

Management Systems for Inland Waterway Traffic Control, Volume I: Identification and Evaluation of Alternatives for Managing Lock Traffic on the Upper Mississippi River



Final Report
November 2005

Sponsored by

University Transportation Centers Program,
U.S. Department of Transportation
(MTC Project 2004-03)



IOWA STATE
UNIVERSITY

About the MTC

The mission of the University Transportation Centers (UTC) program is to advance U.S. technology and expertise in the many disciplines comprising transportation through the mechanisms of education, research, and technology transfer at university-based centers of excellence. The Midwest Transportation Consortium (MTC) is the UTC program regional center for Iowa, Kansas, Missouri, and Nebraska. Iowa State University, through its Center for Transportation Research and Education (CTRE), is the MTC's lead institution.

Disclaimer Notice

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. The opinions, findings and conclusions expressed in this publication are those of the authors and not necessarily those of the sponsors.

The sponsors assume no liability for the contents or use of the information contained in this document. This report does not constitute a standard, specification, or regulation.

The sponsors do not endorse products or manufacturers. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objective of the document.

Non-discrimination Statement

Iowa State University does not discriminate on the basis of race, color, age, religion, national origin, sexual orientation, gender identity, sex, marital status, disability, or status as a U.S. veteran. Inquiries can be directed to the Director of Equal Opportunity and Diversity, (515) 294-7612.

Technical Report Documentation Page

1. Report No. MTC Project 2004-03		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Management Systems for Inland Waterway Traffic Control, Volume I: Identification and Evaluation of Alternatives for Managing Lock Traffic on the Upper Mississippi River				5. Report Date November 2005	
				6. Performing Organization Code	
7. Author(s) Ray A. Mundy, James F. Campbell				8. Performing Organization Report No.	
9. Performing Organization Name and Address Center for Transportation Research and Education Iowa State University 2901 South Loop Drive, Suite 3100 Ames, IA 50010-8634				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No.	
12. Sponsoring Organization Name and Address U.S. Department of Transportation Research and Special Program Administration 400 7th Street SW Washington, DC 20590-0001				13. Type of Report and Period Covered Final Report	
				14. Sponsoring Agency Code	
15. Supplementary Notes Visit www.ctre.iastate.edu for color PDF files of this and other research reports.					
16. Abstract <p>Periodic congestion of the locks in the Upper Mississippi River and Illinois Waterway negatively impacts inland waterway transport. Previous investigation of an appointment system, among other low cost measures, did not result in an acceptable resolution of the traffic issue. Responding to the continued need to improve management and reduce the operational costs of inland water transportation, this research project examines and evaluates alternative traffic management policies for implementation on the Upper Mississippi River (UMR) portion of the inland navigation system.</p> <p>To determine impact on lockage times and transit times, statistical analysis was conducted on different types of vessels using the system, different lockages required, night or day movements, and river flow characteristics. Based on this data, a discrete event simulation model was created and is presented as a tool for investigating traffic changes, explicitly incorporating seasonal and interdependent demands.</p> <p>Research results reveal that current low commercial traffic levels on the UMR system do not warrant implementing an alternative traffic management policy; benefits relative to cost and market disruptions are not sufficient. However, implementing a vessel tracking system may incur benefits of increasing homeland security, improving navigation safety, and protecting environmentally sensitive river habitats. Volume II, research results of a companion project investigating these possibilities, focuses on using vessel tracking with geographic positioning systems to improve operations and to enhance safety, security, and environmental protection of the UMR system.</p>					
17. Key Words inland waterway transportation management—Upper Mississippi River system—lock appointment systems—tow re-sequencing—complete vessel scheduling—discrete event model simulation—seasonal and interdependent traffic demands—homeland security				18. Distribution Statement No restrictions.	
19. Security Classification (of this report) Unclassified.		20. Security Classification (of this page) Unclassified.		21. No. of Pages 105	22. Price NA

MANAGEMENT SYSTEMS FOR INLAND WATERWAY TRAFFIC CONTROL, VOLUME I: IDENTIFICATION AND EVALUATION OF ALTERNATIVES FOR MANAGING LOCK TRAFFIC ON THE UPPER MISSISSIPPI RIVER

**Final Report
November 2005**

Principal Investigator

Ray A. Mundy
Director, Center for Transportation Studies
Professor, College of Business Administration,
University of Missouri-St. Louis

Co-Principal Investigator

James F. Campbell
Professor, College of Business Administration
University of Missouri-St. Louis

Faculty Research Associates

Robert M. Nauss, College of Business Administration, UM/St. Louis
Daniel L. Rust, Center for Transportation Studies, UM/St. Louis
L. Douglas Smith, College of Business Administration, UM/St. Louis
Donald C. Sweeney, Center for Transportation Studies, College of Business Administration, and
College of Arts and Sciences, UM/St. Louis

Research Assistants

William E. Winter, Public Policy Center, UM/St. Louis
Denise M. Franke, Amrita Sinha, and David A. Long, Center for Transportation Studies, UM/St. Louis

Authors

Ray A. Mundy and James F. Campbell

Preparation of this report was financed in part
through funds provided by the U. S. Department of Transportation
through the Midwest Transportation Consortium, Project 2004-03.

A report from
Center for Transportation Research and Education

Iowa State University
2901 South Loop Drive, Suite 3100
Ames, IA 50010-8634
Phone: 515-294-8103
Fax: 515-294-0467
www.ctre.iastate.edu

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	IX
EXECUTIVE SUMMARY	XI
Genesis, Evolution, and Structure of the Report.....	xi
Volume 1 Summary	xi
Volume 2 Summary	xii
Conclusions.....	xiii
Recommendations.....	xiii
INTRODUCTION	1
THE UPPER MISSISSIPPI RIVER NAVIGATION SYSTEM.....	3
CHARACTERISTICS OF THE U.S. ARMY CORPS OF ENGINEERS OMNI DATABASE....	9
Traffic Table	9
Flotilla Table.....	10
Vessel Table.....	11
Operations Table.....	11
STATISTICAL MODELING OF OPERATIONS ON THE UMR SYSTEM	12
Purpose of the Statistical Analysis.....	12
Descriptive Statistics for Waterway Operations and Resource Utilization	13
General Observations from Lock Utilization Statistics and Vessel Itineraries.....	16
Discussion of the OMNI Data.....	17
Statistical Models to Support Enhanced Simulation of UMR Traffic Movements and Lockages	36
Refinement of Vessel Movements and Lockage Activity to Reflect Ambient Conditions (River Conditions and Impairments at Locks).....	38
Acquisition of Industry Data for Vessel Movements and Fuel Consumption	39
Statistical Models for Dynamic Adjustment of Simulation Parameters	40
Lock Impairments	44
Water Conditions	44
Generation of Tows in Pools.....	46
Summary	46
TRAFFIC MANAGEMENT ALTERNATIVES	47
Introduction.....	47
Traffic Management Alternatives	47
Limitations on Evaluating Traffic Management Alternatives	50
A LOCALLY OPTIMIZED VESSEL SEQUENCING ALGORITHM FOR EFFICIENTLY CLEARING A LOCK QUEUE.....	52
Description of the Optimization Model	54
Some Observations on Operational Issues.....	59
THE UMR SIMULATION MODEL.....	60

UMR Simulation Model Components	62
UMR Simulation Model Task Network.....	72
EVALUATION OF THE UMR SIMULATION MODEL	75
EVALUATION OF AN EXAMPLE RE-SEQUENCING POLICY	81
SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS.....	86
Summary	86
Conclusions.....	87
Recommendations.....	88
REFERENCES	90

LIST OF FIGURES

Figure 1. Map of the UMR navigation system (Source: U.S. Army Corps of Engineers)	1
Figure 2. Schematic view of the UMR pool system (Source: U.S. Army Corps of Engineers).....	3
Figure 3. Distribution of lockage times for UMR locks 20 through 25.....	18
Figure 4a. Panel A: the distribution of wait for lockage times for UMR locks 20 through 25	19
Figure 4b. Panel B: the cumulative distribution of wait times for UMR locks 20 through 25.....	19
Figure 5. Number of lockages at UMR locks 20 through 25 by month, 2000 through 2003	25
Figure 6. Aggregated wait for lockage times (hours) for all vessels by lock and month, 2000 through 2003	26
Figure 7. Mean pool transit times (hours) for commercial tows by month, 2000 through 2003 ..	28
Figure 8. Mean lockage times (minutes) for tows at UMR locks 20 through 25 by month, 2000 through 2003	29
Figure 9. Number of tows that have produced at least one lockage in the UMR system but have not produced their final system lockage, 2000 through 2003	30
Figure 10. Day of the year of the first lockage of individual tows at UMR locks 20 through 25, 2000 through 2003	31
Figure 11. Day of the year of the final system lockage of individual tows at UMR locks 20 through 25, 2000 through 2003.....	32
Figure 12. Screen capture of the Micro Saint Sharp display diagram for the UMR simulation model.....	62
Figure 13. UMR simulation model schematic diagram–tow traffic	73
Figure 14. The UMR simulation model schematic diagram–recreation vessels	73
Figure 15. Average annual tow flows at UMR locks 20 through 25, 2000-2003.....	74
Figure 16. Mean simulated values of the total lock utilization percentages for UMR locks 20 through 25 for consecutive ten–day periods	79
Figure 17. Total number of vessels waiting for lockage at selected times compiled from 100 runs of the UMR system simulation model	79
Figure 18. 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.....	84
Figure 19. Total annual wait for lock service time and total lockage time, locks 20 through 25, all vessels, 2000–2004	88

LIST OF TABLES

Table 1. Selected characteristics of the locks in the UMR navigation system (Source: U.S. Army Corps of Engineers).....	4
Table 2. Mean and standard deviations of wait for lockage times UMR locks 20 through 25, 2000 through 2003	7
Table 3. OMNI traffic table details.....	10
Table 4. OMNI flotilla table details.....	11
Table 5. OMNI vessel table details.....	11
Table 6. OMNI operations table details.....	12
Table 7. Observed allocation of available tow time amongst selected activities in the UMR-IW navigation system, 2000-2003.....	17
Table 8. Selected summary statistics of wait time distributions by lock, direction, and lockage type for tows, 2000 through 2003	21
Table 9. Selected summary statistics of lockage time distributions by lock, direction, and lockage type, 2000 through 2003.....	22
Table 10. 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.....	23
Table 11. Selected summary statistics of lockage time distributions for tows traveling downbound, 2000 through 2003	34
Table 12. Selected summary statistics of lockage time distributions for tows traveling upbound, 2000 through 2003	35
Table 13. Selected summary statistics of lockage time distributions for recreation lockages, 2000 through 2003	36
Table 14. Definitions of variables used in statistical models.....	45
Table 15. Annual number of barges processed at UMR locks 20 through 25 (Source: US Army Corps of Engineers lock performance monitoring system	51
Table 16. Mean number of recreation vessel arrivals by direction of travel and month, 2000-2003.....	64
Table 17. Mean hours between recreation vessel arrivals by direction of travel and month, 2000-2003.....	65
Table 18. Mean number of tow arrivals by direction of travel and month, 2000-2003	66
Table 19. Mean hours between tow arrivals by direction of travel and month, 2000-2003	67
Table 20. Vessel lockages, wait times, and lockage times at UMR locks compiled from OMNI data, 2000 through 2003.....	76
Table 21. Selected summary statistics compiled from 100 UMR simulation model runs.....	77
Table 22a. Selected details of the results of 100 UMR simulations and comparison with the 2000-2003 OMNI data.....	77
Table 22b. Mean annual number of tows entering the system	78
Table 22c. Mean annual number of complete pool transits by tows	78
Table 22d. Mean transit times by all tows	78
Table 23. Selected summary statistics compiled from 100 UMR simulation model runs with a locally optimal queue dispatch policy.....	82
Table 24. Selected summary results of changes in selected variables resulting from employing a locally optimal queue dispatch policy.....	82
Table 25. Summary of evaluations of alternative traffic management policies	89

