A Robust Strategy for Managing Congestion at Locks on the Upper Mississippi River

James F. Campbell, L. Douglas Smith, Donald C. Sweeney II, College of Business Administration, University of Missouri-St. Louis
campbell@umsl.edu, ldsmith@umsl.edu, sweeneyd@msx.umsl.edu

Abstract

The Mississippi River is an important waterway in national and global supply chains, especially for agricultural commodities. The tools available for managing traffic congestion on the Upper Mississippi River (UMR) include operational policies such as sequencing vessels at locks, tactical decisions such as using helper boats to speed lockages, and strategic decisions such as constructing new larger locks. We describe the use of our detailed multi-lock discrete event simulation model to evaluate operational, tactical and strategic congestion mitigation measures for the UMR. With a focus on policy issues surrounding lock expansion, we evaluate the national net economic benefits of different congestion mitigation measures and identify a robust strategy for implementing measures that maximizes the national net economic benefit. We also highlight the importance of traffic forecasts for future inland waterway infrastructure investments.

1. Introduction

Traffic congestion is a significant problem for many transportation modes in modern economies. It can be addressed through a variety of measures, requiring often contentious and difficult public sector decision-making at the operational, tactical and/or strategic levels. For example, road traffic congestion may be addressed through operational decisions involving traffic signal timing adjustments; tactical decisions such as replacing stop signs with traffic signals or revising pavement markings; or more strategic decisions such as adding new lanes or building new roadways. The effectiveness and desirability of each of these options depends on the amount of traffic and the cost of the changes. As traffic increases, it may be optimal to move from simpler inexpensive operational measures to more intrusive and expensive strategic capacity expansions.

While inland water transportation may be less familiar than road transportation, options for relieving congestion include similar operational, tactical and strategic decisions. This paper illustrates a process for evaluation of the net economic benefit afforded by the increased productivity of transportation assets on the Upper Mississippi River and shows how such analysis may be used to develop a robust strategy for implementing navigation system improvements to maximize net economic benefits. We use system performance statistics from our detailed discrete simulation model [6,7] and extends work described in the companion paper [8] that analyzes re-sequencing policies at locks.

The remainder of this paper is organized as follows. Section 2 provides relevant background information. Section 3 briefly describes our simulation model and Section 4 presents the analysis of congestion reduction measures. Section 5 discusses implementation strategies and policy implications, and Section 6 is the conclusion.

2. Motivation and Background

The Mississippi River navigation system extends over 1800 miles from the Gulf of Mexico to Minneapolis-St. Paul, Minnesota. It is an important transportation artery into and out of America’s Midwest and a key link in the global supply chains for U.S. agricultural products, especially corn and soybeans. Products are carried in barges (typically 195-200 feet long and 35 feet wide) that can hold approximately 1500 tons each. Barges are joined together into tows pushed by a single powerful towboat.

The Upper Mississippi River (UMR) is the portion of the river extending from the mouth of the Ohio River to just north of Minneapolis-St. Paul, Minnesota. The UMR navigation system includes a series of 29 lock and dam facilities that provide reliable commercial navigation by maintaining a usable
channel depth of nine feet, that allows vessels to navigate the approximately 300 foot elevation difference. On the UMR, tow sizes are generally limited to 15 barges (5 barges long and 3 barges wide) due to navigation channel conditions.

The dams on the UMR have transformed the river into a series of level pools, and each dam includes one or two locks that allow vessels to pass through the dams. Commercial vessels are nearly always locked individually, while groups of recreational vessels may be locked together. The lock and dam system on the UMR was initiated over 75 years ago and most of the original locks were constructed with chambers 110 feet wide and 600 feet in length to accommodate the largest commercial tows of the 1930’s and 1940’s.

