interdependent tow arrivals are generated at successive locks in the system until ultimately the tow either terminates after its next lockage or exits the system upbound at Lock 20 or downbound at Lock 25.

- Large Tows

This group of vessels represents commercial tows which are longer than 600 feet and therefore do not fit fully assembled in the 600 feet long chambers of each of the five locks. Therefore, these vessels must be processed through the locks in multi-cut lockages. Like small tows, these tows are introduced periodically into the system as independent Poisson random variables characterized by direction of travel, arrival lock, and by month of arrival. Consequently, the time between small tow arrivals (the inter-arrival time) by lock, direction of travel, and month of arrival are represented by independent exponential distributions whose means are extracted from the Corps OMNI database and entered as parametric inputs into the simulation model. These tows then complete their initial lockage and make a probability based decision on whether to terminate their trip after that initial lockage or to continue on to the next lock in the same direction of travel without stopping or reconfiguring their flotilla. The probability of continuing to the next lock varies monthly by lock, direction of travel and tow type. In this manner some interdependent tow arrivals are generated at successive locks in the system until ultimately the tow either terminates after its next lockage or exits the system upbound at Lock 20 or downbound at Lock 25.

Tags

A "Tag" is a Micro Saint "system" variable that records the unique identity of each entity when there may be many entities traveling simultaneously through the task network. Tag values in the UMR simulation model are assigned to small tows, large tows and recreation vessels as they are introduced into the system. Once a vessel or tow is assigned a tag value, the value stays with the vessel or tow through the entire simulation until the vessel or tow is ultimately terminated.

Tasks

Tasks are the fundamental building blocks of a Micro Saint Sharp simulation model network. Tasks are activities to be accomplished in the model and are usually, but not always, triggered by the arrival of an entity at a task. A task is characterized by its execution time distribution, the constraints that limit its execution, the effect of its execution on other tasks, the effect of its execution on variables of interest defined for the system, and the effect of its execution on related subsequent tasks. The tasks in a Micro Saint Sharp simulation model are connected by a "task network" which describes how tasks are related to each other and under what conditions tasks are to be completed.

The important tasks defined in the task network of the UMR simulation model are described more completely below.

- Fill the flotilla inter-arrival time distribution arrays with data

This is a task defined to enter the mean inter-arrival times between small tow, large tow and recreation vessel traffic arrivals, respectively, for each lock (20, 21, 22, 24, and 25) by simulation month (1 through 12) and by each direction of travel (Upbound, Downbound). The inter-arrival time distributions are assumed exponentially distributed for each category of flotilla in each simulation month for each lock by each direction. Consequently, mean inter-arrival times do not vary within a simulated month, but do vary from month to month during the simulation of an entire year. Micro Saint Sharp requires only the mean value of exponential random variables associated with task executions which is the reason why only the mean value is entered into the parameter array. This task executes only at simulation time zero and requires no simulated time to complete.

- Define the default prioritization values for the queue dispatch policy at each lock

This task sets the default priority values used by the simulation model to select a vessel to begin its lockage at a lock from the associated queue of waiting vessels. These priorities differ by lockage type, vessel type, and lock. This task executes only at simulation time zero and requires no simulated time to complete.

- Create and display the on-screen map for the model animation

This task displays a map of the UMR system on the personal computer monitor and defines the variables to be displayed on the map as the simulation executes. The variables defined for display are updated in simulated time as the model executes. This task executes only at simulation time zero and requires no simulated time to complete.

- Begin recreation vessel arrivals

This task signals the ten tasks that schedule recreation vessel arrivals at the locks to begin to schedule recreation vessel arrivals. This task executes only at simulation time zero and requires no simulated time to complete.

- Begin tow arrivals

This task signals the ten tasks that schedule small and large tow arrivals at the locks to begin to schedule tow arrivals. This task executes only at simulation time zero and requires no simulated time to complete.

- Generate a new recreation vessel arrival at a lock

There are ten separate recreation vessel arrival tasks included in the task network, two each (Upbound and Downbound) for Lock 20, Lock 21, Lock 22, Lock 24, and Lock 25. Each of these tasks creates the arrival of a recreation vessel at a lock and then reschedules itself to execute again at a later time dependent upon the inter-arrival time distribution for recreation vessels. The inter-arrival time is characterized by an exponential distribution whose mean for each lock and direction of travel varies by month. These tasks execute repeatedly during model execution.

- Generate a new tow arrival at a lock

There are ten separate tow arrival tasks included in the task network, two each (Upbound and Downbound) for Lock 20, Lock 21, Lock 22, Lock 24, and Lock 25. Each of these tasks creates the arrival of a new tow at a lock and then reschedules itself to execute again at a alter time dependent upon the inter-arrival time distribution for recreation vessels. The inter-arrival time is characterized by an exponential distribution whose mean for each lock and direction of travel varies by month. These tasks execute repeatedly during model execution.

- Lock a vessel through a lock

There are five separate lockage tasks included in the “task network”, one each for Lock 20, Lock 21, Lock 22, Lock 24, and Lock 25. Each of these tasks represents the movement of a unique flotilla through a lock. The time to complete each of these lockage tasks is characterized by a lognormal distribution whose mean and standard deviation vary by vessel type (Recreation Vessel, Small Tow, Large Tow), by direction of travel (Upbound, Downbound), by month of occurrence, and by lockage type (Fly, Exchange, Turnback). The lognormal random variable distribution is a pre-defined distribution in the Micro Saint Sharp software characterized by its mean and standard deviation. The lognormal distribution is a reasonable approximation for tasks that cannot be completed much faster than the mean but sometimes take much longer than the mean to complete. This distribution is an appropriate approximation for tasks with no practical upper bound on their time duration, but for which very long completion durations are relatively rare occurrences. The sensitivity of the model to the use of lognormal distributions to characterize the performance of these and other similar tasks was explored by replacing the lognormal distributions with gamma distributions with identical means and standard deviations. The gamma distributional forms produced fewer extreme values in executing the individual tasks in the model than did the lognormal distributional forms, but did not significantly alter the ability of the model to reasonably replicate the observed operations of the UMR system.

These lockage tasks can only each execute when the lock is unoccupied by another vessel and the lock is not otherwise unavailable for some other reason. Any vessels arriving at a lock for lockage during a period when the lock is occupied or otherwise unavailable enter a queue to await the later availability of the lock. Recreation vessels are given first priority in the queue for selection for lockage over tows. Tows are prioritized on a First In, First Out basis. This queue dispatch policy is adopted in the model to reflect the fact that the largest portion of local vessel arrivals observed at these locks is composed of recreation vessels that are given priority in the real UMR lockage queues. When a vessel completes its lockage it is routed into the immediate upstream or downstream pool dependent on its direction of travel and then either begins the task of moving through that pool to the next system lock or terminates in that pool. It is straightforward to alter the model to incorporate more complex and realistic tow behavior; however the Corps OMNI database does not record the actual activities of tows between arrivals at locks and consequently it is not possible to identify precisely where and how a tow changes configuration or direction in a pool. These lockage tasks execute repeatedly as needed and do require simulated time to execute.

- Move a tow through a pool

There are four separate pool transit tasks included in the task network, one each for Pool 21, Pool 22, Pool 24, and Pool 25. Each of these tasks represents the movement of a single tow from a lock to another lock for processing at the next lock. The time to complete each of these pool transit tasks is characterized by a lognormal distribution whose mean and standard deviation vary by vessel type (Small Tow, Large Tow), direction of travel (Upbound, Downbound), and month of occurrence. These tasks execute whenever a vessel enters a pool after completing a lockage and has made a probabilistic decision to continue on to the next sequential lock in the system without stopping or changing configuration. These probabilistic decisions to continue or terminate after lockage vary by vessel type and month of occurrence. An unlimited number of vessels can move in each pool simultaneously and may pass each other in moving to the next lock. These tasks execute repeatedly as required during model execution.

- Create periods of lock unavailability

There are five separate pairs of tasks included in the “task network”, one pair each for Lock 20, Lock 21, Lock 22, Lock 24, and Lock 25, which randomly create a period of unavailability independently for each of the locks. The duration of a period of unavailability at a lock is represented by a lock specific exponentially distributed random variable. The time between lock unavailability is also represented by a lock specific exponentially distributed random variable. These pairs of tasks are designed to independently close each lock to traffic for variable periods of time during the simulation period. These tasks incorporate into the simulation model the observed periods in the OMNI data when locks are unexpectedly unavailable to service tows or local vessels.

- Record data and terminate vessels at the completion of recreation vessel and tow lockages

There are five separate tasks included in the task network, one each for Lock 20, Lock 21, Lock 22, Lock 24, and Lock 25 to record information regarding the recreation vessel and tow lockages completed at the system locks. These tasks are executed whenever a recreation vessel completes lockage at a lock or a tow terminates its travels after completing a lockage at a lock. When a recreation vessel completes its lockage it is always routed to this task and the recreation vessel is terminated. When a tow is determined to not continue to the next lock it is instead routed to this task and terminated. These tasks execute repeatedly during model execution and consume no simulated time to execute. These tasks record the total amount of observable time a tow has spent in the five lock system at its termination. Observable tow time in the simulation model is restricted to the time tows are waiting for lockage, processing through a lock, or transiting from one lock to another of the five locks. This definition of observable tow time facilitates a comparison with similar data generated from the Corps OMNI system.

Task Queues

In a Micro Saint Sharp model, a queue is a waiting area associated with a network task where entities (vessels) accumulate while they are waiting to execute the task. An entity can only execute a task when the "release condition" for executing that task is met. If an entity arrives at a task in the network and the release condition for that task is not met, then the entity enters the queue associated with that task and waits with all other entities that are in the queue for a release to begin executing that task. Each time the release condition for the task becomes true, an entity is selected from the queue to begin execution of the task.

In the UMR simulation model, queues are associated with each lock task. In the model only one lockage may be executing at each lock at any given time. Vessels enter the lock queue only if the lock is occupied by another vessel or the lock is otherwise unavailable when the vessel arrives. The lock queues are assumed to have unlimited storage for vessels waiting for lockage. A waiting vessel is released from the queue when the vessel occupying the lock completes its lockage. Vessels are selected from the pool of vessels waiting in the queue to begin lockage using a queue dispatch policy. Each lock queue has a dispatch policy that utilizes a built in prioritization rule, such as FIFO or LIFO, or a customized priority rule. The UMR simulation model implements a customized dispatch policy in which recreation vessels are given first priority in the queue for completing a lockage over both small and large tows. Tows are prioritized after recreation vessels on a first in, first out basis. This queue dispatch policy is adopted to reflect the fact that the largest portion of local vessel arrivals observed at these locks is composed of recreation vessels which are given priority in the real UMR lockage queues and that for the vast majority of time the UMR operates as a FIFO system for all arriving tows at locks.

Decision Nodes

A decision node is automatically created in the Micro Saint Sharp task network whenever a task has more than one possible path leading to subsequent tasks. There are three different decision types that may be associated with each decision node in a task network: a tactical decision, a probabilistic decision, or a multiple decision. The decision type determines the path or paths that an entity (vessel) will follow upon completion of a given task when more than one path is available. In a tactical decision type, the task with the tactical expression that evaluates to the highest value in the routing condition field of the Decision Node executes next. In a probabilistic decision type, only one of the following tasks executes next. The probability that a particular task follows is equal to its probability value in the routing condition field of the Decision Node. In a multiple decision type, all of the following tasks with nonzero routing conditions begin execution simultaneously following execution of the current task. When this happens, the entity exiting the current task splits into multiple entities, one for each following task. These entities all retain the same tag value.

Variables

Micro Saint Sharp permits definition of variables designed to track the performance of the simulation network, the movement of entities through the network, and record other quantities of interest as the model executes. The variables included in the model may also be structured to influence or alter the execution of tasks and the sequence of tasks to be executed.

Snapshots

Micro Saint Sharp permits the model to schedule “snapshots” of variables of interest at pre-determined times or intervals to record the values of designated variables as the model is executing. These snapshots serve to record the dynamics of the system as it changes through simulation time. There are two snapshots defined in the UMR Waterway Simulation model, an end-of-run snapshot and a periodic snapshot which records the status of selected variables every 240 hours of simulation time. The periodic snapshot is designed to permit an examination of the dynamics of the simulated system in ten day intervals. These periodic snapshots facilitate the comparison of the simulated system to the summaries of the operation of the real system compiled from the Corps OMNI data.

Event Queue

The Micro Saint Sharp Event Queue contains a list of events termed “scenario events”. Scenario events provide a method to cause certain events to occur at specified times during the execution of the model. These events can be one-time events, or they can represent events that repeat at defined intervals. Scenario events are used to change variable values and thereby change the state of the model when the event occurs. Scenario events assign values to variables independent of when an entity begins or ends a task or enters or departs a queue. The Event Queue is used in the UMR Simulation Model to alter the simulation month as time in the simulated year progresses. This facilitates altering the task execution time distributions that are sensitive to the time of the year when the task executes. The Event Queue can also be used to schedule other system altering events such as periods of decreased lock performance or periods of complete lock unavailability.

The UMR Simulation Model Task Network

The task network of the UMR Micro Saint Sharp simulation model is composed of two groups of tasks. The first group of tasks is comprised of tasks that execute only once when the model is launched and that require no simulation time to execute. These tasks populate variables with initial values, define the probability distribution parameters required for the execution of other tasks, and create the scaled map for displaying the model animation. Detailed descriptions of these tasks are presented above.

The second group of tasks forms the core of the model and is composed of tasks that simulate the movement of vessels through the UMR system. These tasks do consume simulation time when moving vessels through the system. The variable quantities of simulation time required to complete these tasks are determined each time these tasks are executed by independent random draws from their associated probability distributions. These tasks schedule vessels to enter the system, move vessels through the locks and the pools of the system, and ultimately schedule vessels to exit the system. The remainder of this section focuses on this portion of the task network that is the core of the simulation model. Figure 13 displays a schematic diagram depicting the relationships of these core tasks for system tows and Figure 14 displays a similar schematic diagram for recreation vessels.

After the initial group of set-up tasks executes the simulation of vessel movements begins. Small and large tows arrive at each lock in both upbound and downbound directions initially independently of each other. The time between the independent arrivals changes monthly to reflect the seasonality of tow arrivals at each lock. If the lock is occupied or otherwise unavailable when a tow arrives at a lock the tow is forced to wait in that lock's queue until the lock is unoccupied and the tow is selected for processing by the queue dispatch policy. When the tow completes its lockage the tow is either removed from the system or moves through the connecting pool to the next sequential lock and the original lock is made available to process the next vessel.

In contrast with tow movements, recreation vessels arrive at each lock in both upbound and downbound directions completely independently. The time between the independent arrivals changes monthly to reflect the seasonality of recreation vessel use of each lock. If the lock is occupied or otherwise unavailable when a recreation vessel arrives at a lock the recreation vessel is forced to wait in that lock's queue until the lock is unoccupied and the vessel is selected for processing by the queue dispatch policy. When the recreation vessel completes its lockage the recreation vessel is removed from the system and the lock is made available to process the next vessel. Recreation vessels do not ever travel through the system, but rather only transit a single lock.

8. EVALUATION OF THE UMR SIMULATION MODEL

This section presents an evaluation of the performance of the UMR simulation model in depicting the operation of the UMR system as represented in the Corps OMNI database and then presents an example application of the model to estimate the changes in the operation of the system resulting from implementing an alternative lock queue dispatch policy for system tows.

Table 18 presents selected summary statistics regarding the annual total number of lockages, the annual total of vessel wait time for lock service, the annual total of vessel lockage time, the mean wait for service time for all vessels, and the mean lockage time for all vessels compiled from the Corps OMNI database for UMR Locks 20 through 25 from 2000 through 2003. This table serves as the initial benchmark to measure, calibrate, and evaluate the performance of the Micro Saint Sharp UMR navigation system simulation model.

Table 19 presents some selected summary statistics compiled from the results of 100 simulated years of system operation by the UMR simulation model. Table 20 presents selected detailed statistics compiled from the 100 simulation model runs and compares the detailed results to similar statistics compiled from the 2000-2003 Corps OMNI data. Both at the system and individual lock level, the simulation model tracks observed average annual system performance remarkably well. The mean total number of simulated lockages per year is within 0.6 percent of the observed total number of lockages per year and the mean number of simulated lockages per year at each of the locks is within 1.9 percent of the observed number of lockages per year. The simulation model does equally well at the system level in tracking the observed average annual wait for lockage times and lock utilization times. The mean simulated total wait for lockage time by all vessels is within 2.8 percent of the observed average annual wait for lockage time and the simulated mean total lockage time of all vessels is within 1.3 percent of the observed average annual total lockage time of all vessels.

Table 20 further indicates that the simulation model also tracks the performance of commercial tows through the system extremely well. The annual average number of simulated tow entrances is within 5.5 percent of the corresponding OMNI statistic at all system entrance points and the simulated annual average of complete pool transits by commercial tows is within 0.4 percent of the OMNI statistic for all lock pools. Finally the mean simulated transit time through the pools connecting the locks is within 2.4 percent of the corresponding OMNI statistic for all four of the lock pools.

Figures 15 and 16 explore some important dynamic properties of the simulated UMR system. Each figure presents a graphic in which the simulated year is portioned into 36 consecutive 240 hour long intervals. Each of these intervals represents a simulated ten day period of system activity. The intervals are labeled by their endpoints and the values displayed in each of the figures are compiled separately over each interval. Figure 15 presents the average percentage of total time in each of these intervals that is utilized by vessels completing lockages in the system. Figure 16 presents the total number of vessels in lock queues at the end of each 240 hour interval.

The seasonality evident in the operation of the real UMR system is clearly also present in these summary figures representing the dynamics of the simulations. Like the real system, the simulated system displays very low demands for lockage, very low lock utilization rates, and very little congestion in the first two simulated months. In the third simulated month system demand begins to ramp up and the number of lockages completed, lock utilization rates, and congestion at the locks begins to increase. The level of system use continues to increase as the simulation progresses until the number of lockages, lock utilization rates, and congestion peak during the seventh and eighth simulated month. After the peak there is a decrease in vessel followed by a rebound in system use evidenced in the late fall simulation months. In the final simulation month vessel use dramatically decreases to the very low levels evidenced in the first two simulated months. The simulated UMR system replicates the seasonal dynamics present in the real UMR system with remarkable accuracy.

The very small sample standard deviation of the total amount of time tows spend in the UMR simulation model measured relative to the mean total amount of time tows spend in the model merits discussion. The sample coefficient of variation for the 100 annual simulations of the total amount of time tows spend in the UMR simulation model is less than 0.03. This very low coefficient of variation indicates an extremely stable simulated system. This is quite remarkable considering the very large relative variability present in the completion of some individual system activities, for example pool transits have individual coefficients of variation of up to 8. The annual stability of the performance of the system is even more remarkable in light of the high degree of seasonality evident in the demand for system use. The primary determinant of annual productivity of the simulated system appears to be quite simply the number of tows that operate in the system rather than the inherent variability of the operating characteristics of the locks and pools that define the system.