ACKNOWLEDGEMENTS

The authors acknowledge the support of the U.S. Department of Transportation through the Midwest Transportation Consortium, MTC Project 2004-03, and the U.S. Army Corps of Engineers' Institute for Water Resources, the Department of the Interior, U.S. Geological Survey and the Curators of the University of Missouri, under Grant Agreement No. 04HQGR0145. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

EXECUTIVE SUMMARY

Genesis, Evolution, and Structure of the Report

In February 2003, the Center for Transportation Studies at the University of Missouri-St. Louis released a white paper produced for the Institute for Agriculture and Trade Policy (IATP) entitled: “Upper Mississippi River and Illinois Waterways: How to Reduce Waiting Times of Vessels While Using the Current Infrastructure.” The white paper recommended investigating an appointment system and revisiting some other low cost measures previously identified but rejected by the U.S. Army Corps of Engineers as a means of reducing the congestion that occurs periodically at locks in the Upper Mississippi River and Illinois Waterway (UMR-IW).

Based on that recommendation, the Center for Transportation Studies initiated a project in March 2004 designed to (1) improve the management of and reduce the operational costs of inland water transportation assets and (2) identify and evaluate specific traffic management measures for implementation on the Upper Mississippi River and Illinois Waterway segment of the inland water transportation system. This project was funded by the Midwest Transportation Consortium with matching funds from the University of Missouri-St. Louis. The Institute for Water Resources (IWR) of the U.S. Army Corps of Engineers provided lock operations data. The IATP was to also contribute to the project, but withdrew because of financial considerations that fiscal year.

In June 2004, the IWR agreed to fund a companion project at the Center for Transportation Studies that would investigate the potential use of vessel tracking systems primarily as an aid in implementing lockage and traffic management policies. Funding this companion project also made the Corps a full partner in the original study. The “vessel tracking” companion project included (1) an investigation of automatic vessel tracking applications and related geographic information systems for inland waterway transport on the Upper Mississippi River (UMR) system, (2) the documentation of appropriate technologies necessary to implement a vessel tracking system, and (3) the development of a prototype vessel tracking geographic information system.

Consequently, this report is structured in two distinct but related volumes. Volume 1, “Identification and Evaluation of Alternatives for Managing Lock Traffic on the Upper Mississippi River,” focuses on identifying and evaluating traffic management alternatives for possible implementation and Volume 2, “Vessel Tracking for Managing Traffic on the Upper Mississippi River,” focuses on the feasibility of using vessel tracking systems to provide real time or near-real time data on tow positions in support of new lockage or traffic management policies. A summary of each volume follows.

Volume 1 Summary

This volume examines and evaluates alternative traffic management policies designed to improve the efficiency of lockage operations in an intermittently congested segment of the UMR

navigation system. The traffic management alternatives examined and evaluated range from lock appointment systems, to re-sequencing tows for processing at a lock or a series of locks, to the complete scheduling of vessel movements on the waterway.

A detailed statistical analysis of U.S. Army Corps of Engineers 2000-2003 OMNI data compiled for the UMR navigation system is presented which indicates that the UMR system segment bounded by Lock 20 upstream and Lock 25 downstream experiences some periodic traffic congestion, is subject to intra-seasonal changes in demands for service, and operates as an interconnected system in that Locks 20-25 share a large amount of common and interrelated commercial tow traffic. The statistical analysis considers the role of many diverse factors in the operation of the UMR such as: the different types of vessels using the system; the different types of lockages required by different vessels; the night or day movements of vessels in the pools connecting the locks, the night or day lockages of vessels; and differing river flow characteristics that affect tow movements, to determine their impact on lockage times and transit times between locks. Equations produced by the statistical analysis are then employed in a new simulation model used to evaluate the results of implementing scheduling and sequencing rules designed to manage queues and vessel traffic more efficiently at Locks 20-25.

The discrete event simulation model is presented, validated against known UMR traffic flows, and used for investigating the effects of these traffic management alternatives. 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. The simulation model is calibrated with historic data and shown to accurately represent the overall operation of the system including the periodic seasonality of the demand for lock use evident in the U.S. Army Corps of Engineers OMNI data.

Volume 2 Summary

This volume examines the feasibility of vessel tracking systems for better managing lockages on the UMR navigation system. Vessel tracking systems are widely available and can be used to improve waterway operations and to enhance safety, security and environmental protection in many settings. This volume describes current vessel tracking applications and technologies and presents a prototype vessel tracking geographic information system for the UMR. A description of automatic vessel tracking and related applications that have been developed for a variety of purposes worldwide and may be relevant to the UMR is presented first. This includes satellite-based vessel tracking systems, automatic identification systems (AIS), vessel traffic services, and vessel traffic management systems. The volume then discusses ongoing efforts to develop comprehensive inland waterway traffic management systems that exploit technological developments to provide stakeholders with information to support better waterway decision-making.

Next, the volume describes technologies necessary to implement a vessel tracking system on the UMR, including methods for acquiring dynamic data for vessels, and for communicating this data to a geographic information system (GIS) for visual display. Important issues in position

reporting, communications, and data integration, as well as key organizational issues involving responsibility and authority associated with vessel tracking on the UMR are highlighted.

Finally, a prototype vessel tracking GIS is presented that provides static displays and an example of dynamic vessel tracking to demonstrate the functionality possible from vessel tracking on the UMR. The prototype is built using the Arc Map 9.0 GIS with the Tracking Analyst extension for managing the dynamic display.

Conclusions

Our analyses reveal that, as a consequence of the low commercial traffic levels currently evident in the UMR navigation system, implementing an alternative traffic management policy does not appear to yield sufficient benefits relative to its costs to warrant the market disruptions its implementation would create. However, the implementation of a vessel tracking system could be designed to provide the additional benefits of enhancing homeland security, improving navigation safety, protecting environmentally sensitive river habitats. It may also provide a basis for implementing future traffic management policies should traffic levels significantly increase or the operational characteristics of the UMR navigation system significantly degrade.

Recommendations

1. New traffic management policies such as appointment and scheduling systems should not be implemented on the UMR at this time because of the small economic benefits they would create relative to their costs at existing traffic levels and the potential disruptions they would create in existing water transportation markets.
2. New traffic management policies such as appointment and scheduling systems should be evaluated under conditions of both significantly increased traffic levels and significantly degraded operating characteristics of the locks comprising the UMR navigation system in order to ascertain the effectiveness of alternative management policies in those circumstances.
3. Vessel tracking systems for lockage or traffic management on the UMR should be designed in concert with the selection of a potential lockage or traffic management alternative.
4. Responsibility and legal authority for lockage and traffic management on the UMR should be clarified before implementing larger scale lockage and traffic management systems.
5. Opportunities to partner with other agencies and private organizations in developing vessel tracking on the UMR should be explored; one area for special attention is to strengthen linkages with the Coast Guard regarding the implementation of AIS.

INTRODUCTION

The purpose of this research is to examine and evaluate alternative traffic management policies designed to improve the efficiency of lockage operations in an intermittently congested segment of the Upper Mississippi River (UMR) navigation system. Figure 1 presents a map of the UMR portion of the inland navigation system.



Figure 1. Map of the UMR navigation system (Source: U.S. Army Corps of Engineers)

The traffic management alternatives examined and evaluated range from lock appointment systems, to re-sequencing tows for processing at a lock or a series of locks, to the complete scheduling of vessel movements on the waterway. The research creates and evaluates 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.

A detailed statistical analysis of U.S. Army Corps of Engineers 2000-2003 OMNI data compiled for the UMR navigation system is presented, which indicates that the UMR system segment bounded by Lock 20 upstream and Lock 25 downstream, as seen in Figure 1, experiences some periodic traffic congestion, is subject to intra-seasonal changes in demands for service, and operates as an interconnected system in that Locks 20-25 share a large amount of common and

interrelated commercial tow traffic. To determine their impact on lockage times and transit times between locks, the statistical analysis considers the role of many diverse factors in the operation of the UMR, including: different types of vessels using the system, different types of lockages required by different vessels, night or day movements of vessels in the pools connecting the locks, night or day lockages of vessels, and differing river flow characteristics that affect tow movements. Equations produced by the statistical analysis are then employed in a new simulation model used to evaluate the results of implementing scheduling and sequencing rules designed to manage queues and vessel traffic more efficiently at Locks 20-25.

The discrete event simulation model is presented, validated against known UMR traffic flows, and used for investigating the effects of these traffic management alternatives. 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. The simulation model is calibrated with historic data and shown to accurately represent the overall operation of the system including the periodic seasonality of the demand for lock use evident in the U.S. Army Corps of Engineers OMNI data.

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 that 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 common tow traffic, the existence of periods of high and low levels of demand for use of the system, and the variability of lock service times provide currently untapped sources of efficiency for the implementation of alternative traffic management policies in the operation of the UMR system. Specifically, system efficiencies might 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.

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.

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.

