Decision Tools for Reducing Congestion at Locks on the Upper Mississippi River

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Abstract

This paper describes the development of tools to support better scheduling and sequencing of barge tows on a congested portion of the Upper Mississippi River. Our study section covers 100 miles and includes five 600-foot long locks that handle commercial tows up to 1200 feet long. Due to the varying nature of the traffic and lockage times (especially the need to split long tows to pass through smaller locks), long queues may form at the locks. This paper provides an overview of our research, including evaluation of lock and traffic management policies, development of a detailed multi-lock simulation model, evaluation of decision rules for sequencing vessels in queues, and development of a prototype GIS-based vessel tracking system. Our findings suggest that better sequencing of vessels at locks would provide small improvements at current traffic levels, but may reduce waiting time by as much as 25% with increasing levels of demand.

1. Introduction

The purpose of this research was to develop decision support tools to examine and evaluate alternative traffic management policies designed to improve lockage operations in a congested segment of the Upper Mississippi River (UMR) navigation system. Our research stems from an ongoing policy debate in the U.S. concerning the multi-billion dollar proposal to replace several 600-foot long locks on the UMR with new 1200-foot long locks to reduce congestion and queues at locks. Before investing in new infrastructure, the US National Academies of Science recommended that less expensive measures be investigated, such as scheduling and traffic management [3]. Because existing models of river traffic and lock operations fail to capture the complexities of this environment, we developed a detailed simulation model to accurately model the stochastic two way (upstream and downstream) traffic patterns with differentiated vessel classes and dependent queues at adjacent locks. We used this model to evaluate rules for re-sequencing vessels in multiple lock queues on the most congested segment of the UMR. We also explored the potential benefits from deploying vessel tracking technologies on the UMR.

This paper provides an overview of our research efforts, and includes new results with increased levels of demand. The remainder of the paper is organized as follows. Section 2 provides relevant background information. Section 3 discusses alternative traffic and lockage management policies that could be deployed and Section 4 focuses on queue re-sequencing rules. Section 5 briefly describes the detailed simulation model we developed and Section 6 provides analysis of re-sequencing rules with different levels of demand. Section 7 provides a conclusion and some directions for future research.

2. Motivation

The UMR navigation system extends approximately 663 linear miles from just north of St. Louis, Missouri to just north of Minneapolis, Minnesota. It provides an important transportation artery into and out of America's Midwest and is a key link in the global supply chains for a variety of agricultural products originating in the U.S. Other products transported on the UMR include bulk commodities such as chemical products, coal, cement, and petroleum products. The total commercial tonnage shipped on the UMR in 2004 was 73.3 million tons. Products are carried on the UMR in large barges (typically 195-200 feet long and 35 feet wide) that can hold 1500 tons each. Barges are joined together into tows pushed by a single towboat. On the UMR tows are generally limited to 15 loaded barges (3 barges wide and 5 barges long) pushed by a 5,000 horsepower towboat. In the lower Mississippi River, downstream from St. Louis, there are no locks and river conditions often allow much larger tows with up to 40 barges (8 barges long and 5 barges wide).

Commercial traffic on the UMR is quite varied. For example, agricultural commodities generally travel downstream on the UMR (to New Orleans for export) through many locks in large 15-barge tows. This tends to generate upstream backhauls on the UMR of 15 or 16 empty barges being positioned for future loads. On the other hand, petroleum, chemical and construction products may travel through only a few locks between terminals in small tows of only one or a few barges. Towboats without barges also transit the system as they are repositioned for future trips.

Reliable navigation conditions are created in the UMR 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. The dams create a series of level pools and the locks allow vessels to pass through the dams.

Each lock includes at least one chamber in which the water level can be raised and lowered (typically 10 to 20 feet) to match the elevations of the pools above and below the lock and dam. The lock chamber includes gates at both ends to allow vessels to enter and exit. A lockage operation consists of a vessel entering the chamber, having the water level raised or lowered as needed, and then exiting the chamber. At each lock, vessels traveling upstream and downstream will form queues if the chamber is occupied. There are separate queues for the commercial barge tows and small private recreation vessels. The locks on the UMR are operated by the U.S. Army Corps of Engineers (Corps), with individual lockmasters at each lock having authority and responsibility for lock operations. (Towboat pilots have ultimate responsibility for maneuvering through the locks.)