Finally, one important dimension of the operations of real tows at these five locks bear repeating at this point: when viewed from the perspective of the total time available of tows that operate on this segment of the UMR, the proportion of time spent by tows waiting for lockage or locking through these five locks is remarkably small. Vessels spent an average of 96.8 % of their annual time in the system in river pools away from the locks. They spent 1.5% of their time waiting for lockage and 1.7% of their time undergoing lockage. The 3.2% of vessel time spent at locks (both waiting for lockage and undergoing lockage) is computed over all Upper Mississippi River and Illinois Waterway locks – not just at the five locks modeled here. While there were some considerable delays in locking vessels in the congested sections of the river, the delays at these five locks obviously constituted a small percentage of the annual operational times for the vessels. This fact suggests that there is limited potential of increasing the utilization of towboat resources by using alternative sequencing rules or even increasing lock capacity, unless the volumes of river traffic increase substantially above 2003 levels. Consequently, any policy designed to alter the operating conditions or performance characteristics of these five locks can have only a very small impact on the total productivity of tows operating in the UMR system.

9. AN EVALUATION OF AN EXAMPLE RE-SEQUENCING POLICY

In the UMR simulation model tows arrive at system locks characterized by direction of travel, upbound or downbound, and by size, large or small. A simple and easy to implement queue re-sequencing policy to model is: (1) if there is no queue at the lock a vessel is processed immediately upon its arrival at the lock ; (2) if there is a queue at a lock, recreation vessels move to the head of the queue in the order that they arrived; and (3) if there are no recreation vessels in the queue, tows waiting in the queue are prioritized by their expected lockage time at the lock as if each tow was the next to be locked and then the tow with the smallest expected processing time is dispatched from the queue for the next lockage. This is a locally optimal queue dispatch policy as described above in Section 6 whenever all tows are treated with equal weights and the objective function is formulated to minimize the opportunity cost of the total time spent by all tows when clearing a local lock queue. This simple policy affords a ready identification of the order of magnitude of the beneficial effect that might be generated by implementing a locally optimal re-sequencing policy at existing locks. With these formulation assumptions this traffic management policy reduces to a fastest tow-first queue dispatch policy where the fastest tow(s) are moved to the head of the tow queue for lock processing whenever there are tows in the lock queue.

Since there are only eight possible combinations of lockage types (turnback or exchange), tow sizes (small or large), and directions of travel (upbound or downbound) that characterize potential tow lockages when selecting a tow from a queue in the simulation model, it is a straight forward exercise to assign a priority to each tow and to identify the tow (or tows) with the fastest expected processing time in the queue. Ties for the fastest expected processing time may be decided by any decision rule, but breaking ties by order of tow arrival preserves the perception of equity in the dispatch policy and is adopted here for this dispatch policy. This queue dispatch policy will strongly favor single cut tows when selecting a tow for lockage from a lock queue, given the fact that the expected lockage time of any small tow is significantly less than the fastest lockage time of any large tow at each system lock. Further, this queue dispatch policy is very nearly a locally implemented SPF tow dispatch policy as described in Ting and Schonfeld (1996) for each of the five UMR locks in the simulation model whenever small tow time is valued equal to or greater than large tow time.

Table 21 presents selected summary statistics compiled from the results of 100 annual simulations by the UMR model with the implementation of this locally optimal tow re-sequencing policy at each of the five system locks. The implementation of this queue dispatch policy has a relatively small, but noticeable, impact in the simulated UMR system when compared to the summary statistics for the system with the existing queue tow dispatch policy displayed in Table 19.

Table 22 summarizes the differential impacts evident in the results of the two sets of simulations. The implementation of the local lock queue re-sequencing policy generally reduces the mean, standard deviation, and the range of the presented summary variables. For example, the mean wait time for all vessels at all locks decreases by 4,307.7 hours (approximately 11%) and the mean wait time for commercial vessels at the individual locks decreases as well. The standard deviation and range of these aggregate and individual lock wait times also decrease with the exception of the range of tow wait times at Lock 22 and the standard deviation of tow wait times at Lock 20.

Table 22 also indicates that the total quantity of tow time required in the model to complete the independent and dependent movements of the tows is decreased by an average of 4,368.88 hours (approximately 2.5%) by the implementation of the tow re-sequencing policy. The tow re-sequencing policy has the secondary beneficial effect of reducing both the range and variability evident in completing the set of tow movements.

Table 22 further reveals that the gain in efficiency of the operation of the system is not shared equally by all groups of commercial system users. The mean annual total wait for lockage time of single cut tows decreases by 7,023.4 hours, but at the expense of large multi-cut tows which as a group experience a mean annual increase in waiting times totaling 2,654.5 hours. Clearly, the implementation of a tow re-sequencing policy creates differential winners and losers within the water transportation market relative to the existing first-come, first-served lock policy. The re-sequencing policy creates a net improvement in efficiency in this case because the smaller tows gain more incremental hours of production hours than the extra hours of production that are now required by large tows. This policy would be somewhat disruptive to existing water transportation markets, but the disruption would lead to a small increase in overall market efficiency.

Figure 17 displays a graphic comparing total lock queue sizes aggregated over all five locks at selected intervals during the simulations employing, first, the existing lock service policy and, second, the tow re-sequencing lock service policy. Figure 17 clearly indicates the reduction in the number of vessels waiting in lock queues is distributed throughout the simulated calendar year, but also indicates that the largest absolute reductions in the number of vessels waiting for lockage occur at times when the locks are busiest.

In summary, the implementation of the tow re-sequencing policy alters the operation of the simulated system by decreasing the expected level of lock delays encountered by tows using the system. The decrease in lock delays averages approximately 11 percent which in turn decreases the mean time needed for tows to complete the simulated movements through this part of the UMR system by approximately 2.5 percent. Stated differently, the seasonality of commercial tow demand for use of the system combined with the very small proportion of the total of the time available that tows engage in activities at these locks somewhat mutes the response of the simulated tows to the re-sequencing policy. Consequently, if real tows operating on the UMR respond similarly to their simulation counterparts, there will likely only be a small response observable in the operations of the system to the reduced expected lock service delays created by the implementation of the management policy.

An average decrease of approximately 4,400 hours in the amount of time required for tows to complete their activities in this portion of the inland navigation system would have a very small impact on the total quantity of barge transportation services available in the national inland water transportation market. Sweeney (2003) estimates that completely eliminating all the hours spent by tows waiting for service at these five locks would represent an approximately 0.3 percent increase in the total tow hours already employed nationally in producing inland waterborne transportation. Consequently, existing market prices serve as a very good approximation of the current willingness to pay (economic value) for the incremental units of increased domestic barge transportation now afforded by the 4,400 tow hours made available for productive use by the implementation of the tow re-sequencing policy. Assuming costless re-use of the freed up tow time and using tow sizes evident on the Upper Mississippi River, Sweeney (2003) estimates a market value of approximately $350 per freed up tow hour which yields a total economic value of approximately $1.5 million resulting from the implementation of the tow re-sequencing policy.

10. CONCLUSIONS, RECOMMENDATIONS AND DIRECTIONS FOR FURTHER RESEARCH

Conclusions

An event based, discrete simulation model has been presented and evaluated for use in investigating changes to the operational characteristics of the lower five 600 feet long lock chambers of the UMR navigation system. The UMR simulation model extends earlier inland navigation simulation models of systems of locks by explicitly incorporating seasonally interdependent traffic demands and seasonally differentiated system operating characteristics into the system simulation. Models that do not account for seasonal and interrelated traffic demands may not yield accurate representations of the operation of systems such as the UMR where seasonality is prevalent and important.

Analysis of Corps of Engineers OMNI data compiled from 2000 through 2003 indicates that these five locks do experience some periodic traffic congestion, are subject to seasonal changes in demands for service, and do operate as a system in that they share a large amount of common commercial tow traffic. The simulation model is shown to accurately portray the overall operation of the system and the periodic seasonality evident in the Corps OMNI data.

The UMR simulation model is employed to identify the potential impacts of the implementation of a specific traffic management policy, namely re-sequencing commercial tows in lock queues, to replace the existing FCFS, first come first served, tow processing policy for this segment of the UMR navigation system. The implementation of this traffic management policy has a relatively small, but noticeable impact in the simulated UMR system when compared to the system operating with the existing queue tow dispatch policy. The traffic management policy increases the expected operating efficiency of the simulated system by a small amount by reducing the expected level and variability of lock delays in the simulated system.

Other more extensive changes to the operating characteristics of the UMR navigation system may be examined using the framework of the UMR simulation model presented here. For example, the operational consequences of altering the performance characteristics of system infrastructure such as improving lock reliability can be readily examined in the framework adopted by the model by incorporating the new performance characteristics of the infrastructure into the simulation model and then evaluating the resulting changes in system performance.

Similarly, the system performance effects of the addition of new infrastructure to the UMR navigation system such as replacing existing 600 feet long locks with larger 1200 feet long locks may be evaluated by employing the performance characteristics of the new infrastructure in the model and then identifying the resulting changes in system performance. Using a simulation model that explicitly recognizes the seasonality of demand and the interdependence of lock operations to represent the operation of the UMR navigation system is a distinct step forward over the modeling techniques currently embedded in Corps navigation system economic models.

The Corps currently uses two very different navigation system economic models, named the Tow Cost Model and the Essence Model, to evaluate new infrastructure. The Tow Cost Model, which is itself a suite of models, typically employs an embedded model to represent the operations of each lock in the system that simulates each individual lock's operating conditions in isolation while assuming steady state, independent traffic arrivals at that lock. Clearly, the Upper Mississippi River locks do not exhibit steady state, independent traffic arrivals and, consequently, the Tow Cost Model will not capture the interdependency effects of processing common and seasonal traffic.

The Essence Model utilizes a steady state approximation derived from queuing theory to describe the operation of each lock in the UMR navigation system. Here again, as the Upper Mississippi River locks do not exhibit steady state, independent traffic arrivals, the Essence Model will not capture the interdependency effects of processing common and seasonal traffic. Detailed descriptions of the most recent applications of both these models to evaluating infrastructure improvements in the UMR navigation system is presented in U.S. Army Corps of Engineers (2004): see especially pages Econ 52-124.

The framework of the UMR simulation model presented here can be used to evaluate a range of alternatives that are not directly addressable in extant Corps of Engineers simulation and inland navigation system economic models. For example, the UMR simulation model could be used to evaluate the effects on system operations of a variable, time-sensitive fee designed to alter the seasonality of the tow demand for system use by providing an economic incentive to increase tow use during periods of typically low demand and decrease system use during periods of typically low demand. This type of analysis cannot be completed in existing Corps navigation models

The UMR simulation model presented here can be improved in at least two directions by further research. First, more explicit detail can be included in the model to represent the activities of tows at waterway locations other than these five UMR locks. Of course, this requires the availability of more detailed information regarding the actual operations of tows and vessels at locations other than these five UMR locks. The Corps OMNI lock database does not contain explicit information on tow activities between appearances at system locks.

The UMR simulation model can be extended using the OMNI data to explicitly incorporate larger segments of the inland navigation system and extending the geographic scope of the model scope will improve the representation of tow activities. However, detailed data regarding tow and barge operations at locations away from system locks is a critical need for improving the UMR system simulation model representation of the behavior of tows. By further partitioning the activities of tows into more, but related, activities of shorter duration the large amounts of time that tows operate away from system locks can be better understood and incorporated into the model.

Secondly, explicitly incorporating the relationship between the dynamics of the economics of tow operations and the seasonal demand exhibited by tow operators for UMR navigation system use into the simulation would add greatly to the utility of the simulation model. Abstracting from the macro-level, climate related operating restrictions evidenced in the system, tow operators can and do make economic choices electing to operate or not operate in the UMS system during different times of the year. In doing so, they superimpose their own economic seasonality onto the macro-level, climate related seasonality and create intra-seasonal dynamics in the operations of the system. Closing the feedback loop between the dynamic operating characteristics of the system and the dynamic seasonal demand exhibited by tow operators for use of the system will provide a complete analytical tool for use in evaluating the economic and operational consequences of any potential change to the operating characteristics of this segment of the inland navigation system.

Recommendation

At current traffic levels on the UMR, the economic benefits of new traffic management policies will be relatively small. There does not appear to be enough congestion in the system to support the disruption that new traffic management policies would create in the operation of existing water transportation markets. Figure 18 below summarizes the last five years of congestion data for these five UMR locks.

Further, the economic benefits of new traffic management policies would accrue differentially across system users, and some users would be disadvantaged by new traffic management policies. For instance, if tows with the fastest expected lockage times always locked first, then companies operating multi-cut tows could expect a negative economic impact on their operations.

At current traffic levels, new traffic management policies such as appointment/scheduling/re-sequencing systems, are not recommended because of the small economic benefits they would create relative to the potentially large disruptions they would create in existing markets. However, if traffic levels dramatically increased, implementing new traffic management policies could yield significant economic benefits potentially outweighing the cost of disruptions in existing markets. Table 23 presents a summary of our evaluation of alternative traffic management policies.

11. ANOTATED LITERATURE REVIEW

1. Abeyrante RIR, **Management of Airport Congestion through Slot Allocation,** *Journal of Air Transport Management*, 2000, 6(1)29-41.
   The lack of airport slots (the time allocated for aircraft to land or take off), particularly at airports which experience congestion, have reached unmanageable proportions in recent years. The International Civil Organization (ICAO) records that, by the end of 1997, there were 132 slot controlled international airports, (118 year round and 14 during peak seasons). Between 1989 and 1998, the reported number of commercial aircraft in service increased by about 60% from 11,253 to 18, 139 aircraft. In 1998, 1463 jet aircraft were order, compared with 1309 in 1997, and 929 were delivered compared with 674 in 1997. In 1998, the total scheduled traffic carried by airlines of the 185 Contracting States of ICAO amounted to a total of about 1462 million passengers and about 26 million tons of freight. These figures are reflective of the rapidly increasing frequency of aircraft movements at airports, calling for drastic management of airport capacity. To cope with

the demand, airlines are forming strategic alliances with themselves by utilizing such commercial tools as franchising, leasing and interchange of aircraft. The management of airport capacity through slot allocation is a critical consideration for the world aviation community. This article analyses the problem and discusses various issues related thereto.

2. Babcock MW and Xiaohua L, **Forecasting Inland Waterway Grain Traffic,** *Transportation Research part E*, 2002, 38, 65-74
The purpose of this paper is to address a neglected area of water transportation forecasting — short-term forecasting of inland waterway traffic. A time series model is used to forecast Mississippi River Lock 27 grain tonnage for the 1989:1-1999:4 period. The model was selected on the basis of several measures of goodness of fit and out-of-sample forecasting performance. The out-of-sample forecasting performance of the model was good, as the percentage difference between the year 2000 actual and forecasted tonnage was less than 5.5% for three of the four quarters and only about 2% for the year.

3. Dai MDM and Schonfeld PM, **Metamodels for Estimating Waterways Delays through a Series of Waterway Queues,** *Transportation Research Part B*, 1998, 32(1)1-19.
A numerical method has been developed for estimating delays on congested waterways. Analytic and numerical results are presented for series of G/G/1 queues, i.e., with generally distributed arrivals and service times and single chambers at each lock. One or two-way traffic operations are modeled. A metamodelling approach which develops simple formulas to approximate the results of simulation models is presented. The structure of the metamodels is developed from queueing theory while their coefficients are statistically estimated from simulation results.
The numerical method consists of three modules: (1) delays, (2) arrivals, and (3) departures. The first estimates the average waiting time for each lock when the arrival and service time distributions are known. The second identifies the relations between the arrival distributions at one lock and the departure distributions from the upstream and downstream locks. The third estimates the mean and variance of the departure times when the interarrival and service time distributions are known.
The method can be applied to systems with two-way traffic through common bi-directional servers as well as one-way traffic systems. Algorithms for both cases are presented. This numerical method is shown to produce results that are close to the simulation results.
The metamodels developed for estimating delays and variances of interdeparture times may be applied to waterways and other series of G/G/1 queues. These metamodels for G/G/1 queues may provide key components of algorithms for analyzing networks of queues.

4. Committee to Review the Upper Mississippi River-Illinois Waterway Navigation System Feasibility Study, National Research Council***, Inland Navigation System Planning: The Upper Mississippi River—Illinois Waterway***, Washington, D.C.: National Academy Press, 2001, 130 pages.

Starting in 1988, the U.S. Army Corps of Engineers investigated the potential costs and benefits of extending locks on the Upper Mississippi River-Illinois Waterway to 1,100 feet in order to relieve traffic congestion. In an environment charged with controversy, the US Army hired the National Academy of Sciences to review its reports on the feasibility of improvements on the waterway. In this present paper, a committee reviews the Corps' economic analysis and concludes, in part, that measures short of constructing longer locks have not been fully investigated. The committee recommends that the Corps take a serious look at the many "relatively inexpensive, nonstructural options" applicable to the UMR-IWW, and assess the potential costs and benefits of such options.

5. Committee to Review the Upper Mississippi River-Illinois Waterway Navigation System Feasibility Study, National Research Council, ***Review of the U.S. Army Corps of Engineers Restructured Upper Mississippi River-Illinois Waterway Feasibility Study***, Washington, D.C.: National Academy Press, 2004, 66 pages.
This report, the first of three, encapsulates the committee's evaluation of the U.S. Army Corps of Engineers Restructured Upper Mississippi River-Illinois Waterway Feasibility Study. The committee reviews the model the Corps developed to aid in forecasting future levels of grain movement on the waterway and related costs. The committee also reviews the planning process and evaluated recommended measures for alleviating waterway traffic congestion. The primary recommendation related to traffic congestion is that non-structural measures should be evaluated, developed, and put into place before the Corps estimated the economic benefits of extending the locks. And in the event the lock chambers were lengthened, small-scale measures of traffic control would become essential during the construction process.

6. Committee to Review the Upper Mississippi River-Illinois Waterway Navigation System Feasibility Study, National Research Council, ***Review of the U.S. Army Corps of Engineers Restructured Upper Mississippi River-Illinois Waterway Feasibility Study: Second Report***, Washington, D.C.: National Academy Press, 2004, 80 pages.
In this second report, the committee reviews the "key issues, data, assumptions, and areas of controversy with the feasibility study." After addressing integrated river system planning and ecosystem restoration, the committee laments that the Corps has still not adequately evaluated "several promising traffic management strategies" including priority rules at locks, the scheduling of tows, and congestion fees. Without a comprehensive analysis of non-structural measures, critics of the Corps' plan to extend the locks can undermine the conclusions of the feasibility study.

7. Dai MDM, Schonfeld PM and Antle G, **Effects of Lock Congestion and Reliability on Optimal Waterway Travel Times,** *Transportation Research Record*, Paper No. 930596, 1993
The congestion and variability of service times at locks significantly affect the cost and reliability of waterway transportation. This paper considers the effects of lock congestion levels and reliability on the operating cost of tows, assuming that tow operators have the opportunity to optimize speed in response to the delays they have already experienced and the delays they expect to encounter. The analysis method in this paper is useful for

evaluating long-term consequences of lock improvements, as well as for optimizing speed from the viewpoint of operators.

This analysis method optimizes tow operations in two stages. The first stage finds the optimal speeds for each individual tow, re-optimizing the speed after every lock. The second stage determines the optimal allowed delivery times and associated optimal speeds based on the lock transit time distributions. The optimization is guided by a total cost objective function which includes penalties for late deliveries.

A four-lock section on the Ohio River is used for a case study in which various congestion levels and speed limits are tested. The resulting total cost functions are U-shaped with respect to the allowed delivery times. At given congestion levels, the optimal allowed delivery times and costs decrease as speed limits increase. The results also show how the optimal allowed delivery times and costs increase as congestion becomes severe.