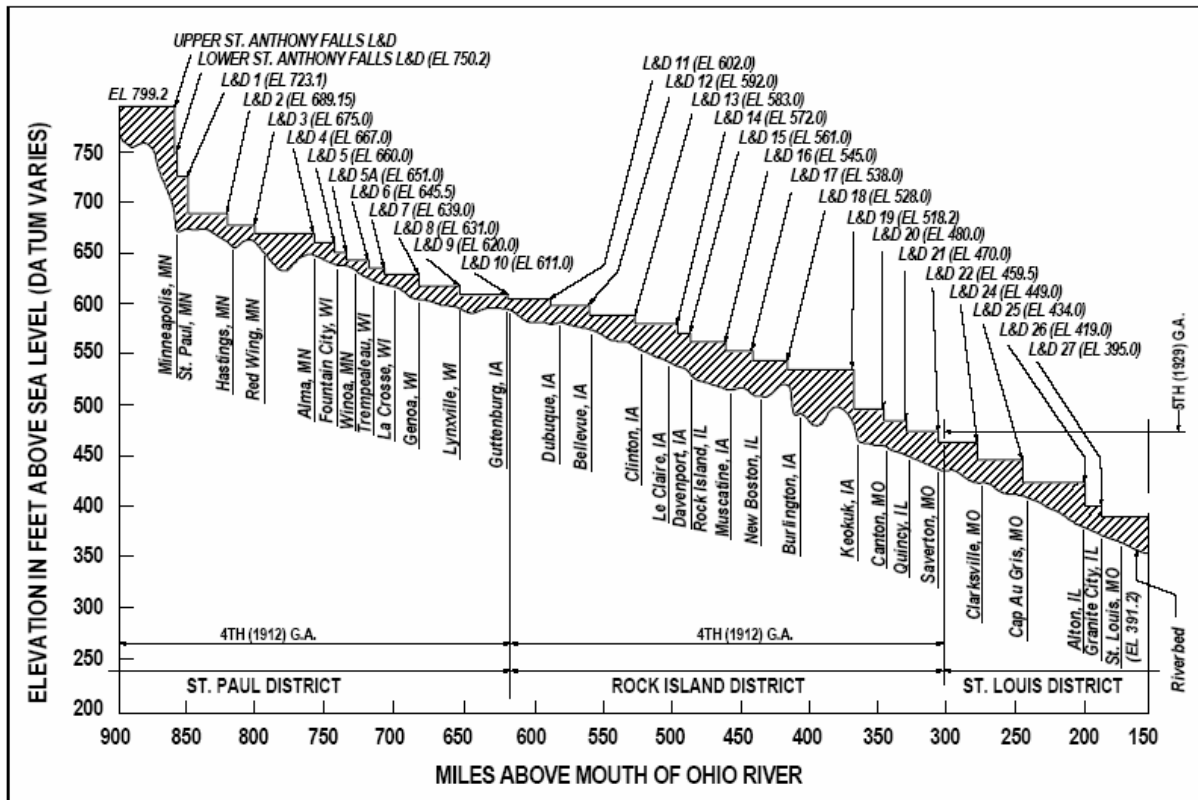


Figure 2. Schematic view of the UMR pool system
(Source: U.S. Army Corps of Engineers)

Most of 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 feet 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 UMR. Selected important physical and operational characteristics of the UMR locks are summarized in Table 1.

**Table 1. Selected characteristics of the locks in the UMR navigation system
(Source: U.S. Army Corps of Engineers)**

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

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.

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% 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% 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 8% 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 relatively large variability of the 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. The lock system was originally designed to readily accommodate tow sizes of up to 600 feet in length. In response to the economies of larger shipment sizes, tows now routinely exceed 600 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 feet 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 feet 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 the five 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 wait even 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 follows.

**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)
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. (continued)

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

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 (Corps) 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 UMR 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. Detailed descriptions 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 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 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.

Table 3. OMNI traffic table details

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_CMRCCL_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.

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.

Table 4. OMNI flotilla 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.

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 horsepower are included in this database table. Table 5 below displays the important data fields contained in the Vessel Table.

Table 5. OMNI vessel 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.

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 (upbound or downbound) of travel of the flotilla associated with the lock operation. Table 6 below displays the important data fields contained in the Operations Table.

Table 6. OMNI operations 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 upbound or downbound.
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.

STATISTICAL MODELING OF OPERATIONS ON THE UMR SYSTEM

Purpose of the Statistical Analysis

The UMR statistical analysis was undertaken for the following reasons:

- To produce performance benchmarks 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 benchmark 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 may be used to moderate the parameters of the simulation model according to the status of the system and the 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 SAS datasets. The OMNI data apply to lockage activity, with key events being the arrival of a vessel 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 vessel tracking 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 vessel position data that may be provided by the barge lines. In the course of our visits with lockmasters, it was mentioned that, in periods of congestion, there was a tendency for towboat pilots to report having arrived at the lock while actually still underway to the call-in point in the river. They do this to establish their position in the lock queue and thus the measure of transit time from departure at a lock to arrival at the next lock may be distorted. 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 as follows:

- 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 lockage type and lockage operation type involved at a 600-foot chamber and whether the movement is upstream or downstream.

There are six lockage types:

- **Single Lockage:** a commercial tow lockage where the entire tow (towboat and barges) is processed through the lock in a single lock chamber operation without any reconfiguration of the tow.
- **Double Lockage:** a commercial tow lockage where the entire tow (towboat and barges) is processed through the lock in two successive lock chamber operations with the tow broken into two separate “cuts” during the lockages and then reconfigured into a single unit at the conclusion of the lockage of the second cut.
- **Jackknife Lockage:** a commercial tow lockage where the entire tow (towboat and barges) is processed through the lock in a single lock operation after the towboat and some barges are realigned so that the entire tow fits into the lock chamber in a single operation.
- **Knockout Lockage:** a commercial tow lockage where the entire tow (towboat and barges) is processed through the lock in a single lock operation after the towboat is repositioned so that the entire tow fits into the lock chamber in a single operation.
- **Other Lockage:** all other commercial tow lockage types.
- **Recreation Lockage:** a lockage consisting of one or more non-commercial recreation vessels processed through the lock in a single lock chamber operation.

There are three lockage operation types:

- **Fly Lockage:** lockage operation in which the lock is unoccupied when the vessel arrives at the lock and the vessel is the next vessel processed at the lock.
- **Turnback Lockage:** A lockage operation 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.
- **Exchange Lockage:** A lockage operation 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-Econ124). 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.

With six lockage types, two directions of travel, and three lockage operation types, there are thirty-six logical combinations of lockage and operation types and direction of travel that completely characterize lockages in the UMR-IW system. Depending upon the sequencing rule employed, lockages 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 of 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 transit time at a lock (from arrival to departure) 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 the other possible pools upstream or downstream (including infeasible transitions caused by data entry errors or unrecorded multiple lockages)

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.

The SAS programs for generating the descriptive statistics from the OMNI data and a set of resulting reports appear in Appendix A.1 (downloadable from <http://www.cts-umsl.org/waterways>).

General Observations from Lock Utilization Statistics and Vessel Itineraries

For the four-year period, 2000-2003, there were a total of just over 23 million hours of tow operations on the Upper Mississippi River-Illinois Waterway navigation system in our database. Table 7 provides the total time and the percentage of total time spent by commercial tows in selected activities in the UMR-IW navigation system in 2000-2003.

Table 7. Observed allocation of available tow time amongst selected activities in the UMR-IW navigation system, 2000-2003

Activity	Hours	Total tow hours on UMR-IW (%)
Total tow time spent waiting for lockage at locks 20-25	164,257	0.7
Total tow time spent locking at locks 20-25	96,112	0.4
Total tow time spent in lock 20-25 segment not waiting or locking	929,797	4.0
Total tow time spent waiting for lockage at UMR-IW locks other than locks 20-25	358,811	1.6
Total tow time spent locking at UMR-IW locks other than locks 20-25	385,125	1.7
Total tow time spent in the UMR-IW outside the lock 20-25 segment not waiting or locking	21,853,840	91.6
Total time spent operating in the UMR-IW	23,044,006	100.0

This shows how delays are concentrated at Locks 20-25, with 164,257 hours waiting, compared to 358,811 hours waiting at the other 32 locks in the UMR-IW system. While the waiting time at Locks 20-25 is 13.8% of the total time spent on the Lock 20-25 segment of the UMR-IW, this is only a very small fraction of the total operating time on the UMR-IW. In fact, during the entire period, 2000 through 2003, commercial tows spent approximately 0.7% of their time waiting for lockage and 0.4% of their time undergoing lockage at Locks 20 through 25. (For more details, see Appendix A.2.) This means that 98.9% of the total time tows are operating in the UMR-IW is spent undertaking activities that will not benefit from relieving periodic lock congestion, increasing lock efficiency, or adding lock capacity at Locks 20-25. This observation shows that there is only a very limited potential of increasing the existing utilization of inland navigation resources by employing traffic management policies or by increasing existing lock capacity, even at the most congested locks, unless the volume of river traffic increases substantially above the recent historic levels evident in our data.

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: (1) for commercial tows that are over 600 feet in length which require two separate cuts to complete a single lockage and (2) for commercial tows and other vessels that are less than 600 feet long which only require a single cut to complete a lockage.

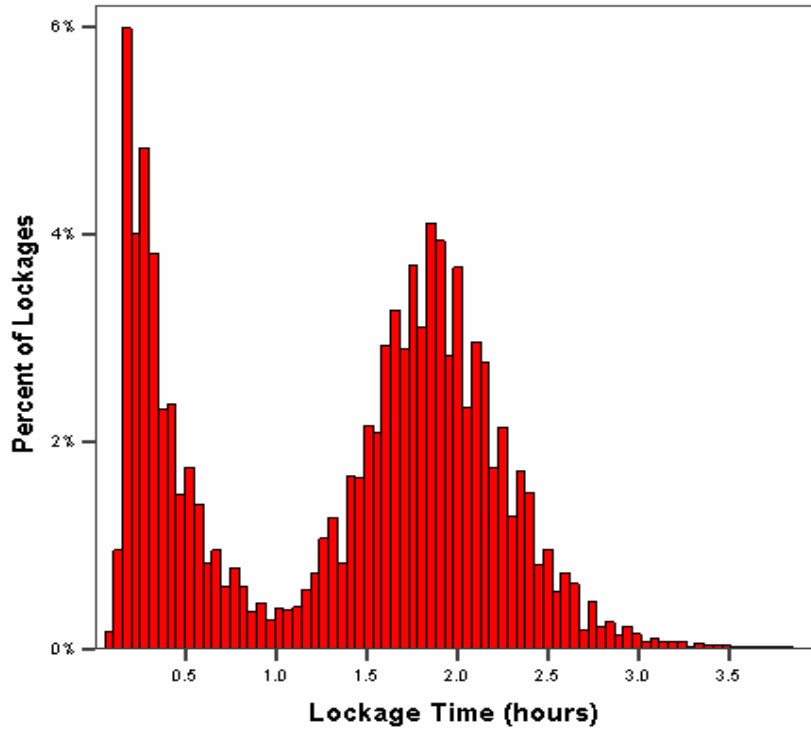


Figure 3. Distribution of lockage times for UMR locks 20 through 25

As evidenced in Figures 4a and 4b, panels A and B, a significant portion of the vessels transiting these five locks, approximately 31%, 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 50% 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 six hours before receiving service. Finally, a small but significant proportion, approximately 10%, of the vessels arriving at the locks waited more than six hours or more before service was provided.