Most of the original locks on the UMR were constructed with main chambers 110 feet wide and 600 feet in length to accommodate the largest commercial tows of the 1930's and 1940's. However, today most tows on the UMR are nearly 1200 feet long (the length of five barges plus the towboat) and 105 feet wide (three barges). Tows over 600 feet in length require a "double lockage" in which the tow is decoupled into two "cuts" to pass through the 600-foot locks.

For example, in an upstream double lockage for a 15 barge tow, the tow boat will push the first 9 barges into the chamber, decouple these, and back away with the remaining 6 barges. The first cut of 9 barges is then raised to the level of the upper pool, and the barges are winched out of the chamber and tied up along the guide wall adjacent to the chamber. The water level in the chamber is then lowered for the second cut. The remaining six barges plus the towboat then enter the chamber and are raised to the level of the upper pool. The tow then pushes the six barges out of the chamber and maneuvers them up against the first cut of nine barges, where they can be reattached. Once the tow is again comprised of all 15 barges, it can proceed upstream to the next lock – and repeat the procedure. Note that until the full tow is reconfigured and safely clear of the lock, it blocks the lock for downstream traffic.

Our study region includes the five southernmost 600-foot long locks in the UMR navigation system, Locks 20, 21, 22, 24 and 25 (there is no Lock 23) and the four intervening pools, covering 100 river miles. These five locks are among the most heavily utilized and most congested locks in the U.S. Current utilization of these locks is 70-85% during the main navigation season from April to November. The locks adjacent to our study region have already been expanded to 1200 feet in length and do not generally experience significant queues. Large waits at Locks 20–25 occur due to the seasonality of commercial traffic, periodic adverse operating conditions, the relatively lengthy time required to process double lockages, and periodic significant use by private recreational craft. In a congested period, commercial traffic on the UMR between Locks 20 and 25 might typically spend 3–10 hours traversing each pool, depending on the direction and length of the pool, several hours in queue at each lock, and 0.5–2.5 hours undergoing a lockage, depending on the condition of the lock and the type of tow. In extreme cases, the wait in a lock queue may be as long as 100 hours.

Increased traffic on the UMR navigation system would create substantial increases in congestion and delays at system locks, increasing tow transit times and possibly decreasing systemic efficiency. In response to the potential increasing levels of future lock congestion, the Corps initiated a feasibility study to examine increasing the size of the existing 600-foot long UMR locks to 1200-feet to eliminate the need for double lockages. This twelve year, $77 million feasibility study ultimately concluded in late 2004 with a recommendation that the 600-foot long lock chambers for Locks 20 – 25 (and others) be replaced with new 1200-foot long lock chambers at a cost of some $2.8 billion [15].

During this feasibility study, the National Research Council (NRC) of the National Academies of Science was engaged to provide an independent review. In a three report series culminating in 2005 [2,3,4] the NRC concluded that the Corps feasibility study was "unsuitable for use in making federal transportation policy" and instead suggested that the Corps evaluate making better use of the existing lock infrastructure before constructing larger locks. Among the policies they recommended for detailed evaluation were: lock scheduling or sequencing, lockage appointments, congestion related fees for lock use, tradable lockage permits, the use of helper towboats to quicken double lockages, and low cost structural measures such as lock guide-wall extensions. Our project evaluated lock re-sequencing, scheduling and appointment systems as a means to reduce lock congestion and improve towboat operating efficiencies.

As part of our research, we reviewed waterway operations around the world, seeking systems with a sequence of congested locks traversed by vessels with widely varying lockage times. While sequences of locks exist on several waterways, such as the St. Lawrence Seaway, the Panama Canal and European inland waterways, the vessels transiting these systems are single ships or self propelled barges and thus the lockage times do not have the wide variances seen on the UMR with different sizes of tows. We also reviewed waterway traffic management systems (TMS), including the ongoing European initiatives in developing comprehensive River Information Services (RIS). While many waterways (and congested ports) have TMS, these are employed primarily for navigational safety, not managing lockages.

The UMR also differs from other major U.S. rivers with sequences of locks, such as the Ohio River, in that locks on the Ohio River have already been expanded to 1200 feet. In addition, traffic patterns on the Ohio River are quite different than on the UMR, with year-round operations and considerable amounts of short-haul traffic (~250 miles) moving coal from mines to power plants. Thus, the UMR is unique in its combination of large multi-barge tows, small lock chambers (relative to the tows) and river conditions.