8. Doxsey L, **Incentive Tolls for Congestion Management,** *Transportation Research Record 1576*, 1997, 77-84.
A congestion pricing planning model was developed for the Port Authority of New York and New Jersey. The model is designed to evaluate possible incentive tolls for their effects on congestion delays at the six bridges and tunnels the authority operates between New Jersey and New York. The study used a stated preference survey administered to bridge and tunnel users, econometric choice models, and plaza volume-delay relationships as a basis for simulating the effects of changes in toll structure. The survey identified characteristics of trips, and the trip makers. A stated preference choice exercise was included to reveal trade-offs among toll, plaza delay, facility choice, and time period when the crossing would be made. Responses to the exercise were combined with other survey data, and econometric models of choice were estimated. The models associate the probability of travel choices with the conditions faced at the alternatives. The policy evaluation planning model combined choice model results, survey responses from individual respondents, and data on facility conditions, volumes, and capacities. As input it accepts a user-specified menu of tolls and discounts, potentially varying both by hour and by facility. As output it predicts automobile volumes, average delays, total delays, and toll revenue by hour and facility. The model is constructed to achieve equilibrium among tolls, delays, and volumes. Application of the model indicates considerable potential for reducing plaza delays.

9. Fellin L and Fuller S, **Effect of Proposed Waterway User Tax on U.S. Grain Flow Patterns and Producers**, *Transportation Research Forum*, 2000(?), pp. 11-25.
The administration recently proposed the barge fuel tax be increased from $0.20/gallon to $1.20/gallon. Because the increased tax could have important implications on U.S. agriculture, quadratic programming models of the soybean/corn sectors are used to evaluate the impact on flow patterns, producer prices/revenues and export levels. Results show the tax increase would divert 10.6 million metric tons from the inland waterways; 70 percent of the diversions are from the upper Mississippi/Illinois systems. The lower Mississippi River port area is projected to lose 9 million tons, while other Gulf, Great Lakes, north Atlantic and Pacific northwest ports increase by 3.35, 1.49, 1.74 and 1.40 million tons, respectively. Soybean/corn producers in Minnesota, Illinois and Iowa incur

annual revenue losses of $151 million and about 75 percent of the expected decline in all producer revenues. Exports of U.S. soybeans are nearly unchanged with the proposed tax increase while corn exports decline 2.16 percent. If the proposed tax were implemented, barge-transported soybeans/corn would increase federal revenues by $89 million per year. The proposed tax increase has unfavorable implications for U.S. producers, grain handling/exporting industries and barge transportation firms, however, the impact is not judged to be calamitous.

10. Ferguson E, **Three Faces of Eve: How Engineers, Economists, and Planners Variously View Congestion Control, Demand Management, and Mobility Enhancement Strategies,** *Journal of Transportation and Statistics*, April 2001, 51-73.
The political acceptability (A) of public policy measures correlates positively with program effectiveness (E) and negatively with program cost (C) and other obstacles to implementation (I) under normal circumstances. Ferguson (1991) observed that the political acceptability of many demand management strategies seemed to correlate negatively with implied program effectiveness. Engineers, economists, and planners each have their own unique professional standards. Increased effectiveness is the primary goal of engineering. Improved efficiency is the generally accepted standard in economics. Process issues are of vital concern in planning. A review of the literature indicates few studies in terms of all four variables of interest (A, E, C, and I) simultaneously. Three relevant studies are identified: one each by an engineer, an economist, and a planner. Raw data, regression results, bivariate correlation, and model output reveal that two of the three studies support the Ferguson hypothesis. The other supports a more traditional public policy model. E is the most influential variable in the engineer's data. C is the most influential variable in the economists' data, while I is the most influential variable in the planner's data. These revealing results suggest the subtle manner in which professional training and experience may alter perceptions of transportation and policies and programs in professional practice.

11. Forsyth P, **Privatisation and regulation of Australian and New Zealand Airports,** *Journal of Air Transport Management*, 2002, 8, 19-28.
A brief background on the Australian and New Zealand airports is provided at the beginning of the paper. This is followed by a discussion of the approach to price regulation which Australian regulators are implementing in other industries; this gives an indication of how the—as yet new—regulation of airports will develop. Some specific regulatory issues are next considered; firstly, the merits of the dual till approach are considered, and then how the regulator is handling investments in new capacity. The New Zealand policy of no formal price regulation is examined; this is a less "light handed" form of regulation than it seems. Finally, the main problems of privatising and regulating Sydney are discussed.

12. Fuller S and Grant W**, Effect of Lock Delay on Grain Marketing Costs: An Examination of the Upper Mississippi and Illinois Waterways**, *Logistics and Transportation Review*, 1993, 29(1)81-95
This paper evaluates the effect of lock delay on the efficiency of marketing the North Central U.S.'s corn and soybean production via the upper Mississippi and Illinois

waterways. The analysis is accomplished with a multi-commodity least-cost network flow model. Lock delay was found to have an important effect on the cost of barging the region's surplus grain production. If the lock and dam system on the upper Mississippi and Illinois waterways is not continually upgraded, grain is redirected to less efficient modes, thus increasing the cost of marketing the region's grain surplus. These increased costs need to be weighed against the costs of upgrading lock capacity.

13. Gervais JP, Misawa T, McVey MJ and Baumel, P, **Evaluating the Logistic and Economic Impacts of Extending 600-Foot Locks on the Upper Mississippi River: A Linear Programming Approach,** *Journal of the Transportation Research Forum*, Fall 2001, 40(4)83-103.
This article uses a highly disaggregated linear programming model to evaluate the short-run benefits of extending five 600-foot locks on the Upper Mississippi River (UMR) to 1,200 feet. We model 1994-1995 corn flows in three counties of eastern, central, and western Iowa. Two scenarios are simulated based on either completed or partial pass-through of the cost savings associated with large-scale improvements on the UMR to grain elevators and producers. The estimate of the total annual costs of lock expansions is 4 cents a bushel. Total annual benefits accruing to grain producers and elevators are in the range of 0.21 to 0.43 cents a bushel. No environmental costs are included in the analysis.

14. Golaszewski R, **Reforming Air Traffic Control: An Assessment from the American Perspective**, *Journal of Air Transport Management*, 2002, 8(1)3-11.
This paper examines institutional and economic reform of the ways in which air traffic control (ATC) services are provided in the U.S. It also contrasts the European and U.S. ATC systems in terms of size, scope, cost and organizational form. The paper suggests that many of the congestion and delay problems experienced in the U.S. result from the inefficient provision and use of air traffic capacity in the airport area, and these conditions are likely to continue or worsen if economic principles are not used to organize and provide ATC services. The paper notes that, while Europe has advanced more rapidly in the organizational and economic reform of providing ATC services, other problems remain. Because most large European airports have slot controls to limit demand in the airport area, its ATC congestion is more pronounced in the enroute environment.

15. Griffiths JD, **Queueing at the Suez Canal**, *Journal of the Operational Research Society*, 1995, 46(11)1299-1309.
This paper describes an investigation into the delays experienced by ships waiting to pass through the Suez Canal. The main objective of the Suez Canal Authority (SCA) is to provide an attractive service to ship-operators, and in doing so maximize the income received from canal tolls. Thus, SCA wishes to maximize the throughput of vessels, but also requires queueing delays to be held at an acceptable level. This paper quantifies both measures (throughput and delays), and illustrates how they are in conflict to some extent. The study is somewhat unusual in that it affords the opportunity to employ more than one OR technique (linear programming and queueing theory/simulation) in the

quantification process. Some of the work reported was undertaken in a consultative capacity, and the remainder as part of an ongoing research programme.

16. Hauser RJ, Beaulieu J and Baumel P, **Impact of Inland Waterway User Fees on Grain Transportation and Implied Barge Rate Elasticities**, *Logistics and Transportation Review*, 1985, 21(1)
This study analyzes the effects of proposed waterway user charges on grain shipments. Two types of full-recovery user fees are included, a fuel tax and a segment-specific ton-mile tax. An interregional linear programming model is used in which cost coefficients of the base model are changed to reflect user-fee effects on barge rates. The model includes over 200 grain originating points to 67 domestic destinations and 15 export areas and from the port areas to 6 overseas regions. Rail, barge and truck loadings are estimated (including combination movements) with and without waterway user-fees. Implied demand elasticities for barge travel are estimated. Significant shifts in shipment patterns take place depending on the location.

17. Kerr GN, **Managing Congestion: Economics of Price and Lottery Rationing**, *Journal of Environmental Management,* 1995, 45(4)347-364.
It is not uncommon for the carrying capacity for congestible facilities to be estimated before the allocation method is known. This paper shows how efficient capacity differs between two competing resource allocation mechanisms, one which is efficient (price) and one which is fair (lottery). The welfare theoretic implications of adopting lottery allocation rather than price allocation are illustrated from the perspectives of economic efficiency and the benefits obtained by resource users and suppliers. It is found that risk-neutral resource users will always prefer lottery allocation to price allocation. While price allocation is efficient, it is never in risk-neutral resource users» interests to have price allocation imposed. Conclusions are tested using a linear constant crowding demand function, in which case it is found that the efficient capacity for lottery rationing exceeds the efficient capacity where price is to be used to allocate a congestible resource. Objectives may be better met by joint use of allocation mechanisms, the implications of which are investigated using the linear demand model.

18. Khisty CJ, **Waterway traffic analysis of the Chicago River and lock,** *Maritime Policy and Management*, 1996, 23(3)261-270.
The vessel-carrying capacity of the Chicago River, Illinois, is restricted by a lock, separating the river from Lake Michigan. Currently, vessels passing through the lock experience long delays during summer months. An investigation and analysis of this system determined that although the system is now generally operating below capacity, the peak periods during summer weekends do approach capacity, and the situation is likely to deteriorate in the future. In addition, the river and lock have safety and traffic conflict problems that need attention. Recommendations to mitigate these problems are described.

19. Lari AZ and Buckeye KR, **Evaluation of Congestion Pricing Alternatives in the Twin Cities,** *Transportation Research Record 1576*, 1997, 85-92.

A congestion pricing study for the Twin Cities metropolitan area was conducted in 1995-1996 by the Minnesota Department of Transportation and the Metropolitan Council of Minneapolis and St. Paul (Twin Cities), with sponsorship by FHWA. The effort was designated a congestion pricing preproject study by FHWA. After an initial screening, 11 pricing options for the Twin Cities were considered. Five regionwide pricing options were ultimately evaluated in detail. Because of the need to understand the relationships and effects of various pricing options, it was necessary to develop and apply adequate evaluation criteria to those options. An evaluation matrix was created to help planners and decision makers make recommendations concerning the implementation of congestion pricing options and pricing features within those options that best meet identified objectives.

20. Logi F and Ritchie S, **Development and Evaluation of a Knowledge-based System for Traffic Congestion Management and Control**, *Transportation Research Part C,* 2001, 9(6)433-459.
This paper describes a real-time knowledge-based system (KBS) for decision support to Traffic Operation Center personnel in the selection of integrated traffic control plans after the occurrence of non-recurring congestion, on freeway and arterial networks. The uniqueness of the system, called TCM, lies in its ability to cooperate with the operator, by handling different sources of input data and inferred knowledge, and providing an explanation of its reasoning process. A data fusion algorithm for the analysis of congestion allows to represent and interpret different types of data, with various levels of reliability and uncertainty, to provide a clear assessment of traffic conditions. An efficient algorithm for the selection of control plans determines alternative traffic control responses. These are proposed to an operator, along with an explanation of the reasoning process that led to their development and an estimation of their expected effect on traffic. The validation of the system, which is one of only few examples of validation of a KBS in transportation, demonstrates the validity of the approach. The evaluation results, in a simulated environment demonstrate the ability of TCM to reduce congestion, through the formulation of traffic diversion and control schemes.

21. Martinelli D and Schonfeld P, **Approximating Delays at Interdependent Locks**, *Journal of Waterway, Port, Coastal and Ocean Eng.,* Nov. 1995, 121(6)300-307.
As with much of the nation's infrastructure, the inland waterway system is in critical need of expansion and repair. Many of the inland waterway lock and dam facilities have become major constraints to navigation due to increased traffic and facility deterioration, leading to costly delays. Because funds for lock and dam improvements are severely limited, comprehensive analysis methods are necessary to ensure efficient allocation of resources among the many proposed improvement projects. Unfortunately, lock and dams are often treated as independent facilities with regards to operations, when in fact, there are likely to be significant interdependencies between locks when considering lock improvements. In this paper, a method is developed whereby the delays of a set of interdependent locks may be calculated. By incorporating interdependencies into benefit calculations of lock improvement projects, a more comprehensive assessment of improvement priorities can be established.

22. Niemeier HM, **Regulation of Airports: the Case of Hamburg Airport - A View from the Perspective of Regional Policy**, *Journal of Air Transport Management*, 2002, 8, 37-48.
There are currently divergent trends in the regulation of airports in Germany. While traditionally airports have been regulated by cost-based regulation, a price cap regulation for Hamburg airport has been implemented in 2000. Given the objectives of economic welfare and efficiency the paper argues that the old system is inefficient and results in a misallocation of resources. Regulation should be reformed by capping prices. An independent regulator should be established. Regulatory reform should be combined with reforms to intensify competition such as slot auctioning, further privatization with cross-ownership controls and open skies.

23. Perakis AN and Li J, **Recent technical and management improvements in US inland waterway transportation,** *Maritime Policy and Management*, 1999, 26(3)265-278.
Over the last several years, the US inland waterway transportation industry has significantly reduced its fuel consumption and improved its efficiency, with the side effect of less fuel tax collected per ton of cargo carried, despite the increase in cargo traffic. Fuel tax revenues are used for rehabilitation and construction projects on the inland waterway system, hence the US Army Corps of Engineers, providing us with relevant data over the interval in question, asked us to investigate this surprising reduction, and determine the main technical and fleet management improvements that caused it. Our research involved both visits with most major US inland waterways fleets, interviews with their engineers and managers, as well as statistical analysis of the above data. Technical improvements (such as engine plant efficiency increases), lighter, stronger building materials (such as light steel), and improved designs for better hydrodynamics, were not as important compared to management improvements (such as the use of computer-aided monitoring systems and advanced telecommunications, optimized tow configuration and speed, and increased triangular trips as opposed to simple round trips with returns empty). In addition, the demand for less expensive, imported steel for the US has resulted in an increased percentage of fully loaded return trips from New Orleans to the US Midwest, and hence also in increased fleet utilization.

24. Pfliegl R, **Innovative Application for Dynamic Navigational Support and Transport Management on Inland Waterways: Experience From a Research Project on the Danube River**, *Transportation Research Record 1763*, 2001, pp. 85-89.
The widespread use of inland waterways as a common transport mode is a main objective of European traffic policy, specifically in view of the expected dramatic increase in transport along the Trans-European Network, a main economic lifeline in Europe. Transport operators' limited acceptance of the inland waterway reflects unreliable calculations of estimated time of arrival, shifting water levels or other environmental events, unexpected delays in passing locks and borders, and insufficient transport monitoring capability. Implementing a telematics-based river information service will help to alleviate waterway transportation problems on the Danube River early in the day and improve the safety and productivity of transportation by integrating river-based transport information services with the intermodal transport chain. The proposed system meets the requirements of the Supreme Shipping Authority of Austria to generate a

tactical and strategic traffic image on the Danube in Austria to fulfill its legal commitments to ensure safe and secure transport operations on the Danube. Communications interfaces will link the Austrian network connecting other users downstream as well (e.g., Hungary, Slovakia). Traffic information services will be provided to ship operators, ship owners, and transport operators carrying people and goods. The system consists of a transponder-based network using radio links embedded in a wire-based communications network on shore controlled by central management facilities providing tactical traffic information on a geographic-information-system-based application. A separate system and network management unit will ensure safe operations with a low failure rate, depending on the level of redundancy implemented. The overall system concept uses the results and provisional standards defined in the European Union project Inland Navigation Demonstrator for River Information Services.

25. Quiroga CA, **Performance measures and data requirements for congestion management systems,** *Transportation Research Part C,* 2000, 8, 287-306.
Many metropolitan areas have started programs to monitor the performance of their transportation network and to develop systems to measure and manage congestion. This paper presents a review of issues, procedures, and examples of application of geographic information system (GIS) technology to the development of congestion management systems (CMSs). The paper examines transportation network performance measures and discusses the benefit of using travel time as a robust, easy to understand performance measure. The paper addresses data needs and examines the use of global positioning system (GPS) technology for the collection of travel time and speed data. The paper also describes GIS platforms and sample user interfaces to process the data collected in the field, data attribute requirements and database schemas, and examples of application of GIS technology for the production of maps and tabular reports.

26. Ronen D, **The Effect of Oil Price on the Optimal Speed of Ships**, *Journal of the Operational Research Society*, 1982, 33, 1035-1040.
The tradeoff between fuel savings through slow steaming on the one hand, and the loss of revenue due to the resulting voyage extension on the other hand is analyzed, and three models for the explicit determination of the optimal speed of a ship are presented. Each model is applicable under different schedule of revenues, and the optimal speed is a solution to a cubic equation over the feasible range of cruising speeds.

27. Ronen D and Nauss R, ***Upper Mississippi River and Illinois Waterways: How to Reduce Waiting Times of Vessels While Using the Current Infrastructure***, Center for Transportation Studies, University of Missouri-St. Louis, February 2003.
The variability of lockage times, not the length of time it takes tows to get through locks, is one of the primary reasons for delays in the Upper Mississippi River and Illinois Waterways system. Reducing the variability of arrivals at locks as well as the variability in service times could speed up the entire system and result in reduced numbers of tows waiting in queues at locks. This paper recommends further investigation of non-structural measures to alleviate waterway traffic congestion.

28. Southworth F, ***Analysis of Lock Transit Curves Options For Use in Modeling Upper Mississippi and Illinois River Locks***, Oak Ridge National Laboratory, 2002.
The purpose of the analysis described in this report was to assess the accuracy and robustness of two simplified lock transit time estimation methods for use in the economic analysis of Upper Mississippi and Illinois River lock improvements. As such, the study is part of a larger effort to estimate the dollar savings to shippers from the provision of a navigable waterway along the Upper Mississippi and Illinois Rivers. This larger study has been charged with analyzing river traffic by using the US Army Corps of Engineers (USACE) Tow Cost – Equilibrium (TCM/EQ) modeling system to simulate annual flows up and down these two rivers, including the passage of tows through locks. Accurate and robust lock transit time estimates are crucial to such a study, because traffic congestion at locks can cause significant and costly delays to tows.

29. Tellis R and Khisty CJ, **Social Cost Component of an Efficient Toll*,*** *Transportation Research Record 1576*, 1997, 140-146.
Efficient tolls are tolls that ensure that the price paid by the roadway user is equal to the increment of social and private costs resulting from the highway use. Setting these tolls accomplishes an important objective: to correct the current practice that allows driving to be subsidized by government and non-users. Without restrictions on vehicle ownership and unlimited access to the nation's cost-free roadways, drivers do not pay for the social costs they generate. If motorists were required to pay their fair share of these social costs, travel decisions would probably be altered. Unwarranted trips, especially during peak hours, would be reduced because roadway space would be priced to accurately reflect the actual cost of driving. Beyond private costs, society is burdened with paying for infrastructure construction and maintenance, highway services, wasted fuel, pollution, accidents, and congestion costs from travel delays. The cost to society of automobile travel is assessed so that a charge can be made for the social cost component in computing what an efficient toll should be. It is found that the social cost fee during non-peak travel comes to 0.67¢/vehicle-km (1.08¢/vehicle-mi). Travel during peak periods is far more expensive with the addition of congestion costs. The value of time drives up these costs, and the charges amount to 5.68¢/vehicle-km (9.14¢/vehicle-mi) for peak-period travel.