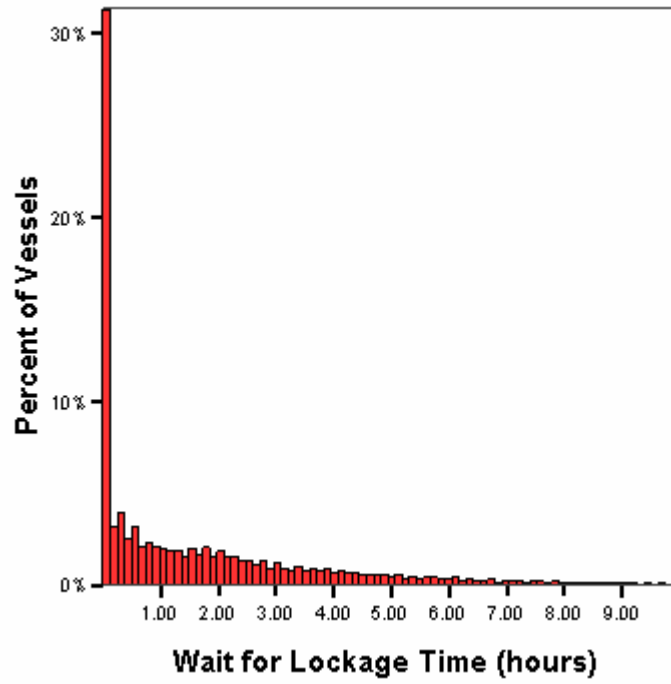


Figure 4a. Panel A: the distribution of wait for lockage times for UMR locks 20 through 25

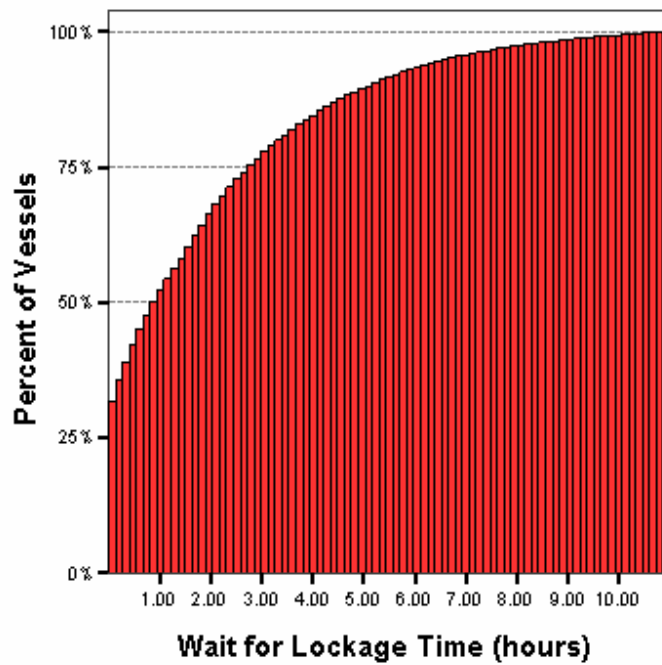


Figure 4b. Panel B: the cumulative distribution of wait times for UMR locks 20 through 25

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 two or more 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 8 and selected summary statistics of the lockage time distributions are presented in Table 9. As evidenced in Tables 8 and 9, the distributions of wait and lockage times characterized by lock, vessel type, and direction of travel exhibit significantly different summary statistics. For example, Table 8 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. Table 9 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.

Table 8. Selected summary statistics of wait time distributions by lock, direction, and lockage type for tows, 2000 through 2003

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
	Upbound	Total	3.25	5805	3.90
		Double	3.90	4327	4.93
		Jackknife	1.35	1	-
		Knockout	4.12	114	4.26
		Other	3.63	138	3.69
24	Downbound	Single	1.77	1179	2.76
		Total	3.46	5759	4.61
		Double	3.64	4717	4.43
		Knockout	3.83	188	3.95
		Other	3.95	80	3.47
	Upbound	Single	1.47	1061	2.36
		Total	3.27	6046	4.20
		Double	3.98	4457	8.37
		Knockout	3.49	124	3.81
		Other	3.99	139	4.50
25	Downbound	Single	1.44	1271	2.91
		Total	3.43	5991	7.47
		Double	3.04	4738	3.99
		Jackknife	0.00	1	-
		Knockout	3.80	193	5.04
	Upbound	Other	3.29	78	3.63
		Single	1.40	1268	2.38
		Total	2.74	6278	3.82
		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 9. Selected summary statistics of lockage time distributions by lock, direction, and lockage type, 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
	Upbound	Double	1.86	5805	0.98
		Jackknife	2.01	4327	0.61
		Knockout	1.17	1	-
		Other	1.17	114	0.77
		Single	1.65	138	0.49
24	Downbound	Double	0.56	1179	0.65
		Jackknife	1.69	5759	0.85
		Knockout	2.10	4717	0.63
		Other	0.95	188	0.39
		Single	1.31	80	0.32
	Upbound	Double	1.31	80	0.32
		Knockout	0.54	1061	0.66
		Other	1.78	6046	0.87
		Single	1.82	4457	0.46
		Total	1.05	124	0.47
25	Downbound	Double	1.43	139	0.35
		Jackknife	1.51	5991	0.69
		Knockout	0.48	1271	0.19
		Other	1.75	1	-
		Single	2.03	4738	0.65
	Upbound	Double	0.94	193	0.49
		Jackknife	1.35	78	0.69
		Knockout	0.42	1268	0.27
		Other	1.66	6278	0.88
		Single	1.83	4474	0.61
25	Upbound	Double	1.01	131	0.40
		Knockout	1.57	139	0.97
		Other	0.38	2037	0.25
		Single	1.37	6781	0.85
		Total	1.37	6781	0.85

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 (without an intervening lockage). 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 10 for multi-cut and single cut tows.

Table 10. 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

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

As evidenced in Table 10 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 10 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. However, most single cut tows do not 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 through time. Figure 5 presents the number of lockages 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 lockages. 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 lockages dramatically increases. The number of vessel lockages increases again at a somewhat decreased rate through May and June until the number of lockages peaks during July. Then there is decrease to September followed by an increase to November. Finally, in December the arrival rates rapidly decrease towards 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.

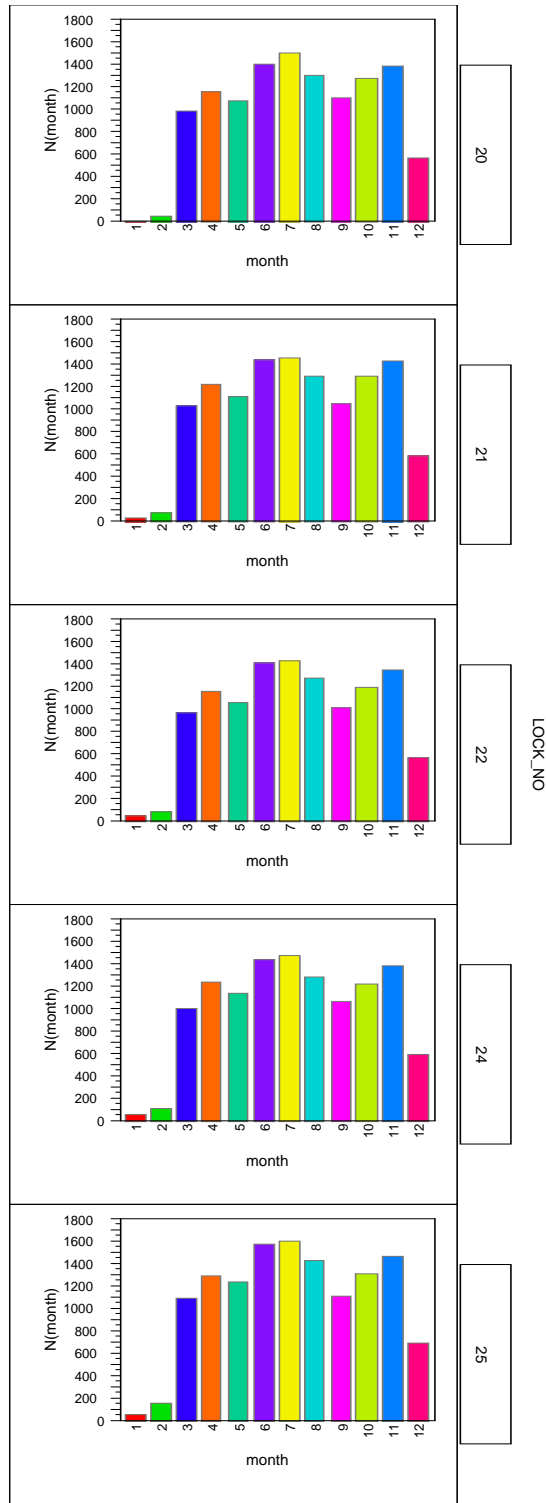


Figure 5. Number of lockages at UMR locks 20 through 25 by month, 2000 through 2003

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.

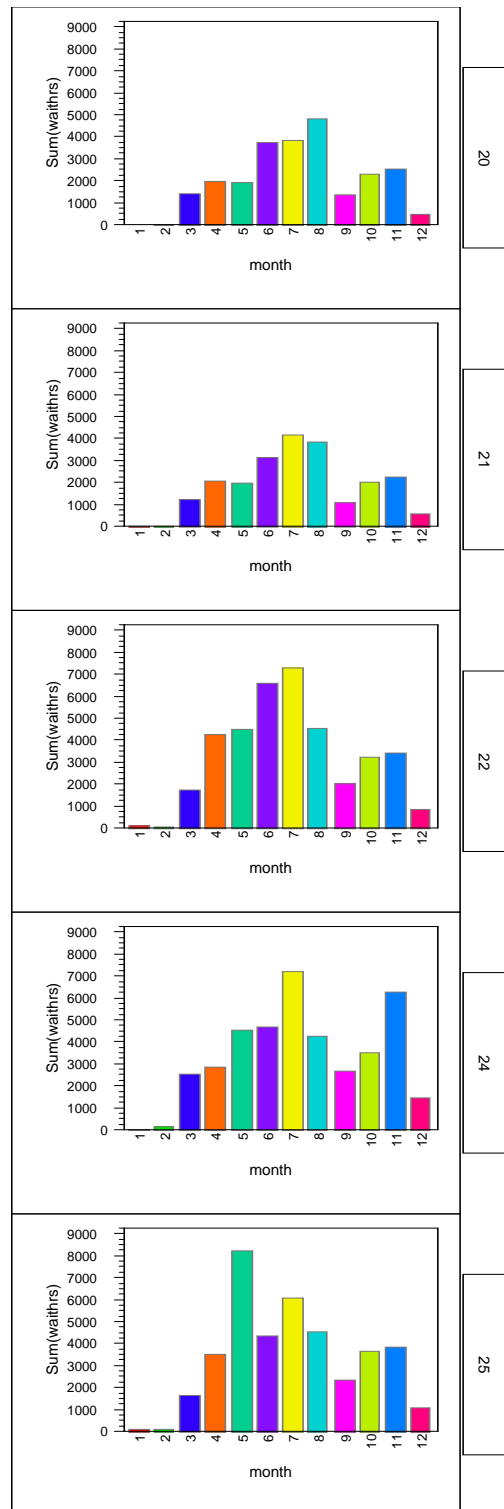


Figure 6. Aggregated wait for lockage times (hours) for all vessels by lock and month, 2000 through 2003

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, drop in the early Fall, rebound to a secondary peak in late-Fall, and then rapidly 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 from 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.