To better understand lockage operations and traffic on the UMR we analyzed lockage data from the Corps' OMNI database for calendar years 2000 through 2003 [7]. This database contains detailed timing information for each phase of a lockage as recorded by the lockmaster. This provides a rich source of data on operations at each lock, although substantial data cleaning and careful data mining were necessary to create reliable data for vessel operations throughout our study section.

The OMNI data for 2000-2003 contained 70,180 lockages at Locks 20-25, for an average of 3,509 lockages per lock per year. Approximately 86% of the lockages were for commercial tows with 14% being for other types of vessels (recreational, governmental, and passenger vessels). The breakdown of commercial tow lockages showed that 74.5% were double lockages, with 17.9% being single lockages of a towboat with barges and 7.6% being single lockages of a towboat without barges.

The lockage data showed a large variability in the distribution of lockage times due to the different types of vessels on the river. Figure 1 displays the distribution of lockage times and clearly shows the bi-modal distribution resulting from separate underlying distributions for double lockages (averaging about 2 hours), and single lockages.

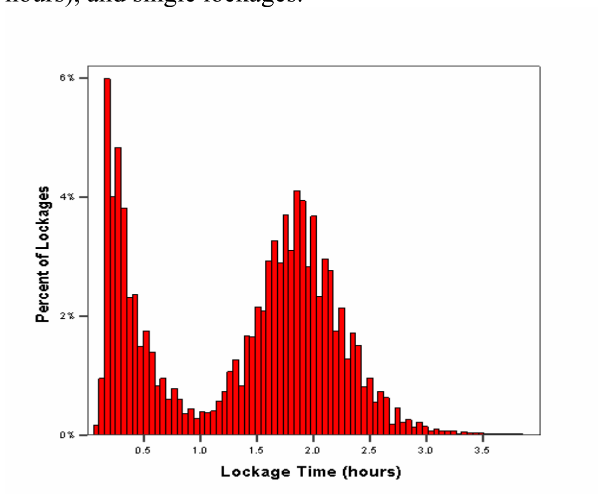

Figure 1. Distribution of lockage times, UMR locks 20 through 25 for 2000-2003

If vessels arrive at a lock while it is occupied they wait in a queue until the lockmaster indicates it is their turn for service (lockage). Currently, vessels travel throughout the UMR in an unscheduled fashion at their own pace, with commercial traffic responding to market demands, and recreational traffic peaking during mid-day and on weekends. Commercial vessels approaching a lock will radio ahead to the lockmaster when they reach a designated call-in point on the river. At this time they may be instructed to proceed to the lock if it is unoccupied, or placed in a queue if the lock is not available. Four different vessel queues are maintained at the lock – with separate physical queues for recreational and commercial vessels in the upper and lower pools.

The current Corps policy for managing lockages is to process vessels at each lock on a first-come, first-served basis, with the exception that recreation vessels receive priority in that they wait no longer than three commercial lockages before receiving service. In actual operations, recreational vessels and some single vessels are often processed earlier than indicated in the policy and as soon as practicable after their arrival. When excessively large queues form at a lock, the Corps and industry representatives may coordinate in deciding the best sequence of lockages to clear the queues.

The data analysis showed the mean waiting time for a lockage was 2.4 hours for all vessels, although a significant portion of vessels (approximately 31%) were processed with little or no wait and approximately 10 percent of vessels waiting six hours or more in queue. The average waiting time at Locks 20-25 for commercial tows was 2.8 hours per lockage, which is slightly longer than the mean wait time for all vessels due to the priority given to non-commercial lockages.

One key finding from our analysis was that this subsystem of the UMR never achieves a steady state as the vessel arrival rates change significantly throughout the calendar year. Traffic and lockages on the UMR annually build from a very low level in the Winter to a peak level in late Summer, and then decline through the Fall back to a very low level in Winter, when ice and adverse operating conditions curtail operations and nearly all towboats and barges relocate to other rivers where they can continue productive operations.

Analysis of lockage data also indicated that recreational lockages and single commercial lockages respond to traditional weekly business schedules and thus reflect significant day-of-week and time-of-day effects. In contrast, the commercial double lockages show little day-of-week and time-of-day effects due to the long-haul nature of their operations. These dynamic behaviors render steady state models and steady state queuing system approximations as unsuitable for these five locks.