30. Ting CJ and Schonfeld P, **Efficiency Versus Fairness in Priority Control: Waterway Lock Case***, Journal of Waterway, Port, Coastal & Ocean Eng*., March/April 2001, 127(2) 82-88.
Delay at a congested service facility, such as a waterway lock, depends on the control policy used. The shortest processing time first (SPF) policy, which is a promising priority control policy, can significantly reduce the average delay/barge compared to the normally used first come first served (FCFS) policy. SPF tends to favor large groups of barges, i.e., tows, at the expense of smaller ones. This paper modifies the SFP policy to consider fairness among tows in queues. One modified algorithm, called fairer SPF (FSPF), limits the number of tows allowed to pass any particular tow. The case study indicates that FSPF can yield most of the benefits of SPF without greatly sacrificing fairness.

31. U.S. Army Corps of Engineers, ***Upper Mississippi River – Illinois Waterway System Navigation Feasibility Study: Final Integrated Feasibility Report and Programmatic Environmental Impact Statement***, September 2004, 705 pages.
Found in two separate volumes in the past, this document combines the Upper Mississippi River-Illinois Waterway System Navigation Feasibility Study and the Environmental Impact Statement. This document outlines improvements for the waterway for the future, specifically addressing navigation efficiency alternatives ranging from small-scale, non-structural measures to the construction of new locks. The study recommends new lock construction as necessary to support anticipated levels of future waterway traffic. Some small-scale measures, such as mooring cells, switchboats, and an appointment scheduling system should be explored for use until large-scale measures are in place.

32. U.S. Army Corps of Engineers**, *Upper Mississippi River - Illinois Waterway System Navigation Study: Summary of Small-Scale Measures Screening (Interim Report),*** April 1999*,* Rock Island, St. Louis, and St. Paul Districts.
The Upper Mississippi River—Illinois Waterway System Navigation Study (Navigation Study) is a feasibility study addressing navigation improvement planning for the Upper Mississippi River and Illinois Waterway (UMR-IWW) systems for the years 2000-2050. This study assesses the need for navigation improvements at 29 locks on the Upper Mississippi River and 8 locks on the Illinois Waterway and the impacts of providing these improvements. More specifically, the principal problem being addressed is the potential for significant traffic delays on the system within the 50-year planning horizon, resulting in economic losses to the Nation. The study will determine whether navigation improvements are justified, and, if so, the appropriate navigation improvements, sites, and sequencing for the 50-year planning horizon. The feasibility study also includes the preparation of a system Environmental Impact Statement (EIS).
The goal of this interim report is to summarize the entire process of identifying and screening the small-scale measures, leading up to the selection of a final set for use along with large-scale measures in developing alternative plans. However, the final product of the System Navigation Study is the feasibility report, which will constitute the decision document for processing to Congress. Small-scale measures are navigation improvements of smaller scope than constructing a new lock or extending the existing lock chamber. The process first identified a universe of 92 potential small-scale measures that might improve system efficiency. The items were then qualitatively screened to select those measures most suitable for further detailed analysis. The first two steps are presented in greater detail in the *General Assessment of Small Scale Measures* report dated June 1995. Following the selection a smaller group of the most promising measures, the *Detailed Assessment of Small Scale Measures (*December 1998) was conducted to quantify the costs, performance, and impacts of the measures. The additional information provided the necessary details for a final secondary screening summarized in this report. The five measures remaining after this screening (guidewall extensions with powered kevels, switchboats with guidewall extensions, congestion tolls/lockage time charges, mooring facilities, and approach channel improvements) will be incorporated into the systemic analysis for use in developing alternative plans and the final evaluation and comparison of costs, benefits, and impacts.

33. U.S. Congressional Budget Office, ***Paying for Highways, Airways, and Waterways: How Can Users Be Charged?,*** May 1992, Congress of the United States, Washington, D.C.
The methods of financing highways, airways, and waterways influence both the amount of revenue that can be raised and the efficient allocation of resources. The concept of revenue adequacy—whether revenues cover costs—is important to the cash-strapped federal government, but it also has implication for efficient allocation of resources in the long run. If the costs of an investment project cannot be recovered from those who use it, the project's feasibility comes into question. But an investment that benefits society is worth making, even though it may not be possible to charge users for it. This often characterizes goods and services provided by the federal government, and it underlies the rationale for government rather than the private activity in certain sectors. Revenue adequacy can provide information about the demand by users for public investments, but it alone cannot be the criterion upon which investment decisions are made.

34. U.S. Department of Transportation, ***Upper Mississippi River and Illinois Waterways: Non-Structural Measures Cost-Benefit Study (Draft)***, September 2003, Prepared for the U.S. Army Corps of Engineers, Mississippi Valley Division, by the John A. Volpe National Transportation Systems Center, 95 pages.
In this report, the Volpe Center examined the issue of non-structural measures to improve the efficiency of the Upper Mississippi River and Illinois Waterways. The report specifically addressed excess lockage time fees and tradable permits. The Center concluded that excess lockage time fees would prompt barge operators to install better line handling equipment on barges and improve personnel training or simply pay the fee, both options generating a modest net benefit. The Center also concluded that tradable permits, as part of a scheduling system, were "infeasible" on the Upper Mississippi River and Illinois Waterway navigation system given the nature of service on the waterway.

35. U.S. General Accounting Office, ***Factors to be Considered in Setting Future Policy for Use of Inland Waterways***, 1975, Report to the Congress by the Comptroller General of the US, Washington, D.C., 58 pages.
This report presents factors which the Congress will need to consider in establishing a national policy for funding inland waterways improvements and operations and in considering proposals for imposition of waterways user charges.

36. Wei CH, Dai MDM and Schonfeld PM, **Computational Characteristics of a Numerical Model for Series of Waterway Queues**, *Transportation Research Record 1333*, 1992, pp. 45-54
A numerical method has been developed for estimating delays on congested waterways represented by series of G/G/1 queues (i.e., with generally distributed arrival and service times and one chamber per lock). It is based on a metamodeling approach that develops simple formulas to approximate the results of simulation models. The functional form of the metamodels is derived from queueing theory, whereas their coefficients are statistically estimated from simulation results. The algorithm scans along a waterway and sequentially estimates at each lock the arrival distributions, departure distributions, and

delays. It can be applied to systems with two-way traffic through common bidirectional servers as well as to one-way traffic systems. Computational results are presented to illustrate the speed and convergence properties of the algorithm and to investigate some of its variants. The algorithm works satisfactorily and flexibly with different convergence criteria and scanning processes. For an illustrative 20-lock system, parameter estimates converge with five iterations and less than 3 sec of CPU time to differences lower than 0.1% between successive iterations. The computation time increases only linearly with the number of locks in the system, thus allowing the analysis of very large systems of interdependent queues.

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

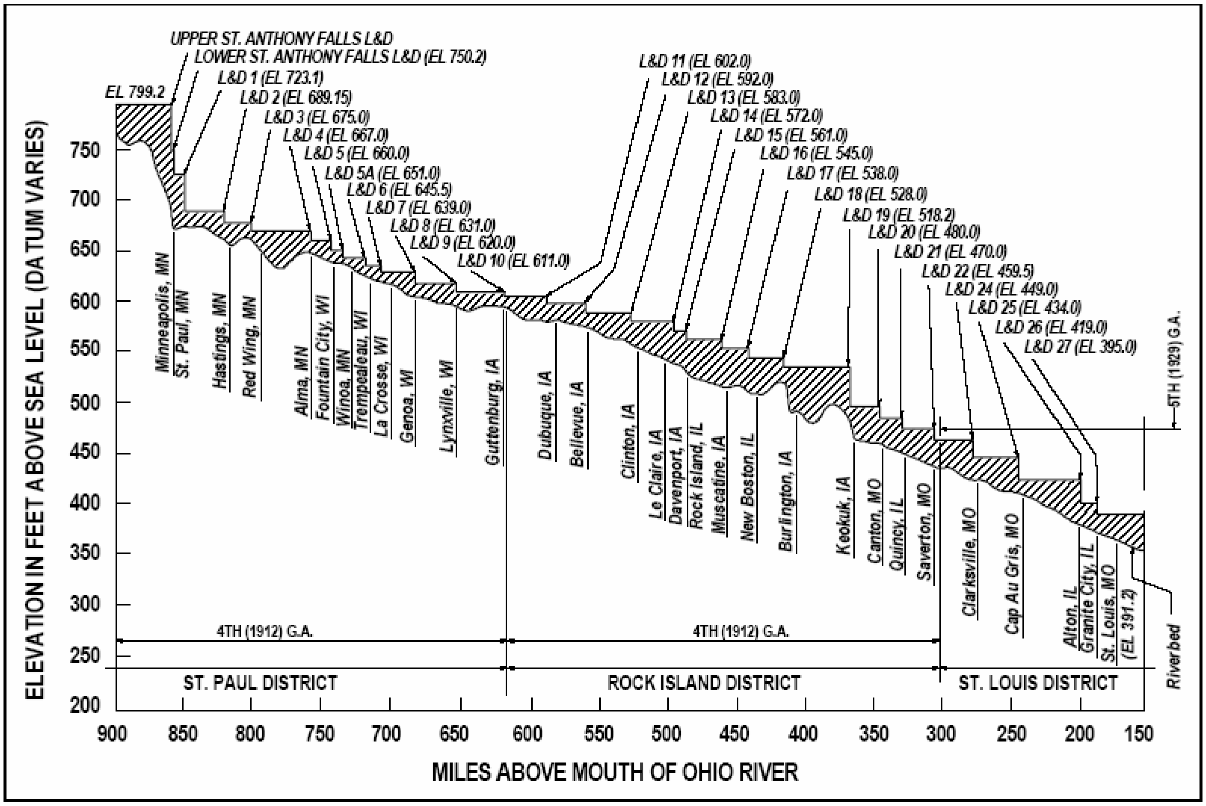

Figure 2 Schematic View of the Upper Mississippi River Pool System
Source: U.S. Army Corps of Engineers

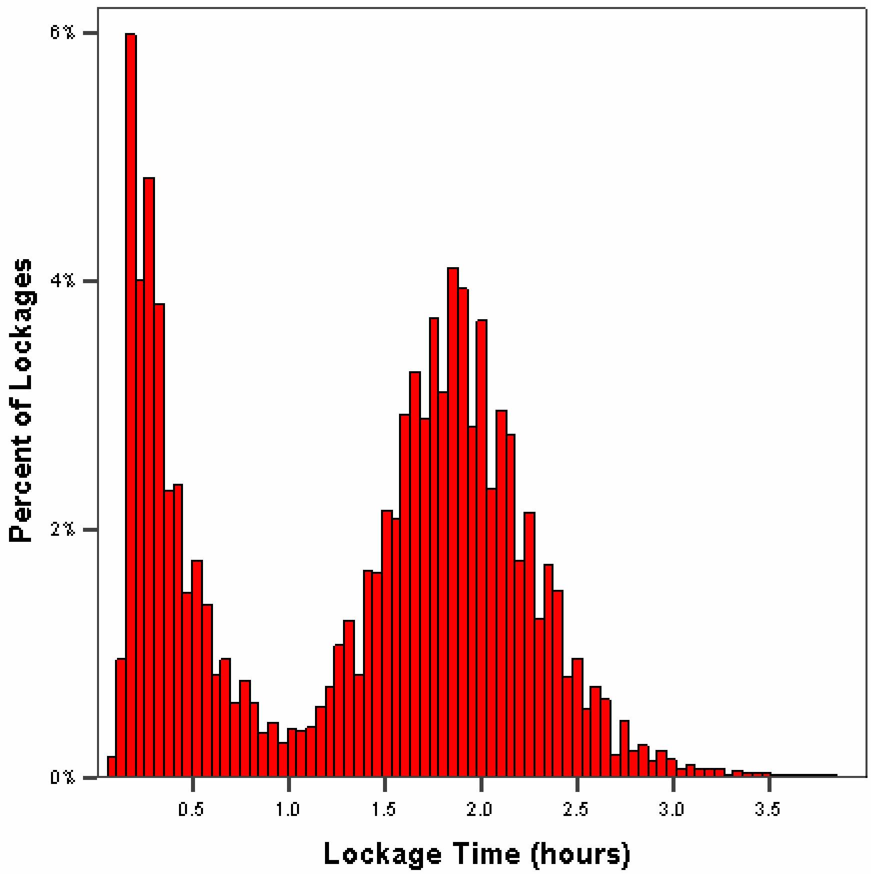

Figure 3 Distribution of Lockage Times, UMR Locks 20 through 25

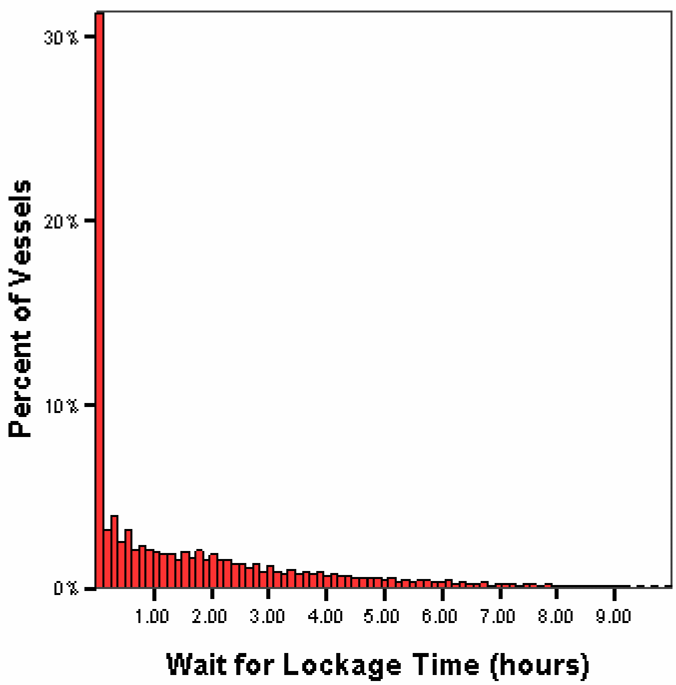

Figure 4 Panel A The Distribution of Wait for Lockage Times, UMR Locks 20 through 25

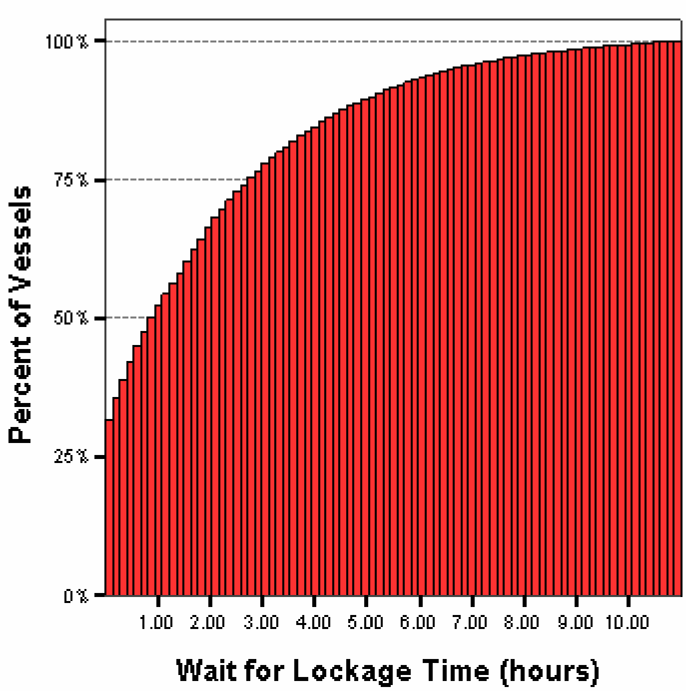

Figure 4 Panel B The Cumulative Distribution of Wait Times, UMR Locks 20 through 25

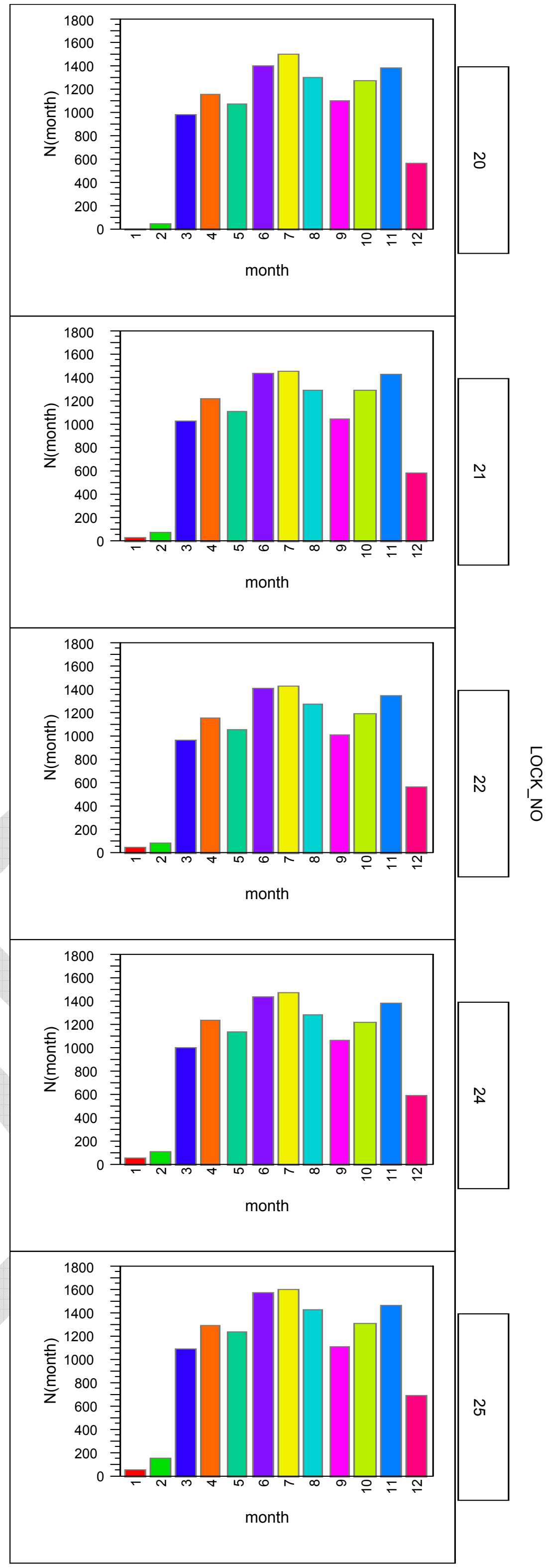

Figure 5 The Number of Lockages at UMR Locks 20 through 25 by Month, 2000 through 2003