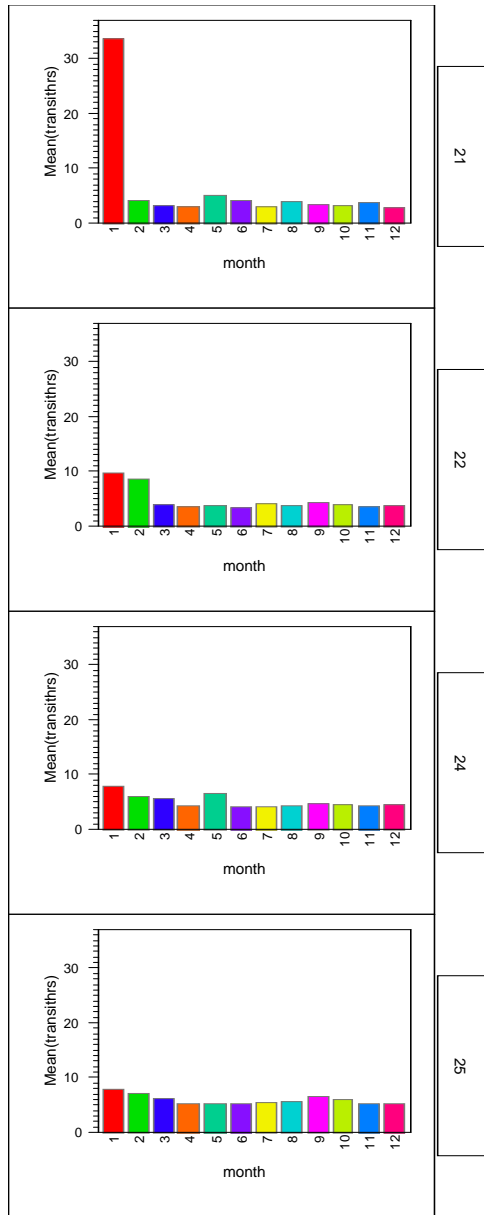


Figure 7. Mean pool transit times (hours) for commercial tows by month, 2000 through 2003

Figure 8 displays the mean lockage times for tows by month for each of the locks during the period from 2000 through 2003. There is little evidence of seasonality present in the monthly distributions of mean tow lockage times observed at each of the locks.

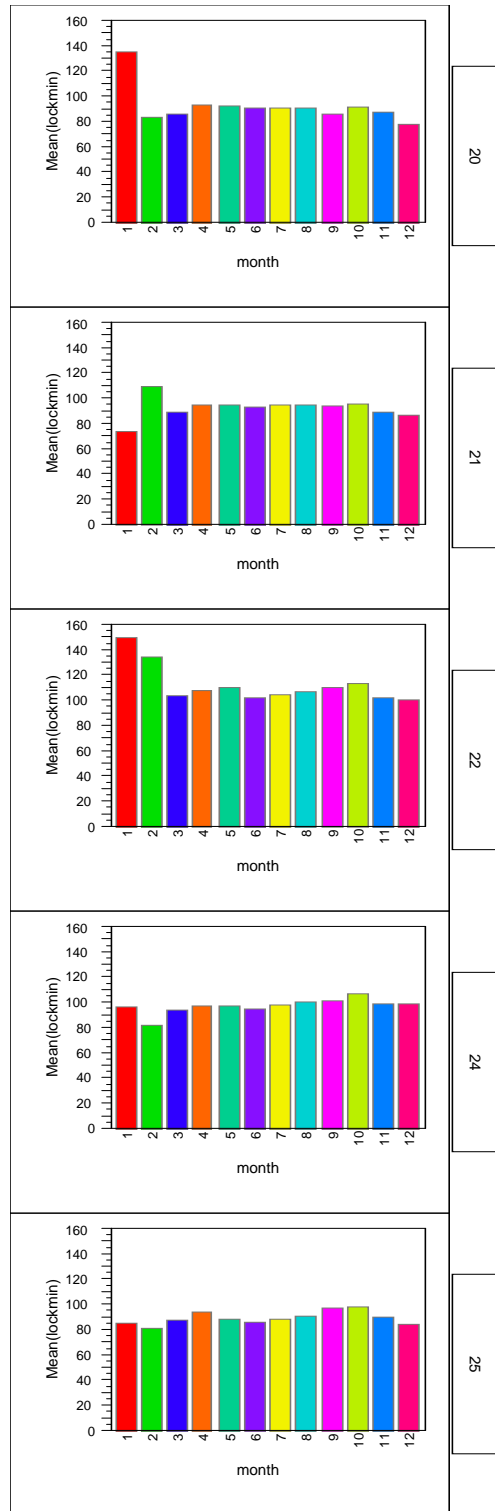


Figure 8. Mean lockage times (minutes) for tows at UMR locks 20 through 25 by month, 2000 through 2003

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.

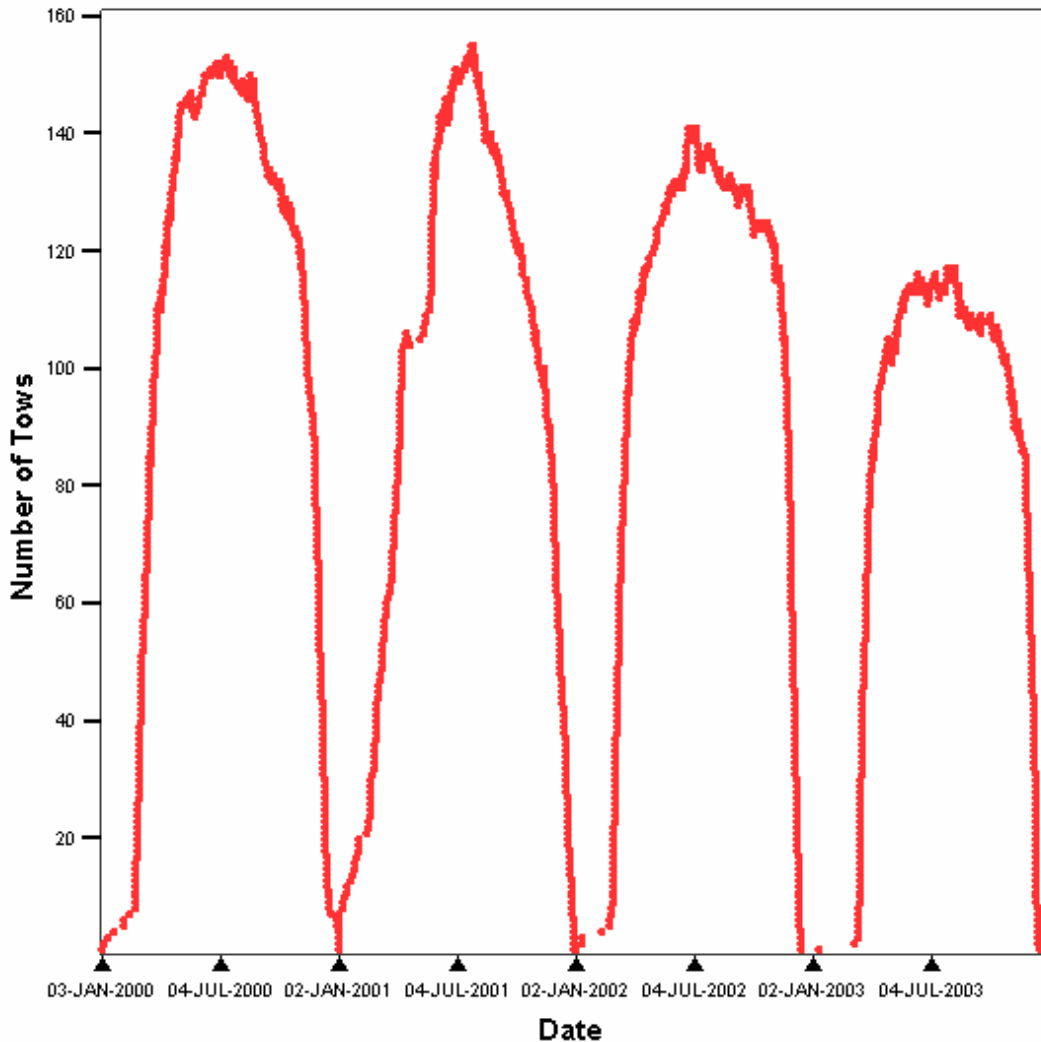


Figure 9. Number of tows that have produced at least one lockage in the UMR system but have not produced their final system lockage, 2000 through 2003

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.

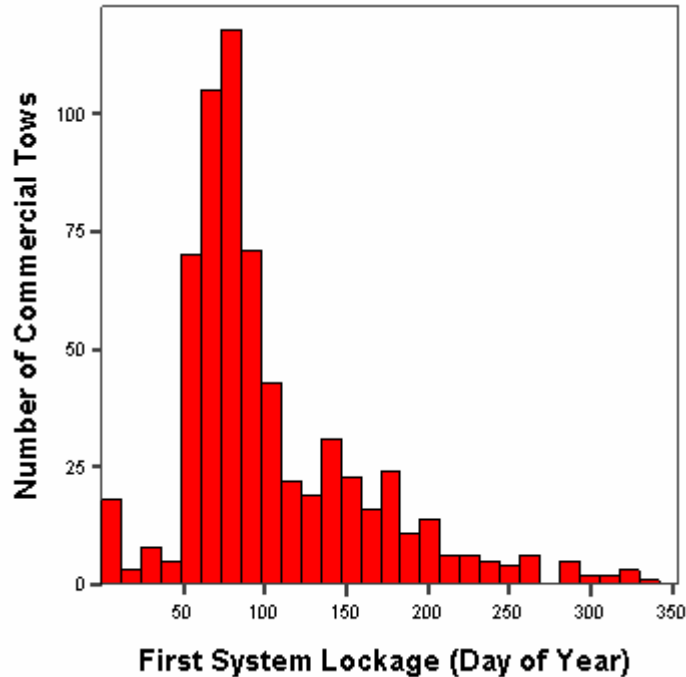


Figure 10. Day of the year of the first lockage of individual tows at UMR locks 20 through 25, 2000 through 2003

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.