Transportation economies of scale have led to the increased use of large barge tows near 1200-feet long (the length of five barges plus the towboat) and 105 feet wide (three barges). These large tows must be decoupled into two sections for transiting the 600-foot long locks, and then re-coupled following lockage. These “double lockages” require almost two hours on average (compared to about 30 minutes or less for smaller “single lockage” tows and recreational lockages) and have been cited as a “key contributor to chronic delays” at locks on the UMR [5]. With large increases in the level of traffic, a large percentage of double lockages could cause considerable congestion at locks on the UMR and substantial levels of lost productivity.

The locks on the UMR are constructed and operated by the U.S. Army Corps of Engineers (USACE). In 1993, the USACE began a detailed Navigation Feasibility Study for the UMR that recommended replacing five 600-foot long locks on the UMR with 1200-foot long locks at a cost of $2.2 billion to eliminate the need for double lockages [14]. During this study, the National Research Council (NRC) was engaged to provide an independent review, from which they concluded that “economic justification of proposed lock extensions on the UMR … has not been established” and suggested that the USACE evaluate making better use of the existing lock infrastructure before constructing larger locks [5]. The NRC suggested a variety of operational and tactical policies that might be evaluated.

Responding to NRC suggestions, the USACE engaged us in 2004 to evaluate lock queue resequencing, scheduling, and traffic management systems for the UMR [3,4]. Our initial research developed a detailed multi-lock discrete-event simulation model to evaluate local lock queue resequencing policies [6,7]. Other studies have developed waterway simulation models for analyzing operational changes and infrastructure investments (see for example, [1,2,9,15]). However, the existing models for U.S. inland waterways generally have employed analytical approaches or simplifying assumptions (such as steady-state methods) that fail to capture the extreme seasonality of operations in the UMR system. Further, most earlier studies have also treated the traffic at individual locks as independent of each other. This is not appropriate since much of the traffic at one lock continues on to subsequent locks.

For any proposed inland navigation infrastructure project, the USACE is mandated to assess its net national economic development (NED) benefits by evaluating the project’s performance over a 50-year planning horizon [16]. Our research is aimed at better quantifying the NED benefits through a more detailed analysis of UMR traffic with different navigation system improvements.

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 connecting pools, covering some 100 river miles just north of St. Louis, Missouri. The locks in our study section form a bottleneck and are among the most heavily utilized and congested locks in the U.S. [3]. The locks immediately upstream and downstream from our study section have already been expanded to 1200 feet in length and are generally uncongested [3].

Traffic in the study region includes large 15-barge tows of agricultural commodities headed downstream for export, backhauls of empty barges being positioned for future loads, small tows of one or a few barges traveling between local terminals, towboats without barges being repositioned, and private recreational craft. The annual total tonnage shipped on the UMR has ranged from 69 million to 85 million tons over the decade 1996-2005 [13], with the majority heading downstream.

Congestion related delays at Locks 20–25 arise from the seasonality of commercial traffic, occasional adverse operating conditions, the lengthy time required to process double lockages, and periodic significant use by recreational craft. In a congested period, commercial traffic in our study region might spend 3–6 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 type of tow. In extreme cases of extended lock closure, the wait in a queue has been as long as 100 hours.

Analytical research on the UMR navigation system is hampered by the limited data on vessel movements. Commercial (and recreational) trips on the UMR follow no set itinerary or schedule, and vessels arrive at the locks in an unscheduled manner. The USACE does collect some traffic data at the locks, along with
limited information on the tow itself. However, individual barges (and tows) are not tracked in real time by the USACE, so that constructing individual itineraries for origins to destinations along the river is problematic. We undertook our data analysis and modeling with a specific focus on activities at the locks and the waiting times in lock queues for three main reasons: (1) the USACE focus is on activities at the locks themselves, (2) the industry is reluctant to provide detailed vessel itinerary data, and (3) congestion is not an issue in the pools between locks.

To undertake our analysis for the UMR (in 2004), we acquired data from the Institute for Water Resources of the USACE for calendar years 2000 through 2003. From these data we documented the strong monthly, daily and hourly seasonality of operations on the UMR, described in detail in [7]. These dynamic behaviors render steady-state queuing system approximations and methods unsuitable for these locks.