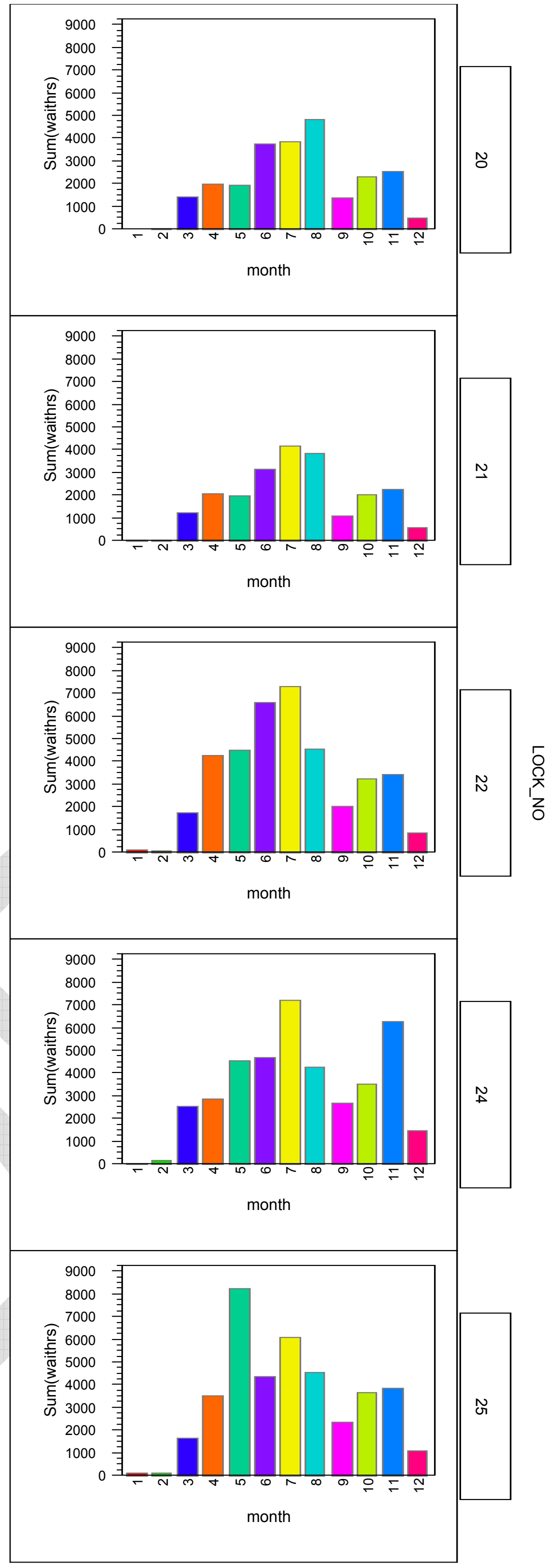

Figure 6 Aggregated Wait (hours) for Lockage Times for All Vessels by Lock and Month, 2000 through 2003

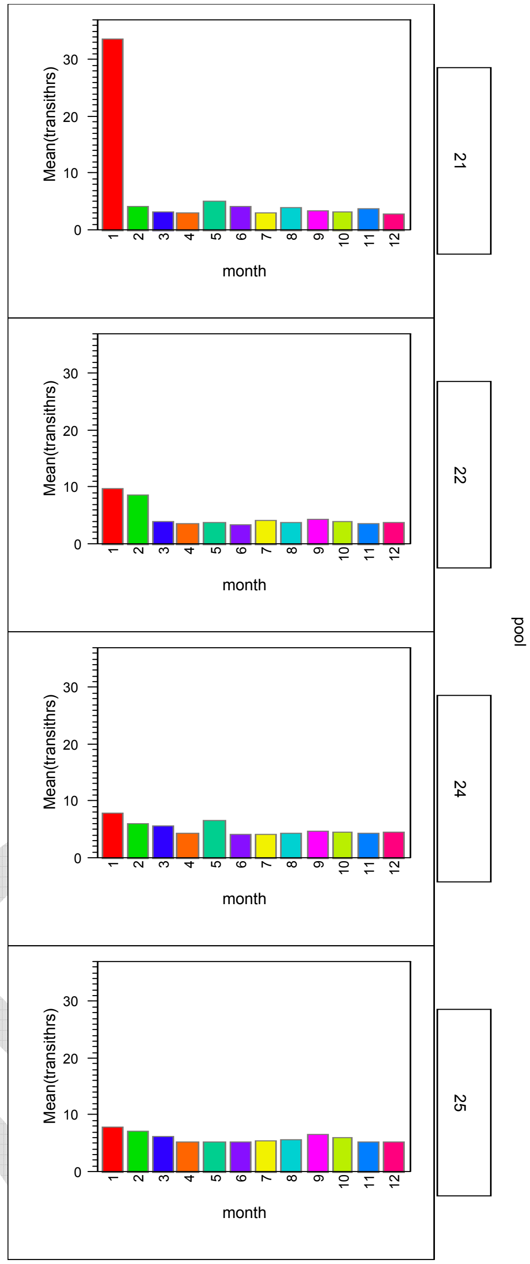

Figure 7 Mean Pool Transit Times (hours) for Commercial Tows by Month, 2000 through 2003

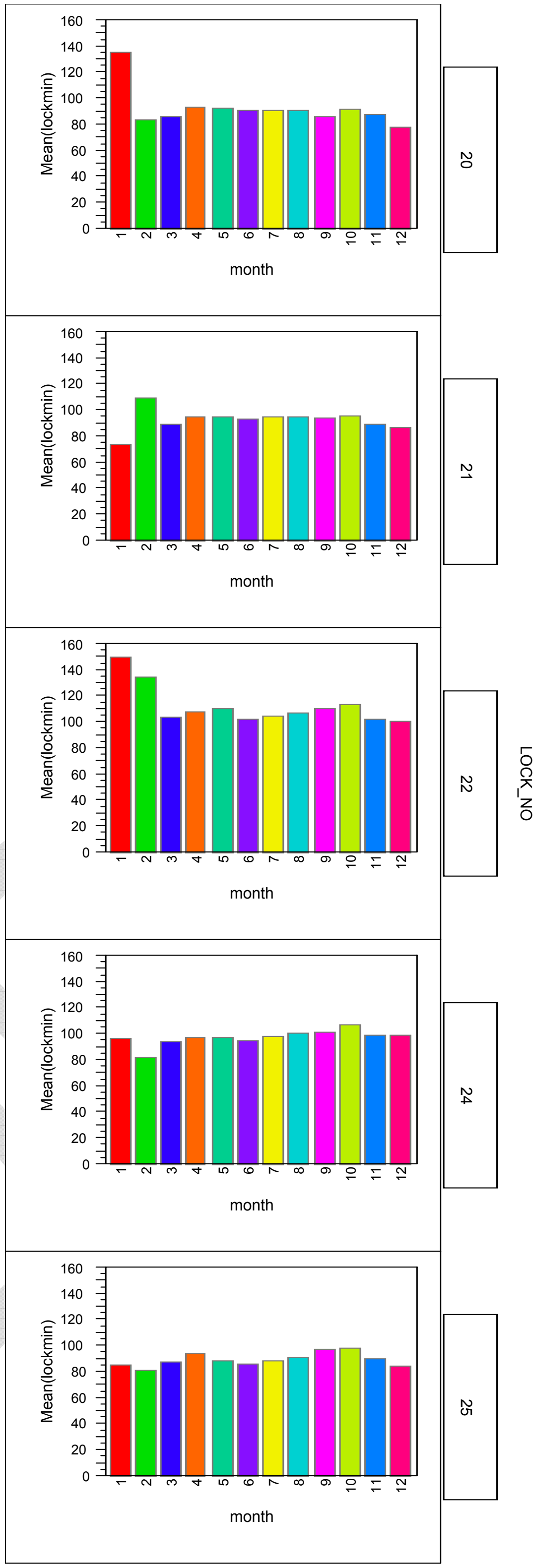

Figure 8 Mean Lockage Times (minutes) for UMR Locks 20 through 25 by Month, 2000 through 2003

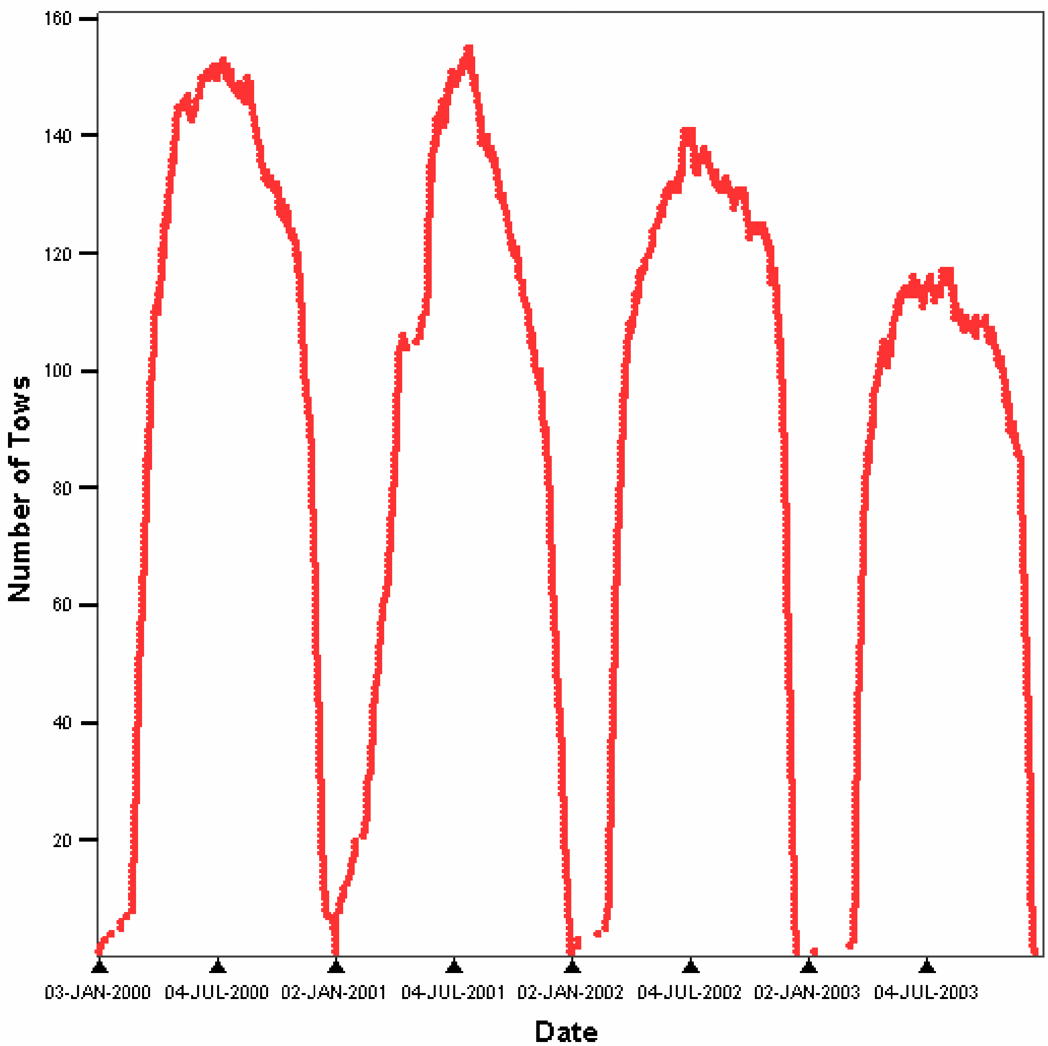

Figure 9 The Number of Tows That Have Produced at Least One Lockage in the System But Have Not Produced Their Final System Lockage, 2000 through 2003

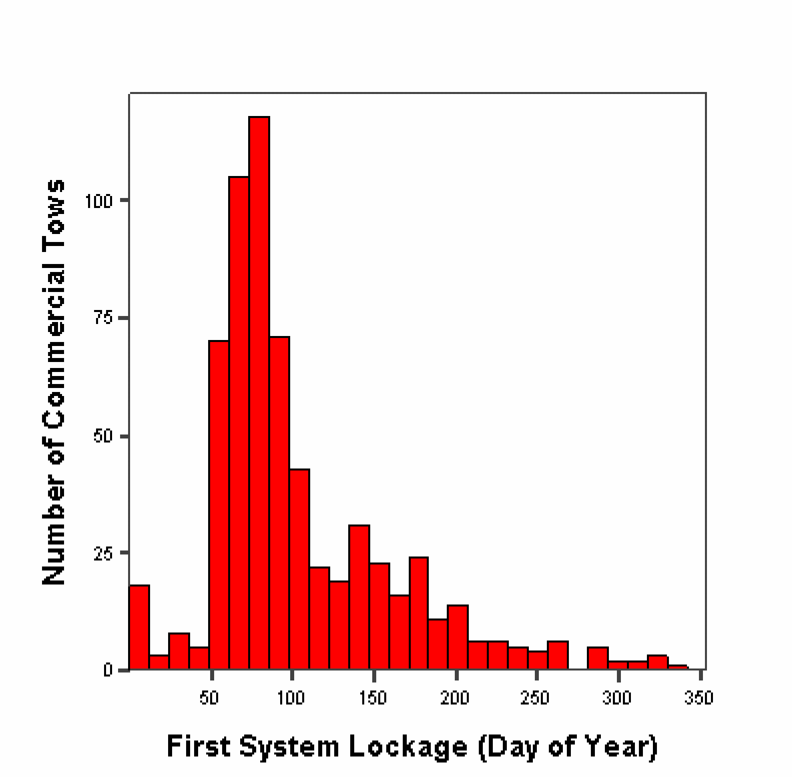

Figure 10 The Day of the Year of the First Lockage of Individual Commercial Tows at UMR Locks 20 through 25, 2000 through 2003

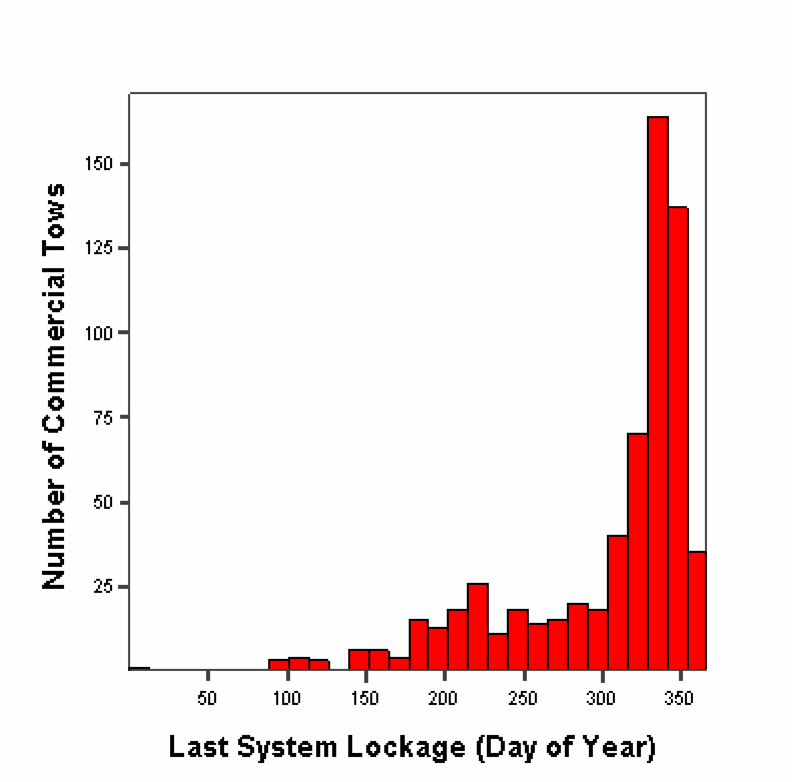

Figure 11 The Day of the Year of the Final System Lockage of individual Commercial Tows at UMR Locks 20 through 25, 2000 through 2003