3. Traffic and lockage management alternatives

The Corps is interested in new policies for managing traffic and lockages to reduce congestion and waiting times and to improve throughput of the locks. The current first come, first served (FIFO) policy for commercial traffic is equitable, but it does not lead to efficient use of the limited infrastructure. Some research suggests potential savings from rules that sequence tows based on expected processing times [13,14]. Consequently, we considered an array of potential traffic and lockage management policy alternatives for the UMR navigation system.

The least intrusive traffic and lockage management policy for the UMR is to maintain the existing policy, which is essentially first-come, first-served, with the exception that recreation vessels receive some priority. This policy allows vessels to continue to operate independently, arriving at locks whenever they choose.

The new policy alternatives considered fall in three broad categories: appointment systems, re-sequencing policies, and comprehensive system-wide traffic management. These alternatives are described briefly in this section in order from least intrusive to most intrusive with respect to their effect in altering current operating practices on the UMR system. See [7] and [8] for more details.

A relatively unobtrusive traffic and lockage management policy is to provide appointments for vessels at the locks during periods of congestion. Upon departure from a lock or terminal, vessels could be given an appointment time at the next lock in their journey. The appointments could be updated as the system changes and the vessel progresses towards the lock, possibly using 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 conserve fuel or undertake other productive activities knowing that their appointment at the lock is secure.

More intrusive traffic and lockage management policies could re-sequence vessels in queues to produce a better solution than the existing Corps policy. This re-sequencing of vessels can be designed to take advantage of possible efficiencies from certain sequences and of the differential economic value of completing individual vessel lockages. The "most valuable" or "most efficient" vessels would typically go to the head of the queue, thereby passing the other "less valuable" or "less efficient" vessels. A local queue re-sequencing policy would treat each lock independently and sequence vessels without regard for the effects created at adjacent locks. A broader queue re-sequencing policy could include "extended lock queues", comprised of vessels currently in queue at a lock along with vessels traversing the adjacent pools upstream and downstream headed to that lock. Again, the "most valuable" or "most efficient" vessels would go to the head of the queue, if they are able to arrive in time for locking.

A more sophisticated traffic and lockage management policy could further broaden the scope of vessels managed by considering queues at multiple system locks simultaneously. In a multiple lock, coordinated, re-sequencing policy, the "most valuable" or "most efficient" vessels might receive expedited lock service at multiple system locks, if they are able to arrive in time and if they are headed to another relatively un-congested lock. Alternatively, vessel priorities might be determined by surcharges. The best multiple lock coordinated re-sequencing policy could be quite complex because of the interactions between locks.

The most intrusive traffic and lockage management policy alternative that we considered is system-wide traffic management with vessel tracking to continually monitor and manage river traffic. The operation of such a system could be similar to current air traffic control systems for all commercial vessels.

Each of the traffic and lock management alternatives described above could be implemented on the UMR, though the various alternatives require quite different costs and levels of organizational and market disruption. The costs could be relatively small to implement a simple appointment or queue re-sequencing system that uses only the existing data at each lock independently. More elaborate lockage management alternatives could require tracking vessels in real time and developing and implementing software to create a lockage management information system (LMIS) that facilitates traffic control. The inputs for such an LMIS may include existing static or dynamic data sources, along with new sources such as a vessel tracking system and automated river condition monitors (e.g., to detect flow rates, wind, fog, etc.).

Note that although vessel tracking is common in maritime (deep-water) operations and in congested port areas, and automated position reporting via automated Identification Systems (AIS) is now mandated on nearly all international commercial voyages, the Corps is not engaged in vessel tracking on the UMR. In our review of vessel tracking, we noted that real time tow tracking is certainly feasible on the UMR – and is currently in use by larger carriers for their own fleet of towboats (for internal operational purposes), and to a limited extent by the Coast Guard for tracking hazardous cargos. While tow tracking on the UMR would provide more accurate locations of the tows to help in better managing lockages (or in support of broader traffic management measures), a host of organizational and data ownership issues would need to be addressed before tow tracking could be implemented. The primary motivation for existing vessel traffic management systems, such as along the St. Lawrence Seaway or the Panama Canal, is navigational safety and security, not managing lockages for improved efficiency.

In our research we also developed a prototype vessel tracking geographic information system (GIS) to provide sample displays that demonstrate the functionality possible from vessel tracking on the UMR. The prototype includes static views of geographic and attribute (tabular) data, along with dynamic views to show tows moving on the UMR. The availability of electronic navigation charts for the UMR and other spatial databases within the Corps facilitates the base mapping required. The prototype system is built using the ArcMap 9.0 geographic information system (GIS) with the Tracking Analyst extension for managing the dynamic tow locations (both are software products of ESRI, Inc.).