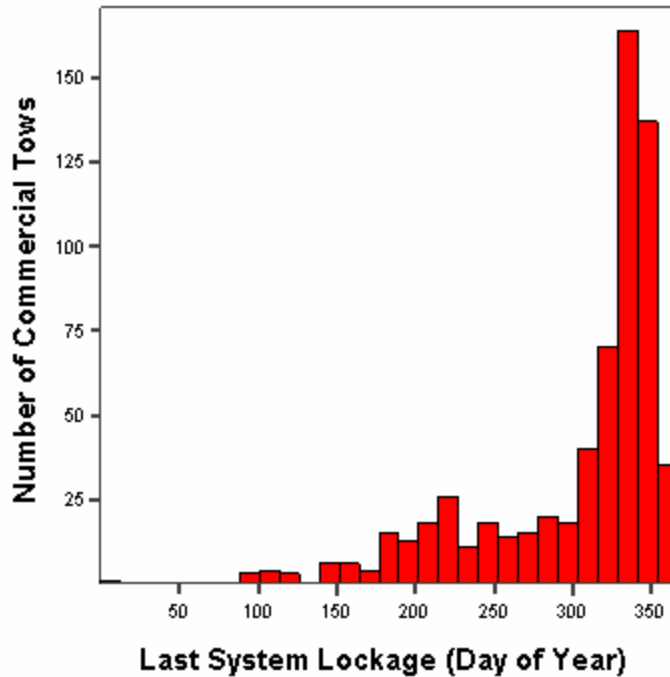


Figure 11. Day of the year of the final system lockage of individual tows at UMR locks 20 through 25, 2000 through 2003

To summarize, there is clear evidence of regular seasonality exhibited in the annual operation of the segment of the UMR between Lock 20 and Lock 25. 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 middle 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 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. As described earlier, to explore this effect, three mutually exclusive lock operation 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.

Tables 11, 12, and 13 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 direction of travel of the vessel and lockage type as defined above. Tables 11 through 13 reveal that there is an important dependency between the 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 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. 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 a relatively lengthy lockage. For similar reasons, turnback lockages for single cut tows are also significantly faster on average than exchange lockages at all locks in both directions with the 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 usually associated with the longest lockage times at all the locks. For recreation vessel traffic at the locks, turnback lockages are quicker than exchange lockages at some locks, exchange lockages are the fastest at other locks, and fly lockages are 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% of the 23,004 turnback lockages identified in the OMNI data began at the end of the 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 ten 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.

Table 11. 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	1.89	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 12. Selected summary statistics of lockage time distributions for tows traveling upbound, 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 13. Selected summary statistics of lockage time distributions for recreation lockages, 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

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

Sweeney (2004) presented an initial version of the simulation model with a simplified representation of traffic movements on the UMR. In this model, tows arrived according to seasonal patterns at Lock 25 (as single or multi-cut tows) and they cycled through the entire section of the river north of Lock 25 through Lock 20. Recreational lockages were generated independently according to seasonal patterns at each lock. Commercial vessels would leave northbound at Lock 20 and later return southbound at Lock 20 for their next lockage. They would leave Lock 25 southbound and then later return for a northbound lockage at Lock 25, finally departing southbound from Lock 25 at the end of the shipping season. The tows never changed 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 where a substantial portion of vessels (especially single tows) stop in a pool for a change in configuration and possibly switch direction rather than continuing on to the next lock. Statistical modeling was therefore undertaken to support two levels of enhancement to the initial simulation model.

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 completing 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

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. After each intermediate lockage, 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 exiting 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 the simulation model are represented, after each upstream or downstream departure from a lock as follows.

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 vessel will either 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; 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).

The likelihood (percentage of occurrence in the OMNI database) is calculated for each possibility.

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: the times and duration of breakdowns at locks and reasons for impaired performance (e.g., fog, equipment malfunction, vessel breakdowns); and the daily sunrise and sunset times for distinguishing night operations.

Impairment data were imported into a SAS dataset. A SAS program was used to create a record for each lock, including start times, end times, and the reasons for each of the impairments 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 A.3 (downloadable from <http://www.cts-umsl.org/waterways>).

Acquisition of Industry Data for Vessel Movements and Fuel Consumption

One purpose of this 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 vessel positioning information might be used to alter the lockage sequence of vessels or permit accurate scheduling of lock appointments and to 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 radio communications, proper traffic etiquette on the river, and collective action when bottlenecks are severe, already achieves some or all of 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 are used to alleviate congestion when necessary. For reasons stated earlier, the OMNI data do not allow us to validate the possibility of fuel savings arising from adjustments in cruising speeds. The data could, however, be used to investigate the extent to which rules other than first-come, first-serve are used to expedite lockages. Industry supplied data would be highly desirable to ensure that we establish an accurate benchmark for system performance and to ensure that simulated traffic movements are consistent 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 initially met with the president of the Midwest Area River Coalition (MARC) 2000, in the early spring of 2004. MARC 2000 is an advocacy group comprised of UMR-IW stakeholders formed to promote navigation infrastructure improvements to the UMR-IW. MARC 2000 originally agreed to help our team gain access to industry leaders. However, no such assistance was forthcoming.

In the light of the difficulty of arranging industry contacts through MARC 2000, we contacted the president of the National Waterways Conference (NWC) requesting that our study team be permitted to interact with industry leaders when they met for the upcoming NWC annual convention in St. Louis. The NWC president declined to facilitate any such interaction.

Unable to get industry cooperation through formal waterway organizations, we contacted senior executives of seven leading barge companies operating on the UMR asking for cooperation with the study in the form of their permitting the study team access to proprietary operational data, including the following:

- Positional information (Vessel ID with longitude and latitude or river and mileage point) at the smallest time interval available; data could be at fixed intervals or event driven
- Fuel burn since previous reporting time
- Tow configuration (number of full barges, number of empties, total weight (or draft))
- Other vessel characteristics affecting fuel consumption (power plant and propulsion)

The executives declined to accommodate our request for their proprietary data. We continued, 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 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:

- 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, estimates the following:

- 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 call-in point 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).

We constructed equations for transition probabilities and operational times:

- 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); 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

- $Ldlockhrs$ = 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); 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)
- $Logstrnhrs$ = 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 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
- $Transithrs$ = 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 the following:

- Logistical models for determining next lockage location and tow configuration, considering month of year and 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) and 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 (downloadable from <http://www.cts-umsl.org/waterways>). Table 14 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. SAS datasets were created giving the time between and the 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 (downloadable from <http://www.cts-umsl.org/waterways>).

Water Conditions

Data from the Corp's Rock Island District 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 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.

Table 14. Definitions of variables used in statistical models

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

Generation of Tows in Pools

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 (non-stationary 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 (downloadable from <http://www.cts-umsl.org/waterways>).

Summary

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

- Seasonal distributions of times between breakdowns at locks and duration of breakdowns at locks are incorporated into the simulation model as independent events at each lock according to seasonal data.
- Water level data and flow rates did not seem to enhance the statistical models and were not complete for all pools, so they are not incorporated in the simulation model.
- Consideration of sunrise and sunset times in determining the percentage of time that an activity occurs in daylight (or conversely, at night) is allowed in some statistical models, but is not incorporated into the simulation model.
- Consideration of the percentage of vessel transit time that occurred during impairment at the succeeding lock is allowed in some statistical models but is not incorporated into the simulation model.

TRAFFIC MANAGEMENT ALTERNATIVES

Introduction

An array of potential traffic management policy alternatives for the UMR navigation system is outlined below. Any of these traffic management policies can be implemented for managing traffic congestion in the Upper Mississippi River navigation system. All of the identified alternatives focus exclusively on the management of commercial tow traffic, but each can be readily extended to manage recreation vessel traffic in the UMR system if desired.

These six alternatives are described below in order from least intrusive to most intrusive with respect to their effect in altering the current operating practices of the water transportation markets currently served by the UMR system. Market disruptions 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 in order to schedule appointments at locks as they progress through the system, to very large, such as requiring commercial tows to schedule their entire itinerary before they receive permission 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. For example, re-sequencing vessels in lock queues will create economic winners and losers depending on if the individual operator's vessels are advantaged or disadvantaged by the re-sequencing policy.

More intrusive alternatives would require development of software to create a lockage management information system (LMIS) that calculates appointment times, re-sequences vessels or facilitates traffic control. The inputs for such an LMIS may be derived from existing static or dynamic data sources (e.g., the Corp's OMNI data) or they may be provided by new sources such as a vessel tracking system. Some discussion of the incremental costs is included for each alternative below and details are presented in Volume 2 of this report.

Traffic Management Alternatives

Alternative 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 (FCFS) basis. Exceptions to this 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 FCFS 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 sustained 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 (FCFS) lock

policy, leaving the system traffic management as it exists is the least intrusive traffic management policy.

Alternative 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 they progress towards a lock. The appointment time for the vessel can be updated as the state of the lock or larger system changes using available information in the Corps OMNI system, possibly 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.

The cost to implement a system that schedules vessel appointments at locks depends on the type of appointment information system implemented. A simple such system could use the existing OMNI data (e.g., lockage completion time and destination), along with historical data on lockage times, to estimate when a vessel would arrival at a lock and the time it could start its lockage. A more sophisticated appointment information system could use real time vessel positions and speeds from a vessel tracking system to better estimate arrival times and start of lockage times. A simple system based only on the OMNI data would likely have a very small cost to implement. The cost for a more sophisticated system with real or near-real time vessel tracking would be larger, but would still be small relative to the market for transportation on the UMR.

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

When queues do form at a lock, vessels could be re-sequenced according to an optimization model designed to produce a better traffic management solution for clearing the queues than the FCFS 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 the other vessels that are relegated to waiting for the more valuable traffic to pass. After this discussion of alternatives, the details of an algorithm is presented that is designed to implement such a policy.

The cost to implement a system that re-sequences vessels in lock queues locally would likely be very small. Such a system would take the list of vessels in the queue and their relevant characteristics as the inputs, and it would produce a suggested lockage sequence as output. A simple system for re-sequencing could be based solely on the current lock queue list as maintained in the Corp’s existing OMNI data. A more sophisticated version might also use historical data on recent lockage times for a vessel to find a better sequence.

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

This traffic management alternative is nearly identical to the policy "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 using available information in the Corps OMNI system, possibly supplemented by information provided by a vessel tracking system.

The cost to implement a system that re-sequences vessels in extended lock queues depends on the type of re-sequencing information system implemented. The input for such a system would include the list of vessels in the extended queue and their relevant characteristics, and the output would be a suggested lockage sequence. A simple such system could use the existing OMNI data to provide the "local" lock queue and to estimate the arrival times of vessels not yet in the "local" queue (e.g., based on the previous lockage completion time and the destination). This could be integrated with historical data (e.g., on lockage times) in the re-sequencing algorithm to provide the suggested lockage sequence for the extended queue. A more sophisticated re-sequencing LMIS could use real time vessel positions and speeds from a vessel tracking system to better estimate arrival times and start of lockage times for vessels not in the "local" lock queue. A simple system based only on existing data would likely have a very small cost to implement. The cost for a more sophisticated system with real or near-real time vessel tracking would be larger than that for a system that re-sequences only the local lock queues, but it would likely still be small relative to the market for transportation on the UMR.

Alternative E: Managing Traffic by Re-sequencing Vessels in Multiple Lock Queues Simultaneously

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 using available information in the Corps OMNI system, possibly supplemented by information provided by a vessel tracking system.

The cost to implement a system that re-sequences vessels in multiple lock queues simultaneously would be larger than that for a comparable system that considers re-sequencing at lock queues separately, due to the needs for data sharing and integration among multiple locks over a larger geographic region. A simple such system that uses only existing data would likely have a small

cost to implement. The cost for a more sophisticated system with real or near-real time vessel tracking would be larger than that for a system that re-sequences lock queues independently.