The lockage data for 2000-2003 included 70,180 lockages in our study region and showed a large variability in the distribution of lockage times. Figure 1 shows the bi-modal distribution resulting from separate underlying distributions for double lockages (averaging about 2 hours), and single lockages (averaging under 0.5 hours). Further analysis of the lockage data revealed six classes of vessels on the UMR differentiated by barge configurations and related locking characteristics. These are: double tows (tows that require double lockages), jackknife tows (tows that must be partly disconnected to fit in the lock chamber), knockout tows (tows for which the towboat must be disconnected from the barges and reconnected after following the barges through the lock), single tows (tows that require a single lockage without reconfiguration), single tows without barges (towboats without barges, or other non-recreational vessels), and recreational vessels.

Table 1 provides the percentage of lockages and the mean lockage times for each of the six types of vessels. The data revealed that the mean waiting time for a lockage was 2.4 hours, with approximately 30% of vessels having little or no wait and approximately 10% of vessels waiting six hours or more in queue.

<table>
<thead>
<tr>
<th>Vessel type</th>
<th>% of Lockages</th>
<th>Mean Lockage Time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double</td>
<td>63.7</td>
<td>117</td>
</tr>
<tr>
<td>Single</td>
<td>11.4</td>
<td>33</td>
</tr>
<tr>
<td>Single-no barges</td>
<td>6.5</td>
<td>24</td>
</tr>
<tr>
<td>Recreation</td>
<td>14.5</td>
<td>14</td>
</tr>
<tr>
<td>Jackknife</td>
<td>1.7</td>
<td>82</td>
</tr>
<tr>
<td>Knockout</td>
<td>2.2</td>
<td>63</td>
</tr>
</tbody>
</table>

3. Simulation Model

To investigate the performance of the UMR system with alternative congestion management tools, we developed a discrete-event simulation model using ARENA 10.0 that incorporates the time-varying dynamics of traffic movements and the complexities of lockage operations on the UMR [6,7]. It accommodates commercial vessels with different barge-tow configurations and recreational vessels, while allowing for the systematic changes in traffic and in the probability distributions of lockage and pool-transit times that occur throughout the year. The model captures the physical realities of upstream and downstream traffic movements and provides for queuing and lockage operations with dynamic service priorities. The model also provides detailed measures of system performance and facilitates tests of statistical significance of differences in system performance.

Several hundred statistical models are used to produce the time-varying parameters that drive system performance. To provide the appropriate mix of arrivals at each lock (reflecting the observed seasonality) we employed nonstationary exponential distributions with complementary intensification and thinning mechanisms. The vessel itineraries were generated probabilistically to capture the time-varying likelihoods of tows either terminating a trip in the current pool or continuing on to the next lock.

The basic structure of the simulation model with five locks connected by four pools is shown in Figure 2. At the completion of a lockage, each commercial vessel may continue to the next lock (horizontal arrow in Figure 2) or terminate its trip in the current pool (diagonal arrows leaving a lock in Figure 2).
Commercial vessel arrivals at each lock may originate from a terminal in the adjacent pool (diagonal arrows entering a lock in Figure 2) or from the previous lock (horizontal arrows in Figure 2). Because lockmasters do not record identifying data for recreational vessels, the model for recreational vessels includes no through traffic (horizontal arrows as in Figure 2). Each lock is modeled as a single server with four queues as shown in Figure 3. There are separate designated waiting locations (termed mooring buoys) upstream and downstream from each lock for recreational and commercial vessels that position the queued traffic so as to not interfere with vessels entering and exiting the lock. Vessels wait at these designated locations for a signal from the lockmaster that it is their turn to enter the chamber.

Figure 2. Schematic of the 5 lock simulation model

Figure 3. Schematic of the lock service system

Three types of lockages are possible depending on the configuration of the lock and the direction of travel of the vessel to be locked. 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. In this case, 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. This requires a recycling 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 water level to allow the vessel to enter without waiting. Different distributions for locking times are employed for each of the classes of vessels and adjusted for whether movement is upstream or downstream.
downstream at a particular lock and whether the lockage operation is an exchange, turnback, or fly.