The costs to develop and implement a lock management information system, including vessel tracking, would depend on the underlying traffic and lockage management alternative being implemented and the geographic region for implementation. A comprehensive traffic and lockage management information systems for the UMR would likely cost several million dollars to develop and implement (though this would likely still be small relative to the market for transportation on the UMR which has been estimated at $350-500 million per year [7]).

Disruptions to the market from implementing a new lockage or traffic management policy can range from very small, such as requiring commercial tows to inform lockmasters of their expected time of arrival earlier than they currently do so – to very large, such as requiring commercial tows to schedule their entire itinerary before they receive permission from a water traffic controller to begin any movement in the UMR system. Further, the implementation of alternative traffic management policies can have differential effects for commercial towing firms using the system. The implementation on the UMR of a LMIS with vessel tracking would also introduce significant changes and disruptions in a relatively unregulated mode of operations. However, a comprehensive system would likely produce benefits for security and the environment that extend well beyond reducing congestion from better managing lockages.

Each of the alternatives described in this section is feasible to implement on the UMR. However, our abilities to evaluate the primary benefits of appointment policies (e.g., fuel savings from altering the speed of vessels) were limited by the lack of data on tow performance characteristics, and a lack of cooperation from the industry. In addition, the large variances in lockage times and the dynamic nature of industry operations limit the prospects for simple appointment systems. (A more complex appointment system that utilizes tradable time-slot permits for lockages has been investigated in [10].)

Because traffic patterns from the past 15 years indicate a declining level of traffic and lock utilization [7], we chose to first focus attention on local lock queue re-sequencing policies. The declining traffic levels suggest that the incremental efficiencies afforded by policies that coordinate traffic management between multiple locks would likely be very small with current traffic levels. Additionally, the added costs and organizational issues surrounding large scale vessel tracking on the UMR suggest that simpler policies that rely on existing information should be investigated first. Therefore, we undertook a detailed economic evaluation of queue re-sequencing policies that attempt to improve the operation of the locks separately.

4. Queue re-sequencing rules

Queue re-sequencing on the UMR can be quite complex and challenging because of the interdependencies between locks and between subsequent lockages at the same lock. (See [9] for a discussion of sequencing and scheduling literature relevant to queues on the UMR.) Even at a single isolated lock, the appropriate sequencing of vessels from the four queues is complicated because the time for a lockage depends on the previous lockage and direction. Three types of lockages are possible. An "exchange" lockage occurs when a vessel enters the chamber after waiting for the completion of lockage by a vessel traveling in the opposite direction. Thus, the water level in the chamber is the same for the exiting and entering vessels, but the entering vessel must wait for the exiting vessel to clear the lock area before it is safe to enter. A "turnback" lockage occurs when a vessel enters the chamber after waiting for the completion of lockage by a vessel traveling in the same direction – and a recycling (turnback) of the lock to bring the water level back to the level of the pool in which the vessel is waiting. A "fly" lockage occurs when a vessel arrives to an empty lock chamber which has been set at the appropriate level to allow the vessel to enter without waiting. For each type of vessel (double lockage commercial, single lockage commercial with barges, single lockage commercial with no barges, recreation, etc.) the lockage time distribution is seasonally dependent and different for each of the three lockage types for each of the five locks in each direction (upstream and downstream).

To evaluate the potential benefits from re-sequencing vessels in a queue we considered six alternative rules for selecting the sequence of vessels for lockage. Recall that each lock is served by four queues, with separate queues in each direction for the commercial tows and the recreational vessels. At each lock, the next vessel for lockage was selected from the front of one these four queues. In some alternatives the queues maintained a FIFO sequence for each vessel type and direction; in other alternatives the queues were sequenced in a more efficient manner so that later arriving vessels were inserted ahead of vessels in queue.

The alternative re-sequencing rule that most closely matches the prevailing Corps policy is denoted FIFORECPRIO, a first-in, first-out policy where priority is given to recreational vessels. However, our analysis of the actual operations as recorded in the Corps' OMNI database indicated that a modified form of this policy, denoted SINGPRIO, may better reflect current practice. SINGPRIO gives priority to recreational vessels as in FIFORECPRIO, but it also gives priority among commercial vessels to single tows (including towboats without barges) that can be locked without a reconfiguration. Thus, SINGPRIO captures some aspects of current Corps locking operations, though FIFORECPRIO more closely represents the stated Corps policy. For comparison we also considered a pure first-in, first-out policy, with no priorities, denoted FIFO.