Alternative F: System-wide Traffic Management Using Vessel Tracking

This traffic management alternative continually monitors and manages the location and direction of all river traffic. It requires a system, operating similar to Air Traffic Control, that 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.

The cost to implement system-wide river traffic management using real time or near-real time vessel tracking would be larger than that for the other options above, but would still be small relative to the magnitude of the industry. System-wide traffic management would likely require a traffic management information system similar to that currently in use at the U.S. Coast Guard's vessel traffic services (VTS) centers or on the St. Lawrence Seaway (see Volume 2 of this report for more details). Such a system would capture vessel position and performance data in real (or near-real) time, integrate the information with relevant data for managing lockages, and provide support for improving traffic flow along the river. While the cost for such a system would likely be measured in the millions of dollars (as with VTS centers), the benefits of such a system could extend well beyond reducing congestion from better managing lockages.

Limitations on Evaluating Traffic Management Alternatives

The lack of industry participation in our study, documented above, severely constrains our ability to complete a quantitative economic evaluation of the alternative traffic management measures. For example, a lock appointment system designed to better schedule tow arrivals at system locks is expected to primarily produce reduced fuel usage by tows relative to their fuel usage under the existing first-come, first-served lock operating policy. Consequently, to measure the economic benefits of reduced transportation costs afforded by reduced fuel usage we require current information on fuel use by tows operating in this segment of the UMR. No tow operating company would share that information with us and a search of the literature revealed no applicable published studies regarding fuel savings resulting from better optimized sailing speeds on the UMR afforded by a time certain lock appointment.

Further, no tow operating companies publish detailed information regarding revenues attributable to their operations on the UMR-IW and none of the tow companies we contacted would share that information with us. As the opportunity to generate additional revenues from the more efficiently utilized transportation assets is the primary source of current economic benefits afforded by reducing waiting times at locks and improving lock efficiency with alternative traffic management policies, we are unable to quantify with any precision the economic benefits of the other alternative traffic management policies.

Finally, the statistical analysis of the Corps OMNI data presented above reveals a decreasing trend in the utilization of these locks during the period 2000 through 2003 with relatively low

levels of annual lock utilization evident in 2003. Low levels of lock utilization reduce the need to coordinate traffic management policies at groups of locks or over large sets of vessels. We investigated the existence of this trend back through the most recent peak usage levels of these locks in the early 1990's. Table 15 presents the annual number of barges processed at each of the five locks beginning in 1990 and continuing through 2004. As evidenced in Table 15, lock utilization measured by the number of barges processed has declined over the fifteen year period by over 40% at each lock and the recent decline in lock utilization evident in our data does indeed appear to be the continuation of a much longer term trend. A continuation of this trend would foretell even lower rates of lock utilization in the future that would further decrease the incremental efficiencies afforded by measures that coordinate traffic management between multiple locks.

**Table 15. Annual number of barges processed at UMR locks 20 through 25
(Source: US Army Corps of Engineers lock performance monitoring system)**

Lock	2004	2003	2002	2001	2000	1999	1998	1997	1996	1995	1994	1993	1992	1991	1990
20	23,445	29,415	34,537	29,307	34,066	37,745	31,403	31,398	35,293	36,454	26,076	23,838	38,728	36,857	41,858
21	24,359	30,460	35,252	31,197	35,760	39,095	33,173	32,975	36,848	37,389	27,393	25,390	39,862	37,945	42,941
22	24,315	30,568	35,472	31,329	36,000	39,237	33,289	33,367	36,905	37,773	27,598	25,780	40,269	38,375	43,513
24	25,304	32,158	38,101	33,068	37,909	40,372	34,258	34,665	38,304	39,326	29,137	27,933	41,863	39,748	45,031
25	25,363	32,201	37,183	33,283	38,064	40,629	34,436	34,654	38,494	39,468	29,192	27,794	41,795	39,797	45,057

Consequently, measures designed to optimize traffic management over extended lock queues or multiple lock queues simultaneously are unlikely to afford significantly more economic benefits than just simply re-sequencing tows optimally at local lock queues whenever a queue occurs. Therefore, we limit our explicit economic evaluations to alternatives that attempt to improve the operation of the locks separately rather than jointly and attempt to gauge the order of magnitude of the extra productivity of the barges and tows operating in the UMR system under Traffic Management Alternative C.

The next section provides an algorithm that may be used to optimize the processing of vessels in local lock queues. The algorithm is readily extendable to optimize extended lock queues that include vessels traversing the upstream and downstream pools at a lock.

A LOCALLY OPTIMIZED VESSEL SEQUENCING ALGORITHM FOR EFFICIENTLY CLEARING A LOCK QUEUE

If queues form at a lock, an optimization model can determine what lockage sequence of tows 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 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 tows processed). For our purposes, cycle time is the sum of queue time plus lockage time for a tow.

In order to highlight the difference between these two objectives, we consider a hypothetical case consisting of two tows in a lock queue. A detailed description of an actual lock queue is presented in Volume 2 of this report. One tow, TOW1, has fifteen barges with an estimated lockage time of 90 minutes heading upstream. The second tow, TOW2, 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 TOW1 (heading upstream) is processed first, there is a delay of 10 minutes until TOW2 (heading downstream) may enter the lock. If TOW2 is processed first, there is a delay of 5 minutes until TOW1 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
TOW1 90	0	90
TOW2 105	90+10	205

or

Est. Lockage Time	Est. Lockage Start Time	Est. Lockage Completion Time
TOW2 105	0	105
TOW1 90	105+5	200

In this example, the queue is cleared in **205** minutes using a TOW1:TOW2 sequence or in **200** minutes using a TOW2:TOW1 sequence. Thus the TOW2:TOW1 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 tow, we see that the TOW1:TOW2 sequence would be preferred when calculating a total weighted completion time, as below, where **4425 < 4575**.

	Weighting	ELT	ELST	ELCT	Weighted Compl. Time
TOW1	15	90	0	90	90*15=1350
TOW2	15	105	90+10	205	205*15=3075
Total Wgt. Compl. Time					4425

or

	Weighting	ELT	ELST	ELCT	Weighted Compl. Time
TOW2	15	105	0	105	$105 \times 15 = 1575$
TOW1	15	90	$105 + 5$	200	$200 \times 15 = 3000$
Total Wgt. Compl. Time					4575

Given this behavior, we seek to find a “best” sequence of tows through a lock. At this point we appeal to results from the production scheduling literature.

Consider a one machine production line where three jobs are to be processed with each job having a different expected processing time. This is known as the “classical job shop scheduling problem.”

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) required for each job.

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 that this is different from the average processing time which is not a function of the job sequence in this example.

Now consider a job sequence of B, A, C.

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

The first is a FCFS protocol. Here we order tows separately on each side of the lock according to FCFS. Then we have an FCFS order for all tows headed downstream and another FCFS order for all tows 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 an N up/M down protocol also serves to reduce the delay for a tow over and above a strict FCFS protocol where tows were processed through the lock regardless of which side of the lock they were on. A strict FCFS protocol simply sequences the tows in the overall order in which they arrived at the lock.

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

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

Description of the Optimization Model

Assumptions

Let N be the total number of tows in queue.

Let N_D be the total number of tows in queue on the downstream side of the lock.

Let N_U be the total number of tows in queue on the upstream side of the lock.

For $i = 1, \dots, N_D$ (N_U) generate an expected lockage time, t_{Di} (t_{Ui}), for each tow. Note that this time may depend on whether the tow is on the downstream (D) or upstream (U) side of the lock. For $i = 1, \dots, N_D$ (N_U) generate a weight, w_{Di} (w_{Ui}), for each tow. 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 tow. For protocols 1 and 2 we set $w_{Di} = w_{Ui} = 1$.

We then order the downstream tows as $1, \dots, N_D$, and the upstream tows as $1, \dots, N_U$ 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) tows 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) tow passing through the lock followed by a downstream (upstream) tow. This is also referred to as an exchange situation. (Generally $OPP > SAME$).

Define a maximum delay constant: let D be the maximum delay time allowed for any tow over and above the *strict* FCFS protocol for sequencing queued tows through the lock. Further, calculate $FCFSx_i$ for $i=1, \dots, N_D$ and $FCFSy_i$ for $i=1, \dots, N_U$. 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 TOW, and let $ENDLOCK_0$ be the starting lockage time for the first tow through the lock.

For $j=1, \dots, N-1$ define

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

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

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

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

For $i=1, \dots, N_D$ and $j=i, \dots, (N_U+i)$ define

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

For $i=1, \dots, N_U$ and $j=i, \dots, (N_D+i)$ 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 tows 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)

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

subject to:

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

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

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

$$(5) \quad ENDLOCK_0 = 0$$

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

$$(6b) \quad ENDLOCK_{(j-1)} + \sum_{i=1}^{N_D} t_{Di} x_{ij} + \sum_{i=1}^{N_U} t_{Ui} y_{ij} + SAME_U Z_{(j-1)UU} + SAME_D Z_{(j-1)DD} + OPP_U Z_{(j-1)UD} \\ + OPP_D Z_{(j-1)DU} = ENDLOCK_j \text{ for } j = 2, \dots, N$$

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

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

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

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

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

$$(12) \quad y_{ik} \leq \sum_{j=k+1}^{N_D+N_U-1} y_{i+1,j} \quad \forall i = 1, \dots, N_U - 1; \forall k = i, \dots, \text{MIN}(N_D + N_U - i, N_D + i)$$

$$(13) \quad \sum_{\substack{i \leq \text{MIN}(j, N_D) \\ i \geq \text{MAX}(1, j - N_U)}} x_{ij} + \sum_{\substack{i \leq \text{MIN}(j, N_U) \\ i \geq \text{MAX}(1, j - N_D)}} y_{ij} = 1 \quad \forall j = 1, \dots, N$$

$$(14) \quad \sum_{j=i}^{N_U+i} x_{ij} (\text{ENDLOCK}_j) \leq \text{FCFS}x_i + D \quad \forall i = 1, \dots, N_D$$

$$(15) \quad \sum_{j=i}^{N_D+i} y_{ij} (\text{ENDLOCK}_j) \leq \text{FCFS}y_i + D \quad \forall i = 1, \dots, N_U$$

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

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

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

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

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

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

From the above formulation we see that constraints (2) and (3) force each tow 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 tow in sequence. Constraints (7) through (10) force the corresponding Z variable to 1 when two particular tows are sequenced through the lock thus incurring one of the four setup times. Constraints (11) and (12) ensure that the tows on each side of the lock are processed in the order $1, 2, \dots, N_D(N_U)$. Constraint (13) ensures that either an upstream or downstream tow is processed through the lock as the j th tow. Constraints (14) and (15) ensure that no tow 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 tows passing through the lock may be modeled as follows.