Smith et al. [7] describe the validation of the model and document the high degree of agreement between the simulated and historical data for all relevant performance measures at the individual lock level and in aggregate. Thus, the simulation model effectively reflects the dynamic behavior of the UMR system and allows a wide range of congestion management tools to be evaluated.

4. Analysis of Congestion Reduction Measures

The simulation model was used in [7] and the companion paper [8] to evaluate several different re-sequencing rules at the lock queues. The baseline for comparison is the USACE current policy of processing tows in order of arrival (First-In-First-Out) with priority to recreational vessels, which wait for no more than three commercial lockages. This policy is denoted FIFORECPRIO. The analyses are based on 100 years of simulated operations and the level of commercial traffic was varied from 20% less than that in Year 2000 to 30% more than that in Year 2000 to give different scenarios. The best re-sequencing rule is based on processing tows in increasing order of lockage time with a dynamic priority shifting so that tows that have waited a long time in queue have an increased priority. This rule is denoted FLTX (Fastest Lockage Time with exceptions for vessels with long waits in queue) and the companion paper [8] describes the detailed derivation of this rule and the priority shifting model.

The results showed that the re-sequencing with FLTX could have only small benefits at current traffic levels (saving on average a few minutes per lockage), though the benefits increase with the level of traffic. However, at higher traffic levels, even the best re-sequencing scheme would still leave unreasonably long waits [8].

Because the re-sequencing rules appear to have limited ranges of effectiveness, we used the simulation model to evaluate the performance of two other congestion mitigation measures. The first is a tactical measure that reduces lockage times for double lockages by 12.5% (about 15 minutes). Helper boats would be positioned immediately upstream and downstream of each lock for the purpose of assisting double tows. The helper boats pull the barges in the first “cut” of a double lockage out of the chamber (instead of being winched out) and then hold them in a location away from the lock for the re-coupling of the first and second “cuts”. This corresponds to one of the suggestions of the NRC [5].

The second improvement we analyzed is the strategic proposal to construct new 1200-foot long locks. Note that with new 1200-foot locks, all lockages will be single lockages and the lockage times will drop dramatically for tows with more than 6 or 7 barges. For the simulation model, we constructed new regression equations for the lockage times of double tows using data from existing 1200-foot long locks and adjusted them slightly to reflect the USACE estimated mean lockage times for the new locks. These mean lockage times ranged from 50-64 minutes and reflected a 42-50% reduction in mean lockage times at these locks (Engineering Appendix of [12]) relative to the times at the existing 600-foot long locks. Because we have no data on the likely composition of tows after lock expansion, we retained the Year 2000 mix of vessel traffic as in our evaluation of the re-sequencing rules.

The results with new locks demonstrated the substantial effectiveness of the larger locks as they nearly eliminate the waiting time for all levels of traffic. Even with a 30% increase in traffic, the new locks reduce the average waiting time to under 100 minutes compared to over 2000 minutes for re-sequencing. New locks also reduce the 95th percentile of waiting time to under 400 minutes for commercial tows - compared to 9981 minutes with re-sequencing. The benefits from helper boats fall between those of re-sequencing and the new locks.

Figure 4 summarizes a large number of simulation runs and displays the average transit time at a lock, which is comprised of the waiting time and lockage time, for the USACE current policy (denoted FIFORECPRIO), re-sequencing (denoted FLTX), helper boats, and new locks, where the zero level corresponds to Year 2000 traffic. These curves reflect results from eight different levels of demand ranging from a 20% decrease to a 30% increase in commercial traffic, relative to Year 2000. The vertical separation between curves shows the savings in mean transit time per lockage for different congestion relief measures. Note that the curves for other re-sequencing rules previously reported by Smith et al. [6,7] would lie between the curves for FIFORECPRIO and FLTX. As expected, at lower traffic levels the re-sequencing rules perform very similarly. However, as traffic levels increase, the advantage of FLTX becomes apparent. This figure clearly displays (1) the limited range of effectiveness of re-sequencing rules as demand on the system increases, (2) the wide range of effectiveness of new locks, and (3) the intermediate performance of helper boats. While the new locks offer substantial benefits in reducing transit and waiting times, even with very high levels of traffic, much of the benefits can also be gained by helper boats – or by other
methods that provide a relatively small reduction in the mean lockage time.