To find the best sequence for lockages at one lock with an existing queue of vessels, we proposed that vessels queued at a lock be sequenced in a manner that would be expected to clear the existing queue in the minimum amount of time. This is formulated as an integer programming problem in [9], using the *expected* lockage times for towboats and for lockages of various types. For the UMR, the optimal solutions could be derived by complete enumeration for queues of reasonable length. Results showed that the optimal sequence derived from historical UMR data (ignoring variances in time estimates) generally placed the "most valuable" or "most efficient" vessels (fastest expected lockage time) at the head of the queue. This re-sequencing principle of selecting the vessel with the minimum expected lockage time underlies the other alternative re-sequencing rules.

The rule denoted FLT (fastest lockage time) re-sequences vessels in each queue in order of their expected locking times (not FIFO) and the next vessel to lock is selected while considering whether the immediate lockage operation can be completed more quickly with a turnback or exchange, considering the additional time involved in turning back the lock and the differences in locking times for the best upstream and downstream candidates. A simpler rule denoted FIFOFLT maintains each queue in FIFO sequence, but the next vessel for lockage is selected as the vessel at the front of one of the four queues with the minimum expected lockage time. One other rule, denoted JPRIO, was also considered. This rule was more complex in treating different configurations of barges at the four separate queues.

While the FLT rule would perform best with static data (expected lockage times), in practice the sequencing problem is dynamic and is subject to error as random events (including normal operations with normal operating variance) occur. Thus, we developed a detailed simulation model to investigate how this dynamic system might operate under the alternative sequencing rules. Note that while a re-sequencing policy may reduce waiting times, it will also create inequities (economic winners and losers) in that some individual operator's vessels are advantaged and others are disadvantaged by the re-sequencing.

5. Simulation model

This section briefly describes the development and validation of a discrete-event simulation model to investigate the impact of alternative decision rules for lockage operations in a congested section of the UMR navigation system. Details on the simulation model are found in [11]. The simulation model was designed to accommodate the complexities and dynamics of operations on the UMR, including commercial vessels with different barge-tow configurations and different seasonal activities, and recreational vessels whose activities are highly dependent on time of year, day of week and time of day. The distributions of the lockage times, the times to transit the pools and the arrival patterns of vessels are derived from recent historical data collected by the Corps.

Discrete-event simulation has been used to study the behavior of many different transportation systems, including inland waterway movements and lockage activity (for example, [1,5,6,12,16]). However, existing models for U.S. inland waterways generally have employed analytical approaches or simplifying assumptions (such as steady-state methods) that fail to accurately model the details of operations of the UMR system. To better capture the dynamic nature of the UMR navigation system, we developed a detailed simulation model using ARENA 10.0. The model accommodates multiple classes of traffic with different arrival patterns at the locks, as well as different itineraries and service characteristics. It captures the physical realities of upstream and downstream traffic movements and provides for queuing and lockage operations with dynamic service priorities. The model provides detailed measures of system performance across the study region and accommodates different levels of traffic and different operating characteristics at each lock. It also facilitates tests of statistical significance of observed effects on system performance. The model uses several hundred statistical models to produce the time-varying parameters that drive system performance. These are described in [11], along with validation of the simulated performance against historical data.

The simulation model includes six different classes of vessels on the UMR, differentiated by barge configurations and related locking characteristics. These are:

1. double tows (tows that require double lockages), with an average lockage time of 117 minutes;
2. jackknife tows (tows that must be partly disconnected to fit in the lock chamber), with an average lockage time of 82 minutes;
3. knockout tows (tows for which the towboat must be disconnected from the barges and reconnected after following the barges through the lock), with an average lockage time of 63 minutes;
4. singles (tows that require a single lockage without reconfiguration), with an average lockage time of 33 minutes;
5. singles without barges (towboats without barges, or other non-recreational (e.g., Corps) vessels), with an average lockage time of 24 minutes; and
6. recreational vessels, with an average lockage time of 14 minutes.