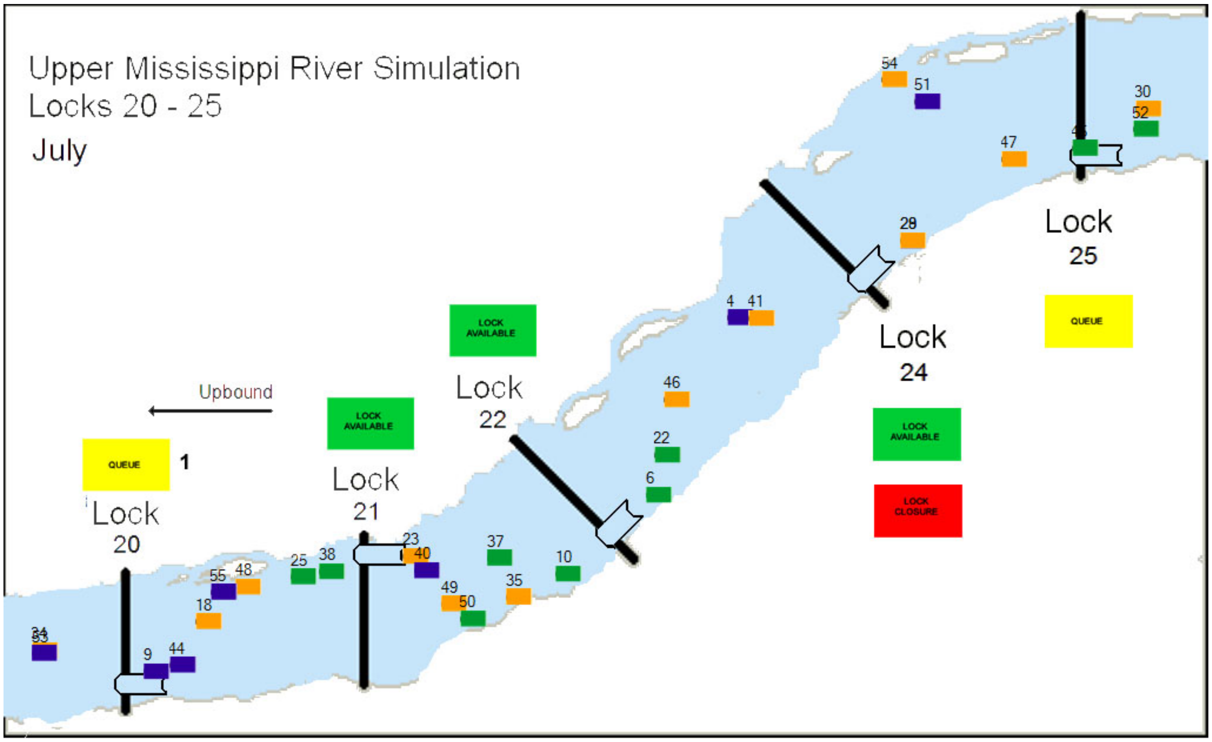

Figure 12 Micro Saint Sharp Display Diagram for the UMR Simulation Model

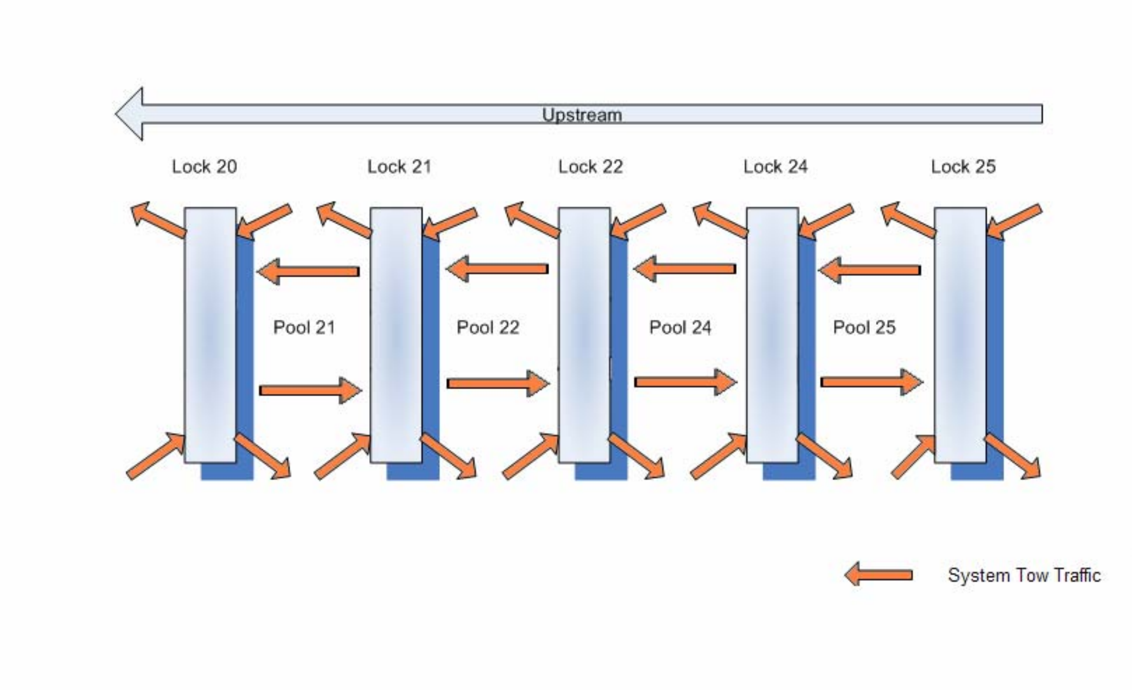

Figure 13 The UMR Simulation Model Schematic Diagram - Tow Traffic

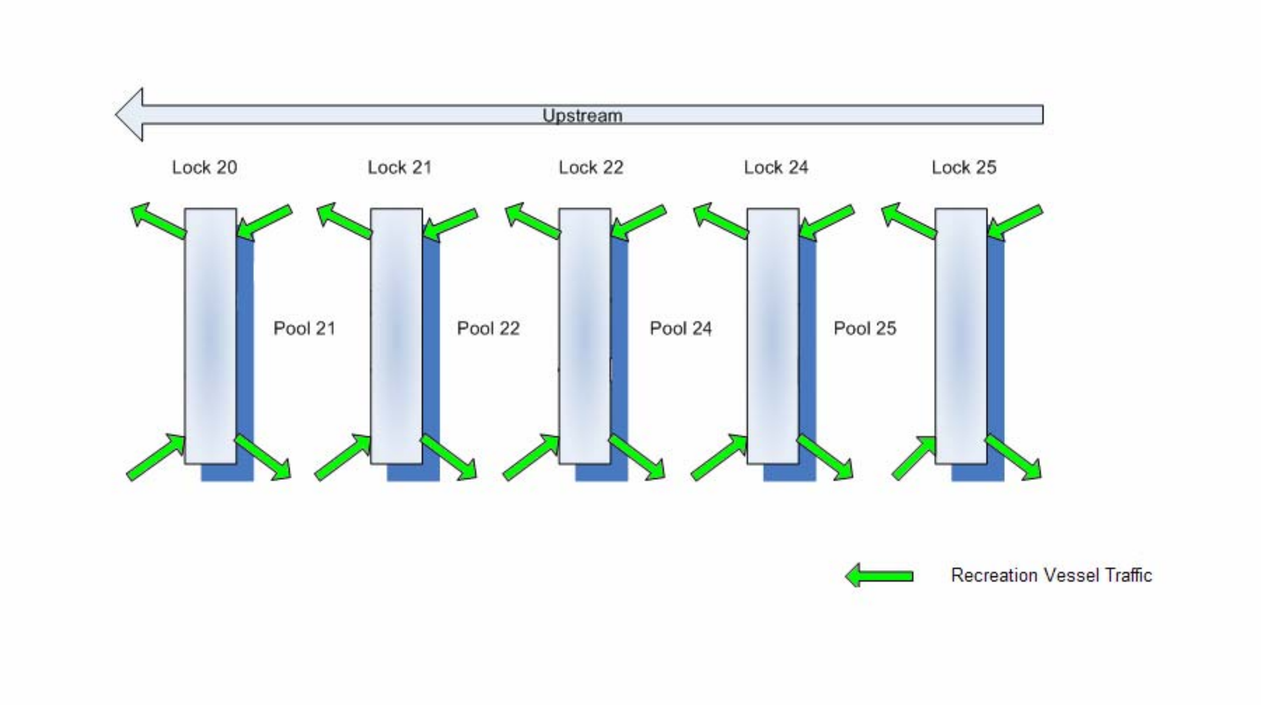

Figure 14 The UMR Simulation Model Schematic Diagram - Recreation Vessels

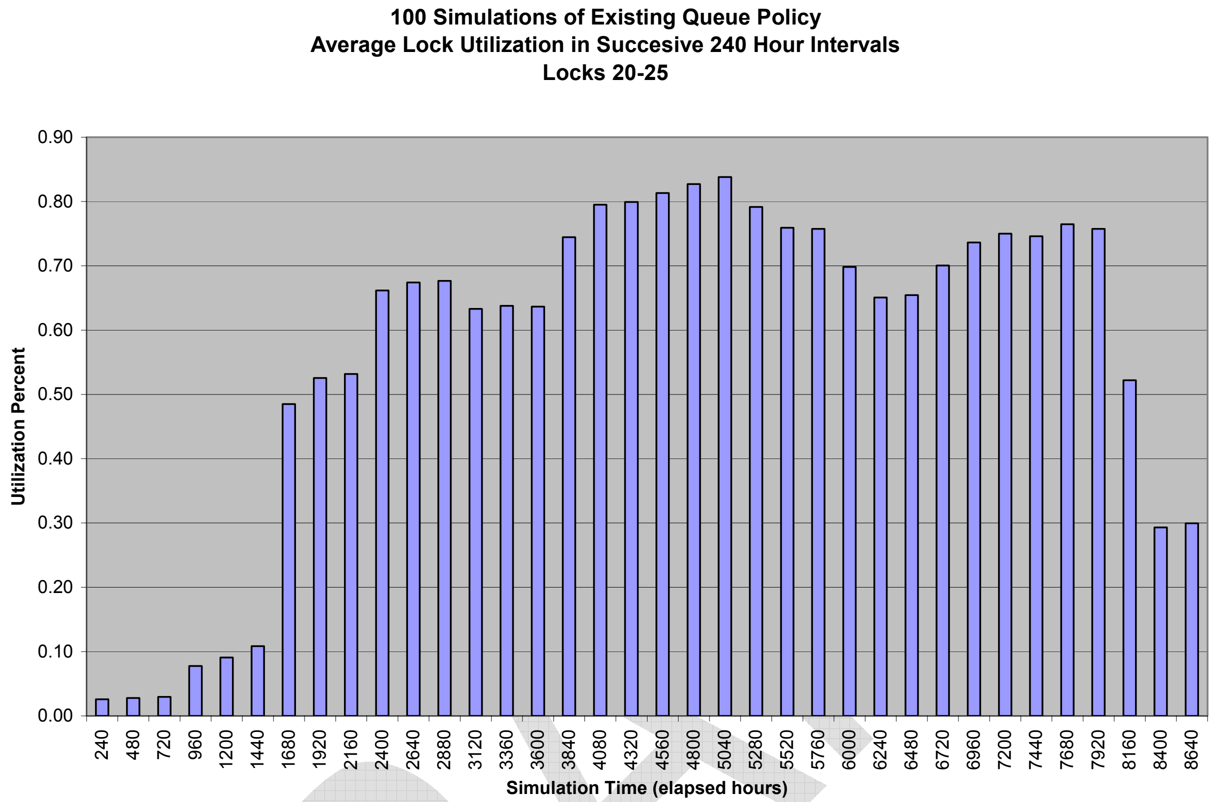

Figure 15 Mean Simulated Values of the Total Lock Utilization Percentages for UMR Locks 20 through 25 for Consecutive 10 Day Periods

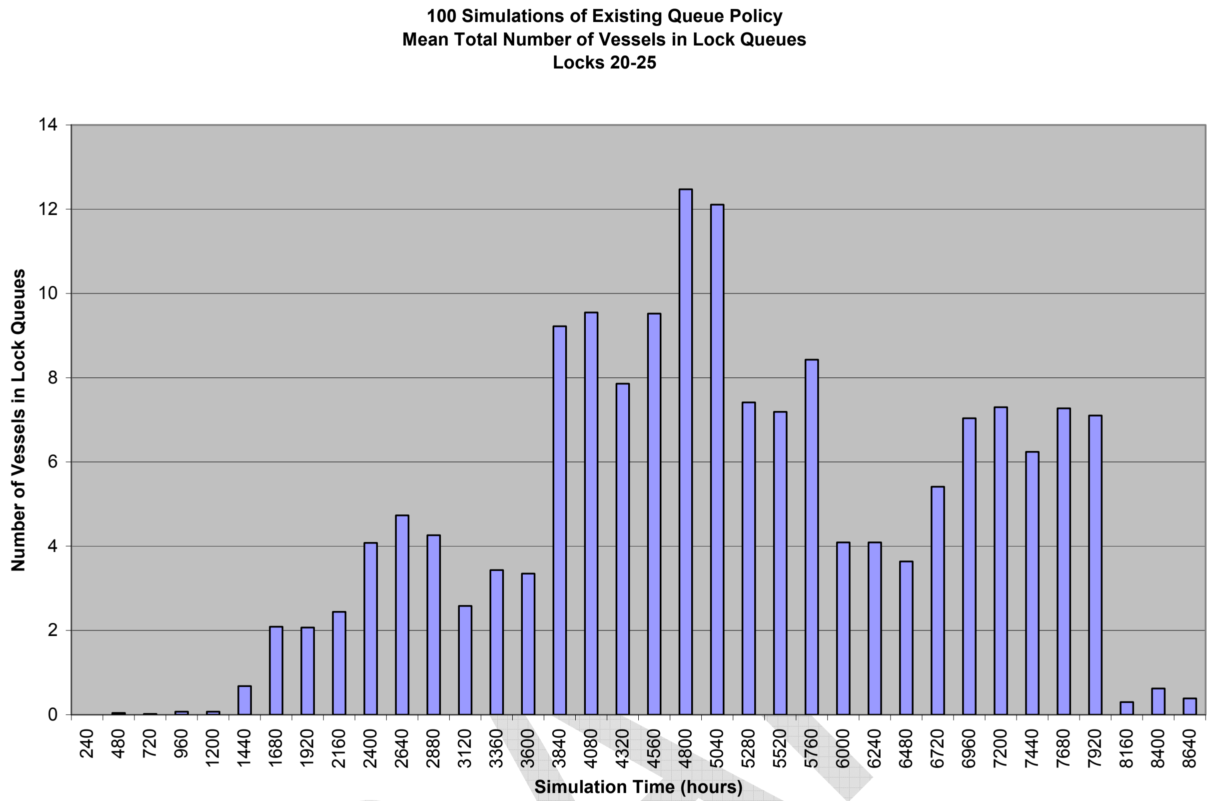

Figure 16 Total Number of Vessels Waiting for Lockage at Selected Times Compiled from 100 Runs of the UMR System Simulation Model

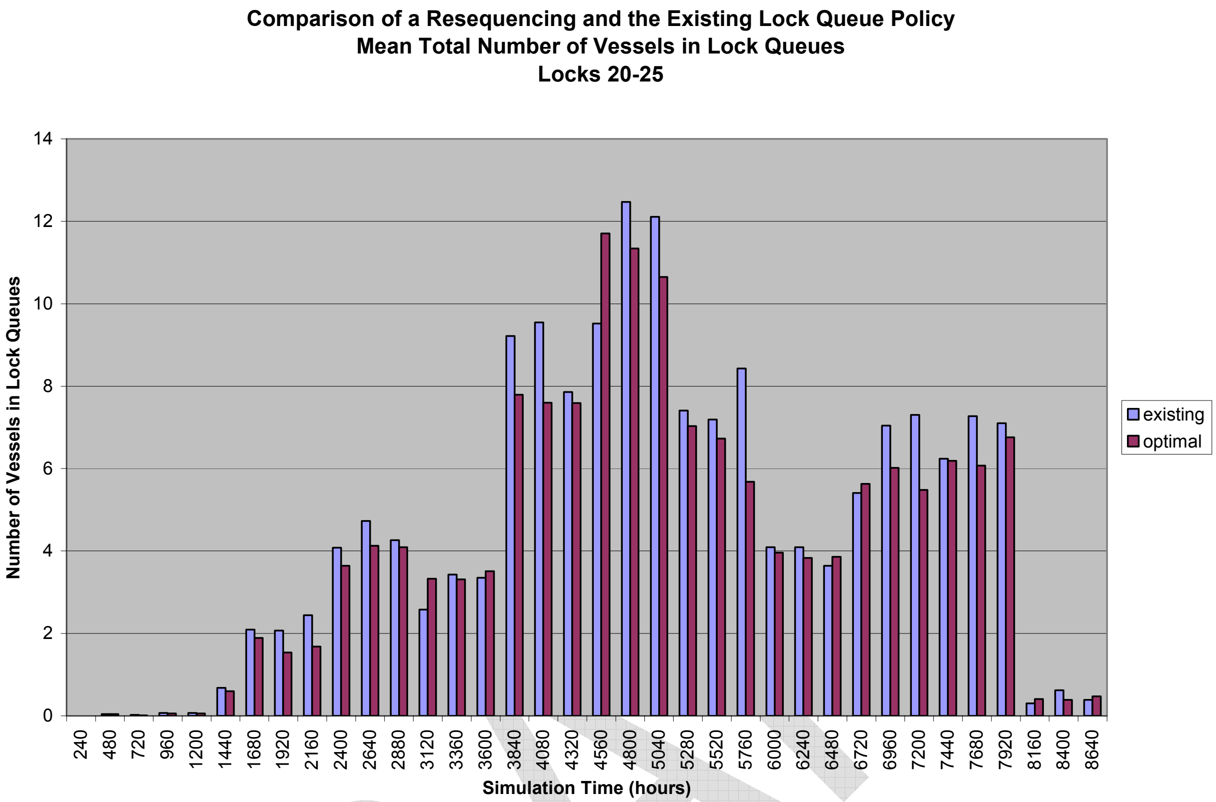

Figure 17 Comparison of the Total Number of Vessels Waiting for Lockage at Selected Times with the Existing and a Locally Optimal Queue Dispatch Policy Compiled from 100 Runs Each of the UMR System Simulation Model

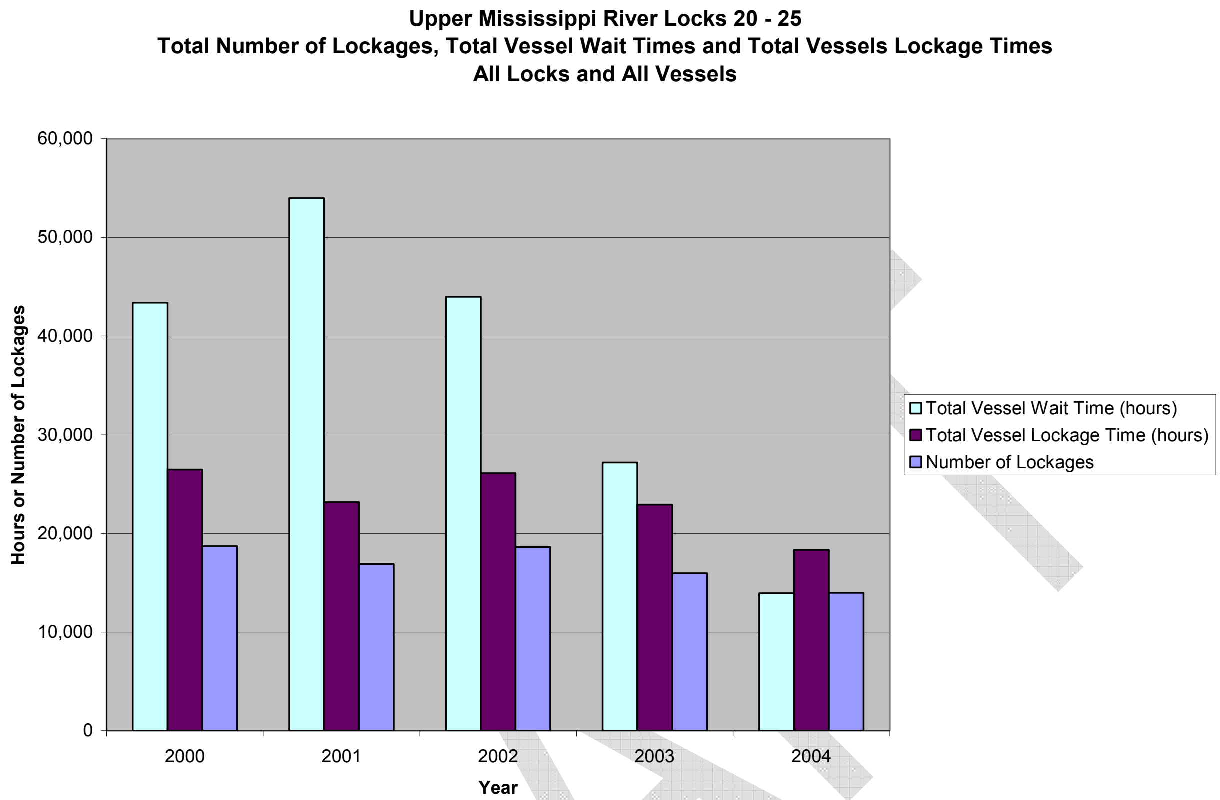

Figure 18 Total Annual Wait for Lock Service Time and Total Lockage Time, Locks 20 through 25, All Vessels, 2000 - 2004

Lock	River Mile	Year Opened	Length (Feet)	Width (Feet)	Lift (Feet)	2002 Utilization (%)
Upper Mississippi River						
USA	853.9	1963	400	56	49	15
LSA	853.3	1959	400	56	25	16
1 (Main)	847.6	1930	400	56	38	17
1 (Auxiliary)	847.6	1932	400	56	38	0
2 (Main)	815.0	1930	500	110	12	36
2 (Auxiliary)	815.0	1948	600	110	12	n.a.
3	796.9	1938	600	110	8	39
4	752.8	1935	600	110	7	35
5	738.1	1935	600	110	9	32
5a	728.5	1936	600	110	5	33
6	714.0	1936	600	110	6	38
7	702.0	1937	600	110	8	40
8	679.0	1937	600	110	11	40
9	647.0	1938	600	110	9	41
10	615.0	1936	600	110	8	44
11	583.0	1937	600	110	11	51
12	556.0	1938	600	110	9	52
13	523.0	1938	600	110	11	50
14 (Main)	493.0	1939	600	110	11	69
14 (Auxiliary)	493.0	1922	320	80	11	7
15 (Main)	482.9	1934	600	110	16	71
15 (Auxiliary)	482.9	1934	360	110	16	14
16	457.2	1937	600	110	9	68
17	437.1	1939	600	110	8	74
18	410.5	1937	600	110	10	71
19	364.2	1957	1200	110	38	56
20	343.2	1936	600	110	10	73
21	324.9	1938	600	110	10	76
22	301.2	1938	600	110	10	82
24	273.4	1940	600	110	15	85
25	241.4	1939	600	110	15	80
Mel Price (26) (Main)	200.8	1990	1200	110	24	61
Mel Price (26) (Aux.)	200.8	1994	600	110	24	16
27 (Main)	185.5	1953	1200	110	21	68
27 (Auxiliary)	185.5	1953	600	110	21	14