Figure 4. Mean lock transit times (in minutes) for UMR locks 20-25.

Figure 4 also displays historical data for 1990-2006 as small circles. The simulation model results with FIFOFORECPRIO fit the historical data very well for traffic levels up to about +10%. At higher traffic levels, the historical data tends to fall below the performance from FIFOFORECPRIO, as shown by the three rightmost historical data points, which are from 1990, 1991 and 1992. An examination of operations in these years revealed that policies in effect at that time allowed double tows to be assisted by other tow boats from the queues (after detaching from their barges), or by helper boats to facilitate the lockage process. This demonstrates how the industry responded to increasing traffic pressures by altering operations to reduce lockage times. However, intensive use of this self-help process was discontinued after 1992, in part due to environmental concerns.

5. Developing an Implementation Strategy

Our research was motivated by the NRC’s recommendation to consider alternative measures to relieve congestion before making the strategic decision to commit to expensive infrastructure improvements. (The Corps has indicated that the existing locks and dams can continue to provide services for another 50 years with appropriate maintenance activities [12].) While the results suggest that new locks would dramatically reduce congestion, especially with very large increases in traffic, other methods may prove more cost effective, especially for moderate increases in levels of traffic.

One method to address the USACE need to estimate the net NED benefits of new projects is to convert the transportation time savings that result from navigation system improvements to monetary values using the observed market willingness of UMR shippers to pay for barge transportation. Mundy and Campbell [3] estimate an average value of approximately $240 per tow hour saved at Year 2000 price levels. With this value, the time savings from resequencing (FLTX), relative to current operations (FIFOFORECPRIO), equate to annual transportation cost savings ranging from approximately $850,000 with the Year 2000 level of traffic to $93.1 million at the +30% level of traffic.

However, our results also show that with high levels of traffic, resequencing queues will not prevent waiting times from growing to very large levels. These larger waiting times will increase the costs of using the river and would cause shippers to shift shipments to other transportation modes [10,11] and might stimulate the industry to explore alternatives such as rescheduling tow arrivals to less congested periods.

New locks on the UMR provide substantially larger savings than resequencing queues, by eliminating congestion and waiting time. The estimated savings range from $9.6 million with the Year 2000 level of traffic to $295.6 million at the +30% level of traffic. Helper boats provide an intermediate level of savings relative to queue resequencing and new locks. While new locks or helper boats can reduce waiting times profoundly with high levels of traffic, each option introduces a different range of costs and disruptions to the system. At one extreme, the new infrastructure required for new 1200-foot locks would require investments of over $2 billion dollars and require several decades to complete. Alternatively, using helper towboats at each lock would require a much smaller investment and could be implemented very quickly.

To better compare the net NED benefits of different navigation system improvements, Figure 5 plots the estimated net transportation cost savings for FLTX, helper boats and new locks as a function of the level of traffic (relative to Year 2000). The net NED benefits are calculated as the annual transportation cost savings resulting from the reduced time required for tows to move the traffic in the study region (using the Year 2000 average price level value of $240 per tow hour) net of the annual costs of implementing the improvements. Annualized costs for helper boats and new locks are estimated to be $12.3 million and $91.3 million, respectively, by the USACE (compiled from the Engineering Appendix of [12]), based on the assumptions of Year 2001 price levels, a fifty year useful life, and a real discount rate of 5.625%. For FLTX, we use an implementation cost estimate of $100,000 per year [4].
Figure 5. Estimated net annual savings (in millions of $) for UMR locks 20-25 (0% = Year 2000)

The net savings in Figure 5 shows the level of traffic at which each option provides a net benefit and the level at which each option becomes relatively most beneficial. (Note that FIFORECPRIO is the assumed baseline at zero net benefits and zero implementation costs). FLTX shows an estimated net savings for all levels of traffic. Helper boats show an estimated net cost of $7.1 million at the Year 2000 traffic level, and positive net savings beyond about the +11% level of traffic. Helper boats provide a greater net savings than FLTX at approximately a 13% increase in traffic over Year 2000, and provide very large net savings for higher traffic levels.