The study section of the UMR is modeled as a network of five service facilities (lock chambers) and queues. Each lock is a single server (the lock chamber) with four queues (for upstream and downstream commercial and recreational traffic). For details on the structure of the simulation model and calibration of the hundreds of regression and logistics models used to estimate relevant values for the arrival process, lockages and pool transits see [11]. The model also incorporates periods of impaired lock operating conditions caused by adverse river conditions or lock or vessel failures that interfere with lock operations. These are imposed randomly and independently at each lock at seasonally varying rates.

Because the locks are surrounded by different terrain, have different approach conditions, experience different river conditions, and handle different mixes of traffic, each lock is unique and the parameters for lockages at each lock are generated to reflect the local conditions and local traffic. Equations that determine base-line parameters for the model were derived using a series of statistical models calibrated with year 2000 data from the Corps' OMNI database. The year 2000 was selected as the most congested year, and the most representative of operations without unusual impairments present in some of the other years.

To validate the model we compared results using the FIFORECPRIO rule with 100 years of simulated operations to the actual system performance in 2000. We noted excellent correspondence between the simulated and historical data for all relevant performance measures (average monthly number of lockages upstream and downstream at each lock, lockage times for the different tows and vessels at each lock upstream and downstream, and utilization statistics and queuing statistics at each lock) at the individual lock level and in aggregate. Simulated monthly, weekly and daily seasonal patterns also closely approximated the recorded year 2000 patterns and the model appeared to perform very well in imposing the systematic periodic effects on the arrivals.

6. Analysis of re-sequencing rules

We examined performance of the simulated system under the six different re-sequencing rules described earlier. The model was used to simulate operations with each rule using 100 replications (years) of a given level of traffic. Table 1 summarizes selected results (from [11]) by type of vessel lockage for four of the alternative sequencing rules using the current level of traffic. Under FIFORECPRIO which reflects the current stated policy, the average waiting time in queue for all lockages is almost 2.5 hours (146.7 minutes). SINGPRIO, which best reflects current practice, reduces the overall average waiting time by about four minutes, with substantial reductions for the single tows that can be locked most quickly, at the expense of about an 11 minute increase in waiting times for double lockages. FIFOFLT provides the same overall average waiting time as SINGPRIO, but with a much different distribution of waiting times among vessel classes. FLT provides the lowest overall average waiting time – and the lowest waiting times for each class of vessels except double lockages. However, the overall average wait time savings with FLT is rather small.

Type	FIFORECPRIO	FIFOFLT	SINGPRIO	FLT
Double	162.9	165.6	174.1	170.6
Jackknife	183.5	144.5	191.6	101.3
Knockout	172.6	177.4	184.3	112.4
Single	163.9	138.7	100.8	94.6
Singles without barges	157.8	120.3	91.8	86.1
Recreation	49.1	48.3	49.1	48.3
All Lockages	146.7	142.5	142.5	136.6

Table 1. Average waiting times (minutes) in study region over 100 simulated years of operation with current demand

In summary, the FLT policy would reduce expected waiting times by approximately ten minutes (about 7%) relative to FIFORECPRIO, though the majority of vessels, which are large tows requiring double lockages, would experience small increases in waiting times. The shift to benefit the vessels that can be locked most quickly at the expense of those vessels that take longer is quite clear in the results. Relative to SINGPRIO, FLT would reduce expected waiting times by about six minutes (about 4%). Tests of statistical significance confirmed that the impact of using alternative priority rules depended on the lock involved and on the direction of traffic.

We also evaluated several re-sequencing alternatives with 10% and 20% increases in the level of demand (keeping the same mix of vessel and lockage types) and results are shown in Table 2. These results demonstrate the increasing benefits of FLT as demand increases, especially for the single tows. With a 10% increase in demand, FLT reduces overall average waiting time by about 25 minutes (about 10%) and about 36 minutes (about 14%) versus SINGPRIO and FIFORECPRIO, respectively. With a 20% increase in demand, FLT reduces overall average waiting time by around 3 hours (about 25%) compared to SINGPRIO and FIFORECPRIO.

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

Table 2. Average waiting times (minutes) in study region over 100 simulated years of operation with increased demand

The distribution of waiting times under different re-sequencing rules is also an important measure of performance. Table 3 provides the median and 95th percentile of waiting times for the rules in Table 2 with a 20% increase in demand. In general FLT reduces the median waiting time substantially relative to FIFORECPIO and SINGPRIO. For example, with a 20% increase in demand, the median waiting times for double lockages are over 5.5 hours with FIFORECPIO and SINGPRIO, but under 3 hours with FLT. However, the 95th percentile of waiting times for double lockages with all three of these rules is over 60 hours; indicating that some vessels will wait a very long time in such a congested system.