Table 1 Selected Characteristics of the Locks in the UMR Navigation System
Source: U.S. Army Corps of Engineers

MONTH	YEAR	Mean (hours)	Lockages	Std. Deviation (hours)
January	2000	.0000	23	.00000
	2001	1.7481	166	4.67527
	2002	.0012	14	.00445
	2003	.0000	4	.00000
	Total	1.4019	207	4.24208
February	2000	1.0760	163	4.60158
	2001	.5648	296	1.27191
	2002	2.5018	19	7.14615
	2003	n/a	0	n/a
	Total	.8161	478	3.20848
March	2000	1.5144	1528	1.84527
	2001	.8234	1066	1.54950
	2002	2.4241	1535	4.85580
	2003	1.7369	1007	2.90295
	Total	1.6865	5136	3.24528
April	2000	3.0814	1873	3.63508
	2001	1.9867	1122	3.01575
	2002	2.0783	1701	2.49104
	2003	2.0323	1591	2.63217
	Total	2.3491	6287	3.03581
May	2000	2.2771	1985	2.53592
	2001	14.3627	744	26.04503
	2002	2.0113	1872	3.18279
	2003	1.4968	1618	1.92785
	Total	3.4399	6219	10.16991
June	2000	2.0439	2046	2.74431
	2001	3.6781	2291	3.89975
	2002	3.0839	2221	4.04113
	2003	1.8256	1880	2.40980
	Total	2.7127	8438	3.48092

Table 2 Mean and Standard Deviations of Wait for Lockage Times
UMR Locks 20 through 25, 2000 through 2003

MONTH	YEAR	Mean (hours)	Lockages	Std. Deviation (hours)
July	2000	1.8013	2434	2.22484
	2001	5.3820	2538	9.49168
	2002	2.8447	2418	3.66686
	2003	2.0228	2168	2.59354
	Total	3.0663	9558	5.67386
August	2000	3.5909	2275	10.91338
	2001	3.6355	2400	4.68905
	2002	1.4085	2242	1.90115
	2003	1.3341	2121	1.84267
	Total	2.5317	9038	6.22536
September	2000	1.5732	1942	2.58004
	2001	1.3466	1866	1.98650
	2002	1.2520	1859	1.93316
	2003	1.3572	1526	9.50882
	Total	1.3856	7193	4.79293
October	2000	2.8339	1885	3.74527
	2001	1.3628	1698	1.92396
	2002	2.2757	2025	2.89381
	2003	1.5882	1733	2.38506
	Total	2.0456	7341	2.90502
November	2000	2.3104	1837	2.87879
	2001	1.8075	1688	2.05200
	2002	3.8051	2135	4.46335
	2003	1.8766	1588	2.31000
	Total	2.5385	7248	3.28951
December	2000	1.7048	709	2.57404
	2001	1.0194	1016	1.73588
	2002	1.6265	587	3.61528
	2003	1.8039	725	2.18968
	Total	1.4840	3037	2.51609
Total	2000	2.3191	18700	4.69654
	2001	3.1955	16891	7.68257
	2002	2.3603	18628	3.50466
	2003	1.7018	15961	3.70364
	Total	2.4006	70180	5.16980

Table 2 (continued) Mean and Standard Deviations of Wait for Lockage Times UMR Locks 20 through 25, 2000 through 2003

EROC	A code indicating the Corps of Engineers District in which the lock is located.
RIVER_CODE*	A code that denotes the river in which the lock is located.
LOCK_NO*	The lock identification number assigned by the Corp of Engineers.
CHMBER_NO*	A code that describes which lock chamber (if the lock has multiple chambers) that the vessel used.
OPS_ID*	The Operation ID assigned for the transaction at the lock.
LOCKAGE_TYPE*	A code that denotes the lockage type. S (Single Cut), C (Multi-Cut), K (Knock Out), or V (Jack Knife)
VESSEL_NO*	The unique Coast Guard ID for the powered vessel completing the lockage.
FLOTILLA_NO*	A number assigned for tow at the each lock associated with the combination of tow and barges that comprise the fully assembled tow.
SOL_DATE*	The date and time that the lockage began.
ARRIVAL_DATE*	The date and time that the vessel arrived for lockage.
END_OF_LOCKAGE*	The date and time that the vessel completed its lockage.
END_OF_ENTRY	The date and time that the vessel completed its entry into the lock chamber.
START_OF_EXIT	The date and time that the vessel began its exit from the lock chamber.
NUM_OF_CMRCL_PSSNGRS	The number of commercial passengers in the vessel (if any).
ASST_CODE	A code that identifies if the vessel was assisted by another vessel during its lockage.

Table 3 OMNI Traffic Table Details

PVESSEL_NO	Relational field that corresponds with the VESSEL_ID field in the Traffic Table.
FLOTILLA_NO	Assigned for each vessel at each lock they transit.
EROC	A code for the Corps of Engineers District in which the lock is located.
FLOT_LENGTH	The length of the flotilla.
FLOT_WIDTH	The width of the flotilla.
FLOT_DRAFT_FT	The draft of the flotilla in measured to the next lowest foot.
FLOT_DRAFT_IN	The remainder of the draft of the flotilla measured in inches.
STOP_CODE	A code that indicates whether the vessel made a stop since its last lockage.
HAZARD_CODE	A code that indicates if there was hazardous cargo present in the flotilla.
NUM_LOADED_BRG	The number of loaded barges in the flotilla.
NUM_OF_EMPTY_BRG	The number of empty barges in the flotilla.
NEW_FLOTILLA_NO	A code that indicates if this is a new flotilla number assigned to a portion of a tow in lockage.

Table 4 OMNI Flotilla Table Details

VESSEL_NO*	The unique Coast Guard assigned vessel number for the towboat.
EROC	A code for the Corps of Engineers District in which the lock is located.
VESSEL_TYPE*	It can be T (Tow Boat), P (Commercial Passenger), G (Government Boat), or R (Recreational).
VESSEL_NAME	The registered name of the vessel.
VSL_FOREIGN_FLAG	An indicator to denote that the vessel has a foreign flag.
VESSEL_OWNER	The registered owner of the vessel.
VESSEL_HP*	The rated horsepower of the vessel.

Table 5 OMNI Vessel Table Details

EROC	A code for the Corps of Engineers District in which the lock is located.
RIVER_CODE	A code that denotes the river in which the lock is located. It can be MI, IL, or KS.
LOCK_NO*	The lock number assigned by Corp of Engineers.
CHMBER_NO	A code that describes which lock chamber (if the lock has multiple chambers) that the vessel used.
OPS_ID*	The Operation ID assigned for the transaction at the lock.
DIRECTION*	The direction of travel of the vessel. It can be up-bound or down-bound.
MULTI_VESSEL	Denotes if more than one powered vessel was included in the lockage.
NUM_LIGHT_BOATS	The number of light boats (towboats without barges) included in the lockage.
NUM_REC_BOATS	The number of recreation boats included in the lockage.

Table 6 OMNI Operations Table Details

Lock	*Direction*	*Lockage Type*	*Mean Wait Time (hours)*	*Number*	*Std Dev (hours)*
20	Downbound	Double	2.45	4358	5.52
		Knockout	2.90	126	3.81
		Other	2.61	90	2.81
		Single	1.29	1313	3.39
		Total	2.21	5887	5.08
	Upbound	Double	2.27	4162	2.96
		Knockout	2.32	92	2.26
		Other	2.36	116	2.73
		Single	1.00	1554	1.77
		Total	1.94	5924	2.74
21	Downbound	Double	2.01	4533	3.93
		Knockout	2.75	126	4.17
		Other	3.05	82	7.55
		Single	1.28	1289	2.21
		Total	1.89	6030	3.73
	Upbound	Double	2.17	4293	4.76
		Knockout	2.16	109	2.11
		Other	1.82	133	1.91
		Single	0.99	1466	1.91
		Total	1.87	6001	4.19
22	Downbound	Double	3.44	4546	3.95
		Jackknife	0.31	2	0.44
		Knockout	4.40	147	4.85
		Other	4.17	81	4.36
		Single	2.17	1029	3.21
		Total	3.25	5805	3.90
	Upbound	Double	3.90	4327	4.93
		Jackknife	1.35	1	
		Knockout	4.12	114	4.26
		Other	3.63	138	3.69
		Single	1.77	1179	2.76
		Total	3.46	5759	4.61
24	Downbound	Double	3.64	4717	4.43
		Knockout	3.83	188	3.95
		Other	3.95	80	3.47
		Single	1.47	1061	2.36
		Total	3.27	6046	4.20
	Upbound	Double	3.98	4457	8.37
		Knockout	3.49	124	3.81
		Other	3.99	139	4.50
		Single	1.44	1271	2.91
		Total	3.43	5991	7.47
25	Downbound	Double	3.04	4738	3.99
		Jackknife	0.00	1	
		Knockout	3.80	193	5.04
		Other	3.29	78	3.63
		Single	1.40	1268	2.38
		Total	2.74	6278	3.82
	Upbound	Double	4.35	4474	11.33
		Knockout	3.75	131	5.20
		Other	3.74	139	5.71
		Single	0.96	2037	2.03
		Total	3.31	6781	9.46

Table 7 Selected Summary Statistics of Wait Time Distributions by Lock, Direction, and Lockage Type for Tow Vessels, 2000 through 2003

Lock	***Direction***	***Lockage Type***	***Mean Lockage Time (hours)***	***Number***	***Std Dev (hours)***
20	Downbound	Double	1.89	4358	0.62
		Knockout	1.04	126	0.41
		Other	1.24	90	0.35
		Single	0.46	1313	0.38
		Total	1.55	5887	0.83
	Upbound	Double	1.81	4162	0.50
		Knockout	0.95	92	0.28
		Other	1.40	116	0.37
		Single	0.47	1554	0.47
		Total	1.44	5924	0.77
21	Downbound	Double	1.99	4533	0.48
		Knockout	1.00	126	0.35
		Other	1.30	82	0.41
		Single	0.47	1289	0.26
		Total	1.63	6030	0.77
	Upbound	Double	1.84	4293	0.53
		Knockout	0.99	109	0.37
		Other	1.45	133	0.36
		Single	0.46	1466	0.25
		Total	1.48	6001	0.75
22	Downbound	Double	2.16	4546	0.66
		Jackknife	1.39	2	1.03
		Knockout	1.36	147	1.16
		Other	1.39	81	0.38
		Single	0.64	1029	1.18
		Total	1.86	5805	0.98
	Upbound	Double	2.01	4327	0.61
		Jackknife	1.17	1	
		Knockout	1.17	114	0.77
		Other	1.65	138	0.49
		Single	0.56	1179	0.65
		Total	1.69	5759	0.85
24	Downbound	Double	2.10	4717	0.63
		Knockout	0.95	188	0.39
		Other	1.31	80	0.32
		Single	0.54	1061	0.66
		Total	1.78	6046	0.87
	Upbound	Double	1.82	4457	0.46
		Knockout	1.05	124	0.47
		Other	1.43	139	0.35
		Single	0.48	1271	0.19
		Total	1.51	5991	0.69
25	Downbound	Double	2.03	4738	0.65
		Jackknife	1.75	1	
		Knockout	0.94	193	0.49
		Other	1.35	78	0.69
		Single	0.42	1268	0.27
		Total	1.66	6278	0.88
	Upbound	Double	1.83	4474	0.61
		Knockout	1.01	131	0.40
		Other	1.57	139	0.97
		Single	0.38	2037	0.25
		Total	1.37	6781	0.85

Table 8 Selected Summary Statistics of Lockage Time Distributions by Lock, Direction, and Lockage Type, 2000 through 2003

Lockage Type	Destination Lock	Destination Direction	Previous Lock	Previous Direction	Mean Transit Times (hours)	Number	Std Dev (hours)
Double	20	Upbound	21	Upbound	3.80	3236	4.11
	21	Downbound	20	Downbound	2.50	3536	3.21
	21	Upbound	22	Upbound	4.74	3863	2.61
	22	Downbound	21	Downbound	3.07	4096	1.85
	22	Upbound	24	Upbound	5.57	3343	9.36
	24	Downbound	22	Downbound	3.95	3907	1.39
	24	Upbound	25	Upbound	7.09	4266	3.39
	25	Downbound	24	Downbound	4.38	4523	1.58
Single	20	Upbound	21	Upbound	5.44	562	16.86
	21	Downbound	20	Downbound	10.18	501	93.07
	21	Upbound	22	Upbound	5.98	356	10.78
	22	Downbound	21	Downbound	4.16	274	10.99
	22	Upbound	24	Upbound	5.54	542	17.00
	24	Downbound	22	Downbound	4.82	518	28.21
	24	Upbound	25	Upbound	5.82	694	4.38
	25	Downbound	24	Downbound	5.59	615	24.80

Table 9 Selected Summary Statistics of Transit Times between Locks for Multi-Cut and Single-Cut Tows that Continue Directly to the Next Lock without Stopping, 2000 through 2003

Lock	Lockage Type	Operations Type	Mean Lock Time (hours)	Number	Std Dev (hours)
20	Double	EXCHANGE	1.89	1691	0.76
		FLY	2.00	1207	0.57
		TURNBACK	1.82	1460	0.45
	Knockout	EXCHANGE	1.10	44	0.43
		FLY	1.13	26	0.47
		TURNBACK	0.95	56	0.33
	Other	EXCHANGE	1.18	34	0.35
		FLY	1.36	18	0.26
		TURNBACK	1.23	38	0.39
	Single	EXCHANGE	0.46	414	0.29
		FLY	0.50	496	0.54
		TURNBACK	0.40	403	0.17
21	Double	EXCHANGE	1.93	1746	0.47
		FLY	2.25	1288	0.42
		TURNBACK	1.83	1499	0.46
	Knockout	EXCHANGE	1.01	42	0.34
		FLY	1.27	31	0.43
		TURNBACK	0.84	53	0.18
	Other	EXCHANGE	1.28	26	0.39
		FLY	1.59	18	0.53
		TURNBACK	1.17	38	0.28
	Single	EXCHANGE	0.44	449	0.27
		FLY	0.56	418	0.29
		TURNBACK	0.41	422	0.20
22	Double	EXCHANGE	2.14	1874	0.57
		FLY	2.52	934	0.86
		TURNBACK	2.00	1738	0.56
	Jackknife	FLY	2.12	1	
		TURNBACK	0.67	1	
	Knockout	EXCHANGE	1.53	62	1.58
		FLY	1.52	25	0.51
		TURNBACK	1.11	60	0.72
	Other	EXCHANGE	1.39	34	0.38
		FLY	1.68	12	0.28
		TURNBACK	1.29	35	0.36
	Single	EXCHANGE	0.51	377	0.28
		FLY	0.98	245	2.10
		TURNBACK	0.56	407	0.84
24	Double	EXCHANGE	2.16	1824	0.62
		FLY	2.18	909	0.70
		TURNBACK	2.01	1984	0.59
	Knockout	EXCHANGE	0.95	66	0.29
		FLY	0.97	35	0.23
		TURNBACK	0.94	87	0.49
	Other	EXCHANGE	1.33	33	0.33
		FLY	1.40	11	0.35
		TURNBACK	1.27	36	0.29
	Single	EXCHANGE	0.51	407	0.62
		FLY	0.57	313	0.29
		TURNBACK	0.54	340	0.92
25	Double	EXCHANGE	2.03	2325	0.47
		FLY	2.35	697	0.70
		TURNBACK	1.89	1716	0.77
	Jackknife	FLY	1.75	1	
	Knockout	EXCHANGE	1.08	79	0.67
		FLY	1.04	24	0.28
		TURNBACK	0.80	90	0.24
	Other	EXCHANGE	1.28	32	0.32
		FLY	1.57	11	0.21
		TURNBACK	1.35	35	0.98
	Single	EXCHANGE	0.42	423	0.27
		FLY	0.49	401	0.31
		TURNBACK	0.37	444	0.20

Table 10 Selected Summary Statistics of Lockage Time Distributions for Tows Traveling Downbound, 2000 through 2003

Lock	Lockage Type	Operations Type	Mean Lock Time (hours)	Number	Std Dev (hours)
20	Double	EXCHANGE	1.93	1594	0.41
		FLY	1.91	1109	0.59
		TURNBACK	1.60	1459	0.45
	Knockout	EXCHANGE	1.02	24	0.30
		FLY	1.00	22	0.18
		TURNBACK	0.90	46	0.31
	Other	EXCHANGE	1.64	39	0.39
		FLY	1.41	28	0.29
		TURNBACK	1.21	49	0.29
	Single	EXCHANGE	0.48	570	0.50
		FLY	0.51	601	0.54
		TURNBACK	0.38	383	0.15
21	Double	EXCHANGE	1.93	1730	0.40
		FLY	2.01	1153	0.61
		TURNBACK	1.58	1410	0.48
	Knockout	EXCHANGE	1.13	36	0.36
		FLY	1.18	22	0.39
		TURNBACK	0.82	51	0.27
	Other	EXCHANGE	1.55	54	0.39
		FLY	1.61	36	0.25
		TURNBACK	1.21	43	0.27
	Single	EXCHANGE	0.43	573	0.25
		FLY	0.56	494	0.28
		TURNBACK	0.37	399	0.14
22	Double	EXCHANGE	2.13	1780	0.51
		FLY	2.28	775	0.62
		TURNBACK	1.78	1772	0.62
	Jackknife	EXCHANGE	1.17	1	
	Knockout	EXCHANGE	1.48	35	1.25
		FLY	1.19	16	0.39
		TURNBACK	1.00	63	0.33
	Other	EXCHANGE	1.78	61	0.58
		FLY	1.76	24	0.36
		TURNBACK	1.46	53	0.35
	Single	EXCHANGE	0.49	525	0.26
		FLY	0.83	297	1.17
		TURNBACK	0.43	357	0.24
24	Double	EXCHANGE	1.91	1772	0.51
		FLY	1.94	848	0.36
		TURNBACK	1.68	1837	0.42
	Knockout	EXCHANGE	1.11	46	0.57
		FLY	1.32	22	0.41
		TURNBACK	0.90	56	0.32
	Other	EXCHANGE	1.51	53	0.37
		FLY	1.51	27	0.38
		TURNBACK	1.31	59	0.30
	Single	EXCHANGE	0.46	542	0.19
		FLY	0.56	347	0.21
		TURNBACK	0.43	382	0.17
25	Double	EXCHANGE	1.94	1802	0.59
		FLY	2.05	809	0.75
		TURNBACK	1.62	1863	0.49
	Knockout	EXCHANGE	1.17	49	0.42
		FLY	1.19	25	0.39
		TURNBACK	0.79	57	0.27
	Other	EXCHANGE	1.61	56	0.54
		FLY	2.00	22	1.63
		TURNBACK	1.39	61	0.92
	Single	EXCHANGE	0.37	693	0.18
		FLY	0.41	804	0.23
		TURNBACK	0.35	540	0.33

Table 11 Selected Summary Statistics of Lockage Time Distributions for Tows Traveling Upbound, 2000 through 2003