Because of their large construction costs, new locks produce substantial negative net savings for levels of traffic below +20%. For larger increases in traffic, new locks show a positive net savings estimated at $204 million at the +30% level of traffic. However, up to a 30% increase in traffic, the net savings of helper boats strongly dominates that from new locks. In summary, Figure 5 suggests the use of re-sequencing via FLTX for levels of traffic up to about a 13% increase in traffic over Year 2000, and provide very large net savings for higher traffic levels.

For example, increases in fuel costs will substantially decrease the annualized net savings for helper boats, but slightly increase the annualized net savings for new locks because of fuel savings in lockage operations. Similarly, increases in local labor costs will substantially decrease the annualized net savings for helper boats and slightly decrease the annualized net savings for new locks because of the planned use of helper boats during the construction period. In contrast, increases in real construction costs and in the real discount rate will substantially decrease the annualized net savings for new locks, but have limited effects on helper boats and re-sequencing. Increases in the hourly value of vessel time savings, as reflected in the market willingness to pay for barge transportation (for example, because of higher commodity costs or higher operating costs), will slightly increase the annualized net savings for re-sequencing (or other scheduling systems) and greatly increase the annualized net savings for helper boats and new locks.

With large changes in the cost structures, relative to current conditions, the curves in Figure 5 would shift and the optimal policy may be to transition from FLTX to new locks – without an intervening period of helper boats. For example, with a 300% increase in the average hourly value of time savings (i.e., the market willingness of UMR shippers to pay for barge transportation) from $240/hour to $720/hour and a 50% decrease in the opportunity cost of capital from the Corps’ base case of 5.625% to 2.8125%, while holding new lock construction costs constant, the NED benefits from new locks would dominate those from helper boats, and the optimal policy would be to transition from FLTX to new locks at approximately an 11% increase in traffic – without an intervening period of using only helper boats.

In practice, the cost to provide helper boats and the value of transportation time savings are closely related and change similarly, because the primary benefit from reducing the waiting time of tows in transit is the opportunity to deploy those towboats productively elsewhere on the system. The same is true for helper boats. Figure 6 identifies the optimal transition policy regions as a function of the real discount rate and the real hourly cost factor, where the hourly cost factor is the percentage cost change in both the cost of providing helper boats and the value of transportation time savings relative to the base values employed by the USACE (as in Figure 5).

In Figure 6 the new lock construction costs are held constant. The “X” in Figure 6 shows the values for the USACE base case (as in Figure 5) and the triangle in Figure 6 shows the example described above with a 300% increase in the average hourly value of time.
savings and a 50% decrease in the opportunity cost of capital, relative to the USACE base case. The small diamonds in Figure 6 show historic values from 1990-2007. Note that at the base discount rate of 5.625%, the costs for helper boats and the value of time savings would need to increase over 450% to remove helper boats from the optimal policy sequence. Only in the circumstances of small discount rates and large increases in helper boat costs and in the value of transportation time savings (but not in lock construction costs), are helper boats removed from the optimal policy. This figure shows that over a wide range of realistic conditions, the optimal policy sequence in response to increasing traffic levels is “first use re-sequencing, then use helper boats, and then use new locks”.