The time savings from the FLT re-sequencing rule can be translated into economic benefits using the year

2000 price level value of approximately $170 per tow hour [7]. The time savings from FLT, relative to FIFORECPRIO, equate to about $100,000 annually under current levels of traffic, $420,000 annually with a 10% increase in traffic and $2.5 million annually with a 20% increase in traffic.

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

Table 3. Median and ninety-fifth percentile of waiting times (minutes) in study region over 100 simulated years of operation with 20% increase in demand

Table 2 also shows the increasing wait times expected in a congested system like the UMR as demand increases. With a 20% increase in traffic, even under FLT, the average waiting times exceed nine hours and the average waiting time for double lockages exceed 13 hours. With this level of traffic, more sophisticated traffic and lockage management policies might provide some additional benefits, though in such a congested system, there may be little that can be done operationally to prevent waiting times from far exceeding current levels.

7. Contributions and conclusion

Our research has developed tools that could help reduce congestion and lock queues on the Upper Mississippi River. We identified a range of traffic and lockage management alternatives that could be deployed and we evaluated several queue re-sequencing policies in detail using current and increased levels of demand. To evaluate these rules we developed a detailed simulation model that accurately captures the dynamics of operations on the UMR. We also developed a prototype vessel tracking system for the UMR to demonstrate the types of capabilities that could be deployed to assist in broader scale traffic management.

Our results suggest that at current traffic levels, the savings from re-sequencing queues of vessels on the UMR would be rather small (about $100,000 annually), and these benefits would be distributed quite unevenly, with some users disadvantaged by new policies. Furthermore, vessels will likely adapt to traffic and locking operations and unscheduled lockage impairments will certainly occur (as in the past). These factors will tend to reduce the actual benefits below the levels that we have found. Considering the equity tradeoffs involved and the fact that the time that vessels spend in this section of the river constitutes a very small portion of their overall annual operating times, we conclude that there is insufficient justification to introduce new sequencing rules at current traffic levels.

Under greater traffic levels, the benefits from re-sequencing increase substantially, as do the waiting times. According to the "Central Trade Scenario" forecast of traffic on the UMR in [15], demand could increase by some 20% during the next two decades. Our results suggest that with a 20% increase in demand, annual cost savings of $2.5 million are possible from better sequencing of vessels in queues – but also that long queues will remain with this level of demand.

If traffic levels dramatically increase or lock performance dramatically degrades, implementing new traffic and lockage management policies could yield significant economic benefits that potentially outweigh the costs of disruptions on the UMR. More sophisticated traffic and lockage management systems and policies could be implemented (analogous to that for air traffic control), though it would be a daunting task – perhaps more from a legal and organizational perspective, than from a technological perspective. Such systems with real time vessel tracking could lead to additional efficiencies in operations, as well as contribute to improved safety, security, and environmental protection.

With very high levels of demand, new traffic and lockage management policies would be insufficient to alleviate congestion and infrastructure improvements may be appropriate, though these have a very large cost ($2.8 billion for new locks on the UMR) and a several decade long time frame for construction.

Our results with increased traffic levels highlight the important role of forecasting long term demands for system use – and forecasting long-term demand for the UMR has proven very difficult. From the opening of the UMR system in the 1930's up until the 1980's, traffic increased at about the rate of GDP growth in the U.S. Since the 1980's, however, traffic on the UMR (and on U.S. inland waterways overall) has been flat. Forecasting long-term demand for inland waterway transport on the UMR depends on a wide variety of future developments around the world, including such diverse issues as the market for grain in Asia, new competing production from South America and Eastern Europe, ethanol production and consumption in the U.S. and overseas, tariffs and subsidies for various products, availability and reliability of alternate transportation modes such as rail to west coast ports, etc.

Future areas of research (some underway) include modifications to the simulation model and consideration of new rules and traffic management policies. The simulation model provides a robust and accurate tool that could be used for a variety of analyses to consider new rules that increase the priorities for vessels that have experienced long waits, coordinated policies that manage multiple locks together, performance with new 1200 foot lock chambers, new operating policies that shift the mix of vessels to decrease the number of double lockages, and further increases in the level of demand.

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