Lock	Direction	Operations Type	Mean Lock Time (hours)	Number	Std Dev (hours)
20	Downbound	EXCHANGE	0.20	360	0.06
		FLY	0.23	291	0.08
		TURNBACK	0.20	253	0.07
	Upbound	EXCHANGE	0.23	296	0.52
		FLY	0.22	189	0.08
		TURNBACK	0.18	170	0.05
21	Downbound	EXCHANGE	0.20	373	0.08
		FLY	0.22	391	0.10
		TURNBACK	0.20	269	0.06
	Upbound	EXCHANGE	0.19	309	0.06
		FLY	0.22	301	0.07
		TURNBACK	0.20	179	0.09
22	Downbound	EXCHANGE	0.23	404	0.09
		FLY	0.28	198	0.11
		TURNBACK	0.25	287	0.09
	Upbound	EXCHANGE	0.24	369	0.12
		FLY	0.29	168	0.13
		TURNBACK	0.23	194	0.09
24	Downbound	EXCHANGE	0.25	22	0.11
		FLY	0.25	1040	0.10
		TURNBACK	0.25	78	0.10
	Upbound	EXCHANGE	0.26	19	0.09
		FLY	0.26	902	0.10
		TURNBACK	0.24	59	0.09
25	Downbound	EXCHANGE	0.23	358	0.10
		FLY	0.23	769	0.11
		TURNBACK	0.21	255	0.11
	Upbound	EXCHANGE	0.23	332	0.10
		FLY	0.24	659	0.11
		TURNBACK	0.23	218	0.11

Table 12 Selected Summary Statistics of Lockage Time Distributions for Recreation Lockages, 2000 through 2003

Variable Name	Definition
Jan, Feb, etc.	Indicator (0-1) variables with values=1 for respective months
Psingle	Single lockage just completed (0-1)
Pdouble	Double lockage just completed (0-1)
Pjackknife	Jackknife lockage just completed (0-1)
Pknockout	Knockout lockage just completed (0-1)
Pothtype	Other lockage just completed (0-1)
Pctlcknite	Percent of lockage time occurring at night
Pdoubnite	Pdouble*Pctlcknite
Psingnite	Psingle*Pctlcknite
Pothnite	Pothtype*Pctlcknite
Pturnback	Turnback required for lockage (0-1)
Pexchange	Exchange occurred fro lockage (0-1)
Pctlckdn	Percent of time lock was impaired during lockage
Thrudouble	Vessel continues nonstop to next lock as a Double tow (0-1)
Thrusingle	Vessel continues nonstop to next lock as a Single tow (0-1)
Thruother	Vessel continues nonstop to next lock as other than a Single or Double tow (0-1)
Pcttrannite	Percent of transit time to next lock (including stop) that occurs at night
Thrudoubnite	Thrudouble*Pcttrannite
Thrusingnite	Thrusingle*Pcttrannite
Pcttrandn	Percent of transit time to next lock (including stop) during which the destination lock is impaired
Contdouble	Vessel stops in pool for possible reconfiguration and continues to next lock as a Double tow (0-1)
Contsingle	Vessel stops in pool for possible reconfiguration and continues to next lock as a Single tow (0-1)
Contother	Vessel stops in pool for possible reconfiguration and returns to lock as other than a Single or Double tow (0-1)
Retdouble	Vessel stops in pool for possible reconfiguration, reverses direction and returns to same lock as a Double tow (0-1)
Retsingle	Vessel stops in pool for possible reconfiguration, reverses direction and returns to same lock as a Single tow (0-1)
Retother	Vessel stops in pool for possible reconfiguration, reverses direction and returns to same lock as other than a Single or Double tow (0-1)
Gauge	Gauge reading for water level in pool just entered
Flow	Flow reading for pool just entered

Table 13 Definitions of Variables Used in Statistical Models

Direction	Month	LOCK 20	21	22	24	25	Grand Total
Downbound	1	0.3	0.3			0.3	0.8
	3	0.8	1.5	1.0	1.0	0.8	5.0
	4	1.5	3.8	2.0	4.0	5.3	16.5
	5	6.0	10.8	7.8	11.8	15.8	52.0
	6	20.8	29.3	23.3	26.8	36.0	136.0
	7	49.3	55.3	46.3	56.3	69.3	276.3
	8	60.0	63.0	53.3	62.0	78.3	316.5
	9	43.5	45.8	41.8	63.3	75.5	269.8
	10	35.0	38.5	36.8	44.5	49.5	204.3
	11	8.0	9.5	9.0	13.8	13.0	53.3
	12	1.0	0.8	1.3	1.8	2.0	6.8
Downbound Total		226	226.0	258.3	222.3	285.0	345.5
Upbound	1	0.3	0.3			0.3	0.8
	3	1.3	2.0	1.8	2.8	2.0	9.8
	4	5.3	6.5	6.0	7.8	11.3	36.8
	5	15.5	19.0	16.5	18.5	24.8	94.3
	6	23.0	29.3	27.8	34.5	38.5	153.0
	7	40.3	46.8	41.5	52.0	63.0	243.5
	8	47.8	52.8	48.3	67.3	81.0	297.0
	9	24.3	33.3	32.8	44.3	58.3	192.8
	10	5.8	6.5	7.3	15.3	19.5	54.3
	11	0.3	1.0	1.0	2.5	3.0	7.8
	12	0.3			0.3	0.8	1.3
Upbound Total		163.75	163.8	197.3	182.8	245.0	302.3
Grand Total		389.75	389.8	455.5	405.0	530.0	647.8

Table 14 Mean Number of Local Vessel Arrivals by Direction of Travel and Month of Arrival UMR Locks 20 through 25, 2000 through 2003

Direction	Month	LOCK 20	21	22	24	25	Grand Total
Downbound	1						
	3	1007.9	371.1	70.1	435.5	886.5	2771.1
	4	392.9	144.1	189.5	128.1	105.1	959.7
	5	97.7	88.2	90.5	96.6	56.8	429.8
	6	39.9	26.9	35.5	28.0	21.0	151.3
	7	15.0	13.1	16.0	13.2	10.7	67.9
	8	12.5	12.0	14.1	12.2	9.5	60.3
	9	16.8	15.7	17.0	11.4	9.6	70.5
	10	21.0	19.3	19.3	16.5	14.8	91.0
	11	63.0	46.7	59.1	42.5	44.8	256.1
	12	181.3	328.8	301.5	201.2	223.7	1236.4
Downbound Total		1848.1	1065.8	812.6	985.0	1382.6	6094.2
Upbound	1						
	3	677.1	375.1	122.3	169.2	502.0	1845.7
	4	130.3	104.3	96.2	83.9	60.2	475.0
	5	56.5	45.2	55.5	46.0	33.3	236.5
	6	30.6	24.9	26.8	21.5	19.2	122.9
	7	18.3	15.1	16.9	13.8	11.7	75.7
	8	16.0	14.7	16.2	11.5	9.4	67.8
	9	29.2	21.7	21.7	16.0	12.1	100.7
	10	96.2	90.5	78.5	43.6	32.2	340.9
	11	523.0	494.7	184.9	118.6	90.5	1411.6
	12	981.8			424.0	478.9	1884.6
Upbound Total		2559.0	1186.1	618.9	948.0	1249.4	6561.5
Grand Total		4407.1	2252.0	1431.6	1933.0	2631.9	12655.6

Table 15 Mean Hours between Local Vessel Arrivals by Direction of Travel and Month, 2000 through 2003

Direction	Month	LOCK 20	21	22	24	25	Grand Total
Downbound	1	0.3	4.5	4.0	5.0	3.3	17.0
	2	4.0	7.5	4.8	5.8	6.5	28.5
	3	98.3	51.0	33.0	36.8	25.8	244.8
	4	139.8	50.5	39.8	43.5	21.5	295.0
	5	129.0	33.8	25.3	32.5	17.5	238.0
	6	175.8	39.5	31.3	35.5	24.3	306.3
	7	185.8	39.0	26.0	36.3	25.0	312.0
	8	169.0	46.3	31.0	31.5	26.0	303.8
	9	136.5	46.8	31.5	37.8	19.5	272.0
	10	156.8	55.0	34.0	39.0	19.8	304.5
	11	190.0	50.3	27.0	31.5	19.3	318.0
	12	86.8	28.5	18.8	22.0	11.5	167.5
Downbound Total		1471.75	1471.8	452.5	306.3	357.0	219.8
Upbound	1		1.8	3.0	3.0	7.5	15.3
	2	4.0	2.8	2.5	2.0	24.0	35.3
	3	47.0	32.5	32.8	14.0	170.8	297.0
	4	40.8	34.8	36.0	14.0	172.8	298.3
	5	35.3	33.5	30.3	13.0	172.8	284.8
	6	41.3	34.5	46.8	20.5	206.5	349.5
	7	47.0	37.5	45.0	19.8	207.5	356.8
	8	50.5	34.3	43.5	17.3	177.3	322.8
	9	51.3	36.5	41.0	20.3	143.8	292.8
	10	62.8	47.8	45.0	16.3	171.0	342.8
	11	66.3	59.3	57.5	34.8	172.3	390.0
	12	36.8	32.3	25.8	18.5	69.3	182.5
Upbound Total		482.75	482.8	387.3	409.0	193.3	1695.3
Grand Total		1954.5	1954.5	839.8	715.3	550.3	1915.0

Table 16 Mean Number of Tow Vessel Arrivals by Direction of Travel and Month of Arrival UMR Locks 20 through 25, 2000 through 2003

Direction	Month	LOCK					Grand Total
		20	21	22	24	25	
Downbound	1		43.3	59.2	58.2	79.1	239.8
	2	130.1	66.6	44.2	69.4	114.6	424.9
	3	7.1	13.3	29.4	17.6	41.0	108.3
	4	4.8	13.6	16.8	15.6	29.8	80.5
	5	6.2	23.6	31.2	23.9	46.2	131.1
	6	4.1	18.1	22.6	20.4	29.3	94.6
	7	4.0	18.9	28.9	20.5	29.9	102.2
	8	4.4	16.1	23.5	23.6	27.7	95.4
	9	5.3	15.5	23.6	19.1	36.3	99.7
	10	4.8	13.6	21.9	18.8	39.9	99.0
	11	3.8	14.2	26.3	23.5	36.6	104.3
	12	7.0	22.1	25.5	23.3	43.3	121.2
Downbound Total		181.5	279.0	353.0	334.0	553.6	1701.1
Upbound	1		137.3	78.7	29.4	53.1	298.5
	2	29.0	145.2	61.3	291.2	29.3	556.0
	3	15.5	24.9	30.6	48.5	6.1	125.5
	4	16.0	19.2	18.5	49.2	4.1	107.0
	5	23.1	22.9	25.8	56.5	4.4	132.7
	6	17.3	21.5	15.9	36.6	3.5	94.8
	7	15.6	20.0	16.4	37.9	3.6	93.5
	8	14.9	21.6	17.4	43.5	4.2	101.6
	9	14.1	20.1	17.3	35.0	5.0	91.6
	10	11.9	15.4	16.7	46.0	4.4	94.4
	11	10.9	12.1	12.6	21.7	4.2	61.4
	12	16.3	19.1	17.7	24.0	7.9	85.0
Upbound Total		184.5	479.4	328.8	719.6	129.6	1841.9
Grand Total		366.1	758.4	681.9	1053.5	683.2	3543.0

Table 17 Mean Hours between Tow Vessel Arrivals by Direction of Travel and Month, 2000 through 2003

YEAR	*LOCK*	*Lockages*	*Total Vessel Wait Time (hours)*	*Total Vessel Lockage Time (hours)*	*Mean Wait Time (hours)*	*Mean Lockage Time (hours)*
2000	20	3,528	7,883	4,786	2.23	1.36
	21	3,704	6,686	5,086	1.81	1.37
	22	3,517	10,666	5,686	3.03	1.62
	24	3,800	8,304	5,391	2.19	1.42
	25	4,151	9,827	5,507	2.37	1.33
	Total	18,700	43,366	26,456	2.32	1.41
2001	20	3,164	6,113	4,107	1.93	1.30
	21	3,294	7,185	4,508	2.18	1.37
	22	3,162	13,882	4,966	4.39	1.57
	24	3,430	10,984	4,745	3.20	1.38
	25	3,841	15,810	4,829	4.12	1.26
	Total	16,891	53,975	23,156	3.20	1.37
2002	20	3,546	6,610	4,841	1.86	1.37
	21	3,708	5,266	5,077	1.42	1.37
	22	3,499	8,932	5,483	2.55	1.57
	24	3,742	14,479	5,438	3.87	1.45
	25	4,133	8,682	5,258	2.10	1.27
	Total	18,628	43,969	26,097	2.36	1.40
2003	20	3,126	4,393	4,203	1.41	1.34
	21	3,139	4,009	4,415	1.28	1.41
	22	3,000	5,977	4,803	1.99	1.60
	24	3,177	6,835	4,764	2.15	1.50
	25	3,519	5,950	4,728	1.69	1.34
	Total	15,961	27,163	22,914	1.70	1.44
Means All Years	20	3,341	6,250	4,484	1.86	1.34
	21	3,461	5,786	4,772	1.67	1.38
	22	3,295	9,864	5,234	2.99	1.59
	24	3,537	10,150	5,085	2.85	1.44
	25	3,911	10,067	5,081	2.57	1.30
	Total	17,545	42,118	24,656	2.39	1.41

Table 18 Vessel Lockages, Wait Times, and Lockage Times at UMR Locks Compiled from OMNI Data, 2000 through 2003

	N	Minimum (hours)	Maximum (hours)	Mean (hours)	Std. Deviation (hours)
Wait Time - All Vessels All Locks	100	32,531.47	55,099.77	40,942.23	4,682.06
Total Tow Time	100	171,696.58	199,140.45	182,834.99	5,657.53
Tow Time - Large Tows	100	109,396.61	132,129.86	118,937.60	4,861.36
Tow Time - Small Tows	100	60,031.55	67,468.85	63,897.39	1,581.48
Tow Wait Lock 20	100	4,178.51	8,149.14	5,508.74	749.87
Tow Wait Lock 21	100	3,822.53	7,014.62	5,150.77	634.79
Tow Wait Lock 22	100	5,801.72	11,920.32	8,662.97	1,408.49
Tow Wait Lock 24	100	6,170.31	19,965.69	9,787.61	2,221.42
Tow Wait Lock 25	100	6,664.81	13,924.74	9,965.10	1,566.70

Table 19 Selected Summary Statistics Compiled from 100 UMR Simulation Model Runs

Results of 100 Annual Simulations Compared with 2000 - 2003 OMNI Data

	Lock 20	Lock 21	Lock 22	Lock 24	Lock 25	Totals	Percent
Observed Lockages per Year	3,341	3,461	3,295	3,537	3,911	17,545	
Mean Simulated Lockages per Year	3,313	3,452	3,277	3,471	3,902	17,415	99.3%
Observed Wait Time per Year (hours)	6,250	5,786	9,864	10,150	10,067	42,117	
Mean Simulated Wait Time (hours)	5,763	5,462	9,004	10,185	10,528	40,942	97.2%
Observed Lock Usage per Year (hours)	4,620	4,868	5,367	5,262	5,273	25,390	
Mean Simulated Lock Usage (hours)	4,477	4,748	5,264	5,134	5,181	24,804	97.7%

Mean Annual Number of Tows Entering the System

	Lock 25 Up	Lock 24 Up	Lock 22 UP	Lock 21 Up	Lock 20 Up
Simulation	1,702.33	196.14	409.59	381.66	482.41
OMNI	1,695.25	193.00	409.00	387.25	482.50
Comparison	100.42%	101.63%	100.14%	98.56%	99.98%

	Lock 25 Down	Lock 24 Down	Lock 22 Down	Lock 21 Down	Lock 20 Down
Simulation	216.61	367.32	314.89	456.15	1,471.82
OMNI	219.75	357.00	306.50	482.50	1,471.75
Comparison	98.57%	102.89%	102.74%	94.54%	100.00%

Table 20 Selected Details of the Results of 100 UMR Simulations and Comparison with the 2000-2003 OMNI Data

Mean Number of Annual Complete Pool Transits by Tows

	Pool 25 Up	Pool 24 Up	Pool 22 Up	Pool 21 Up
Simulation	1,314	1,040	1,126	994
OMNI	1,305	1,031	1,113	998
Comparison	100.74%	100.94%	101.19%	99.55%

	Pool 25 Down	Pool 24 Down	Pool 22 Down	Pool 21 Down
Simulation	1,353	1,152	1,138	1,053
OMNI	1,350	1,155	1,145	1,055
Comparison	100.24%	99.81%	99.36%	99.76%

Mean Transit Times by All Tows

	Pool 25	Pool 24	Pool 22	Pool 21
OMNI Time	5.56	4.34	3.76	2.88
Simulation Time	5.41	4.31	3.76	2.95
Comparison	102.82%	100.52%	99.86%	97.67%

Table 20 (continued) Selected Details of the Results of 100 UMR Simulations and Comparison with the 2000-2003 OMNI Data

	N	Minimum (hours)	Maximum (hours)	Mean (hours)	Std. Deviation (hours)
Wait Time - All Vessels All Locks	100	31,062.22	53,470.08	36,634.54	3,783.58
Total Tow Time	100	170,606.51	196,562.82	178,466.11	4,422.38
Tow Time - Large Tows	100	111,702.22	139,504.35	121,592.09	4,626.93
Tow Time - Small Tows	100	52,803.52	59,410.97	56,874.02	1,025.80
Tow Wait Lock 20	100	3,815.54	8,211.37	5,230.26	825.97
Tow Wait Lock 21	100	3,659.05	6,232.74	4,758.34	461.81
Tow Wait Lock 22	100	5,766.83	12,605.38	7,991.90	1,246.89
Tow Wait Lock 24	100	6,009.74	13,661.27	8,746.56	1,527.49
Tow Wait Lock 25	100	6,250.73	11,928.92	8,037.93	1,079.87
Valid N (listwise)	100				

Table 21 Selected Summary Statistics Compiled from 100 UMR Simulation Model Runs with a Locally Optimal Queue Dispatch Policy.

	N	Minimum (hours)	Maximum (hours)	Mean (hours)	Std. Deviation (hours)
Wait Time - All Vessels All Locks	100	-1,469.25	-1,629.69	-4,307.69	-898.48
Total Tow Time	100	-1,090.07	-2,577.63	-4,368.88	-1,235.15
Tow Time - Large Tows	100	2,305.61	7,374.49	2,654.49	-234.43
Tow Time - Small Tows	100	-7,228.03	-8,057.88	-7,023.37	-555.68
Tow Wait Lock 20	100	-362.97	62.23	-278.48	76.10
Tow Wait Lock 21	100	-163.48	-781.88	-392.43	-172.98
Tow Wait Lock 22	100	-34.89	685.06	-671.07	-161.60
Tow Wait Lock 24	100	-160.57	-6,304.42	-1,041.05	-693.93
Tow Wait Lock 25	100	-414.08	-1,995.82	-1,927.17	-486.83
Valid N (listwise)	100				

Table 22 Selected Summary Results of Changes in Selected Variables Resulting from Employing a Locally Optimal Queue Dispatch Policy

Alternative	Incremental Benefits	Incremental Costs	Market Disruption
1. Existing conditions	none	none	none
2. Schedule appointments at locks			
Using existing available information	very small	very small	negligible
Using enhanced vessel tracking	very small	small+	negligible
3. Re-sequence vessels in local lock queues	small	very small	some
4. Re-sequence vessels in extended lock queues			
Using existing available information	small	very small	some
Using enhanced vessel tracking	small	small+	some
5. Re-sequence vessels in multiple lock queues			
Using existing available information	small	small	significant
Using enhanced vessel tracking	small	small++	significant
6. System-wide traffic management using enhanced vessel tracking	small	large	extensive

Table 23 Summary of Conclusions and Recommendations