![Figure 6. Navigation system improvement policy sequence regions](image)

While our results help identify the best sequence for implementing navigation system improvements, the optimal timing of each implementation depends heavily on the future levels of traffic. Historical traffic levels on the UMR have evidenced a growth rate closely following the increase in the rate of GDP growth in the United States up until the mid-1980’s. Since then traffic on the UMR has been flat and recently declining. For example, between 2000 and 2007 tonnage at Locks 20-25 declined by 22.5% and the number of lockages declined by 20.4%. Thus, a substantial increase in traffic over current levels would be needed just to reach the base level used in our analysis (Year 2000). However, forecasting long-term demand for commercial transportation in the UMR is extremely difficult as long-term traffic patterns depend on a variety of global issues including the market for grain in Asia, new agricultural competition from South America and Eastern Europe, ethanol production and consumption in the U.S. and overseas, tariffs and subsidies for various products (especially ethanol), and the availability and reliability of alternate transportation modes, such as rail to west coast ports.

Recent forecasts completed by the USACE for traffic on the UMR in 2050 range from an increase in tonnage of 38.1% for a “high traffic scenario” with new locks – to a decrease in tonnage of 2.5% for a “low traffic scenario” without new locks relative to the Year 2000 [14]. Further complicating the forecasts of demand for lockages on the UMR is that an increase in upstream tonnage does not necessarily translate into a corresponding increase in the number of lockages, as empty backhauls of barges can readily be replaced with loaded movements of non-grain products, thereby increasing tonnage without a corresponding increase in the number of barges or lockages. Given the large fraction of empty barges (approximately one-third) passing through the locks in our study region, and projected increases in non-grain backhaul tonnages contained in the USACE forecasts [14], it is likely that the increase in the number of lockages would be less than the forecast increase in tonnage.

Examinining the results of this type of analysis for a wide range of parametric assumptions, we conclude that substantial growth of commercial traffic (more than (30%) above the year 2000 levels) would be required to generate a higher net economic benefit from construction of new locks than from other lower-cost strategies for relieving seasonal congestion.

**6. Conclusion**

The UMR is a complex series of interdependent dynamic queues with seasonality and varying mixes of traffic. Our simulation model allows congestion mitigation tools ranging from operational policies to strategic structural changes to be analyzed with greater detail and realism than previous models. The results from our modeling suggest that at current traffic levels, the savings from re-sequencing queues of vessels on the UMR would be rather small, relative to the size of this market, 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, which will reduce the actual benefits below the levels that we have found. Considering these issues and the small amount of time that vessels actually spend transiting these five locks (relative to their total operating time), we conclude that there is insufficient justification to introduce re-sequencing rules at current traffic levels.

With higher traffic levels, queue re-sequencing will not alleviate congestion and more intrusive congestion relief measures are needed to eliminate seasonal
bottlenecks. The preferred sequence of navigation system improvements is “re-sequence queues, then implement helper boats, then build new locks” and this is very robust to reasonable sets of economic drivers. The time at which to transition from one option to the next depends on the level of traffic and the relative values of the relevant cost components. The best policy for the present time is to monitor traffic levels and prepare for implementing re-sequencing at lock queues only if traffic increases. Only after a substantial increase in traffic would helper boats or improvements such as new locks become attractive.

If lock performance dramatically degrades or traffic levels dramatically increase in the future, then only significant capacity expansion, such as new locks, would keep waiting times to reasonable levels. At high traffic levels new locks could yield significant economic benefits that potentially outweigh the costs of disruptions on the UMR. However, a number of recent trends create concerns about the future of shipping on the UMR and infrastructure investments.

Our research helps quantify the net economic benefits from a range of possible navigation system improvements on the UMR to identify optimal policies for improving inland water transportation. While at present there seems to be little economic justification for expensive navigation system improvements, the ultimate decision of the appropriate policy (including whether or not to construct new locks) is also influenced by a variety of social, environmental and regional factors that are difficult to quantify or monetize. And, ultimately, the appropriation of the funds required for navigation system improvements is a political decision as part of the federal budgeting process.

Areas for future research include models that combine congestion mitigation strategies (such as re-sequencing and helper boats) and models that incorporate economic responses to shift traffic off the river at high levels of congestion.

7. References