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

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

$$\begin{aligned}
Z_{1UU} + Z_{2UU} + Z_{3UU} + Z_{4UU} &\leq 3 \\
Z_{2UU} + Z_{3UU} + Z_{4UU} + Z_{5UU} &\leq 3 \\
&\vdots \\
Z_{16,UU} + Z_{17UU} + Z_{18UU} + Z_{19UU} &\leq 3 \\
Z_{1DD} + Z_{2DD} + Z_{3DD} + Z_{4DD} &\leq 3 \\
Z_{2DD} + Z_{3DD} + Z_{4DD} + Z_{5DD} &\leq 3 \\
&\vdots \\
Z_{16DD} + Z_{17DD} + Z_{18DD} + Z_{19DD} &\leq 3
\end{aligned}$$

Throughout this section we have invoked a protocol ordering on each side of the lock. That is, we require that for tows on one side of the lock, the ordering invoked will be the ordering used to process tows through the lock (although tows from the other side of the lock may be interspersed). We now provide 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, FCFS.

Let $\text{ENDLOCK}(\cdot)$ be the end of lockage time for (\cdot) under a TOW1:TOW2 ordering, and let $\text{ENDLOCK}(\cdot)$ be the end of lockage time for (\cdot) under a TOW2:TOW1 ordering.

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 TOW1 and TOW2 approach the lock from the same side. Let TOW1 have an unweighted lockage time of A units and TOW2 have an unweighted lockage time of $A + B$ units where $B > 0$. Then according to protocol 2, TOW1 should be processed through the lock before TOW2. We would then have $\text{ENDLOCK}(\text{TOW1}) < \text{ENDLOCK}(\text{TOW2})$ and we let $\text{ENDLOCK}(\text{TOW2}) = \text{ENDLOCK}(\text{TOW1}) + S + A + B$ where $S > 0$ denotes the setup and processing time for tows from the other side of the lock that are processed between TOW1 and TOW2 (if any—if none, then S denotes the setup time required to process TOW2 directly after TOW1).

Now assume that in an optimal solution TOW2 precedes TOW1. Since TOW2 is processed before TOW1, we have $\text{ENDLOCK}(\text{TOW2}) < \text{ENDLOCK}(\text{TOW1})$ and $\text{ENDLOCK}(\text{TOW2}) = \text{ENDLOCK}(\text{TOW1}) + B$. Also $\text{ENDLOCK}(\text{TOW1}) = \text{ENDLOCK}(\text{TOW2}) + S + A$.

Compare the objective values.

For the TOW1:TOW2 ordering our objective function is:

$$\begin{aligned}
&\text{ENDLOCK}(\text{TOW1}) + \text{ENDLOCK}(\text{TOW2}) = \text{ENDLOCK}(\text{TOW1}) + \text{ENDLOCK}(\text{TOW1}) + S + A \\
&+ B = 2 * \text{ENDLOCK}(\text{TOW1}) + S + A + B.
\end{aligned}$$

For the TOW2:TOW1 ordering our objective function is: $ENDLOCK(TOW2) + ENDLOCK(TOW1) = ENDLOCK(TOW1) + B + ENDLOCK(TOW1) + B + S + A = 2*ENDLOCK(TOW1) + S + A + 2B$.

The latter total is clearly larger than the former implying that the ordering must be TOW1:TOW2.

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 $N=20$, $2^{20} \sim 10^6$ while $20! \sim 2*10^{18}$.

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 tows 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 twelve or fewer tows 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 ten with the sum being less than twenty). For queues larger than 24, we arbitrarily drop those in excess (say S tows) having the largest weighted times or the latest in terms of FCFS. Once S tows have passed through the locks we re-optimize with the S tows that were initially dropped.

Suppose the first tow upstream is to be sent through the lock. Then there are the following possibilities for the second tow through the lock: either the next tow 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 tow 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

Tows 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 tow to be locked through on one side of the lock may not be the tow that is closest to the lock. If, for example, a tow 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 tow 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 tows for passage by the weighting scheme and the next scheduled tow is then directed to tie up at the nearest tie up while waiting for passage through the lock.

Policy 2: When a queue forms, the tow 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 tow 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.

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.

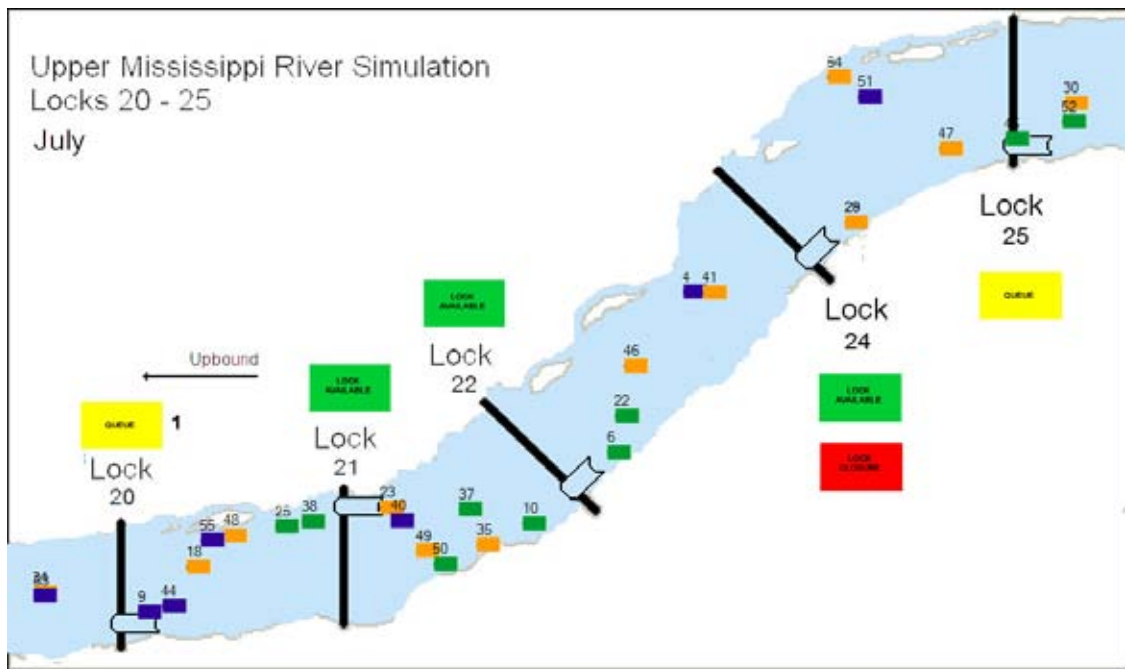


Figure 12. Screen capture of the Micro Saint Sharp display diagram for the UMR simulation model

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 (2002).

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. 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 next.

1. Recreation Vessels

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 16 displays the mean number of recreation vessel arrivals by lock and direction for each month of the simulation and Table 17 displays the inter-arrival times (time between arrivals) of recreation vessels similarly categorized.

Table 16. Mean number of recreation vessel arrivals by direction of travel and month, 2000–2003

Direction	Month	Lock					Grand Total
		20	21	22	24	25	
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
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
Grand Total		389.75	389.8	455.5	405.0	530.0	647.8

Table 17. Mean hours between recreation vessel arrivals by direction of travel and month, 2000–2003

Direction	Month	Lock					Grand Total
		20	21	22	24	25	
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
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
Grand Total		4407.1	2252.0	1431.6	1933.0	2631.9	12655.6

2. 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 feet 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.

3. 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. Table 18 and displays the mean number of tow arrivals by lock and direction for each month of the simulation, and Table 19 displays time between arrivals of tows similarly categorized.

Table 18. Mean number of tow arrivals by direction of travel and month, 2000–2003

Direction	Month	Lock					Grand Total
		20	21	22	24	25	
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 19. Mean hours between tow arrivals by direction of travel and month, 2000–2003

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

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 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 require no simulation time to execute. 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. A brief description of each task is provided 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 an altered 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 force 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 pre-defined intervals. Scenario events are used to change the operating conditions of the model at the time 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 increment 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.

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; Figure 14 displays a similar schematic diagram for recreation vessels; and Figure 15 displays the average annual number of commercial tows undertaking each of the tasks displayed in Figure 13.

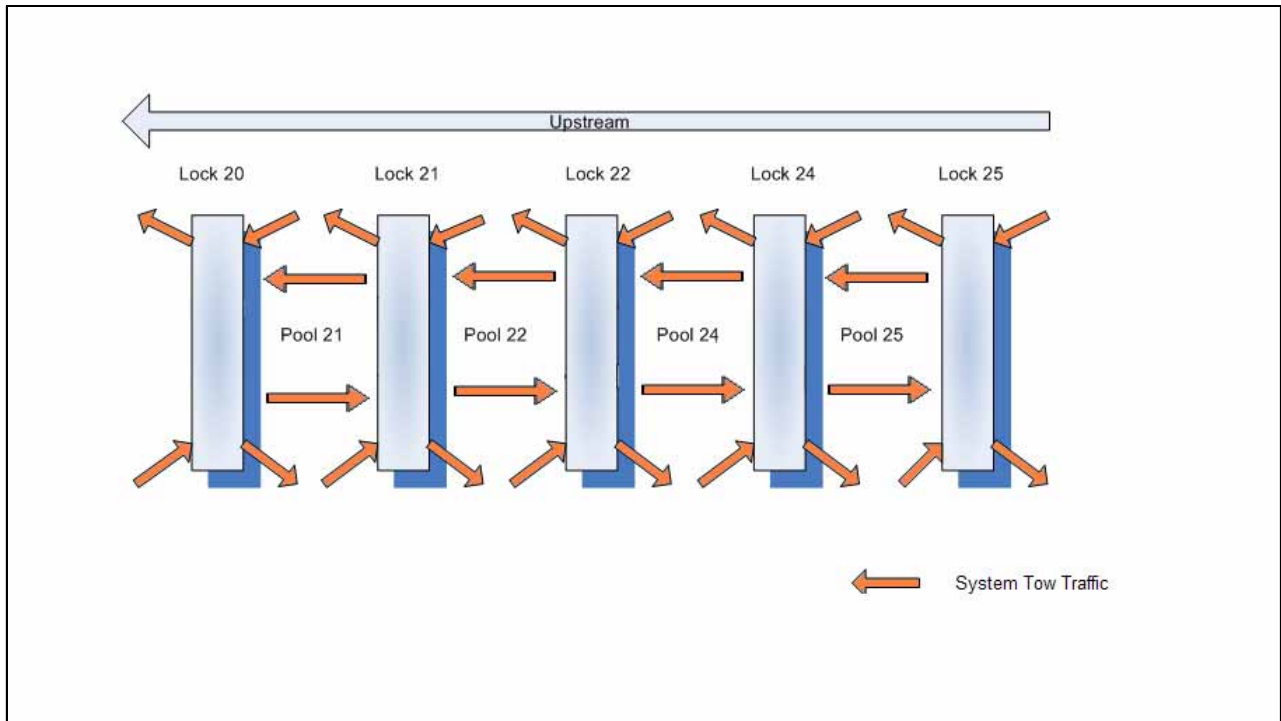


Figure 13. UMR simulation model schematic diagram–tow traffic

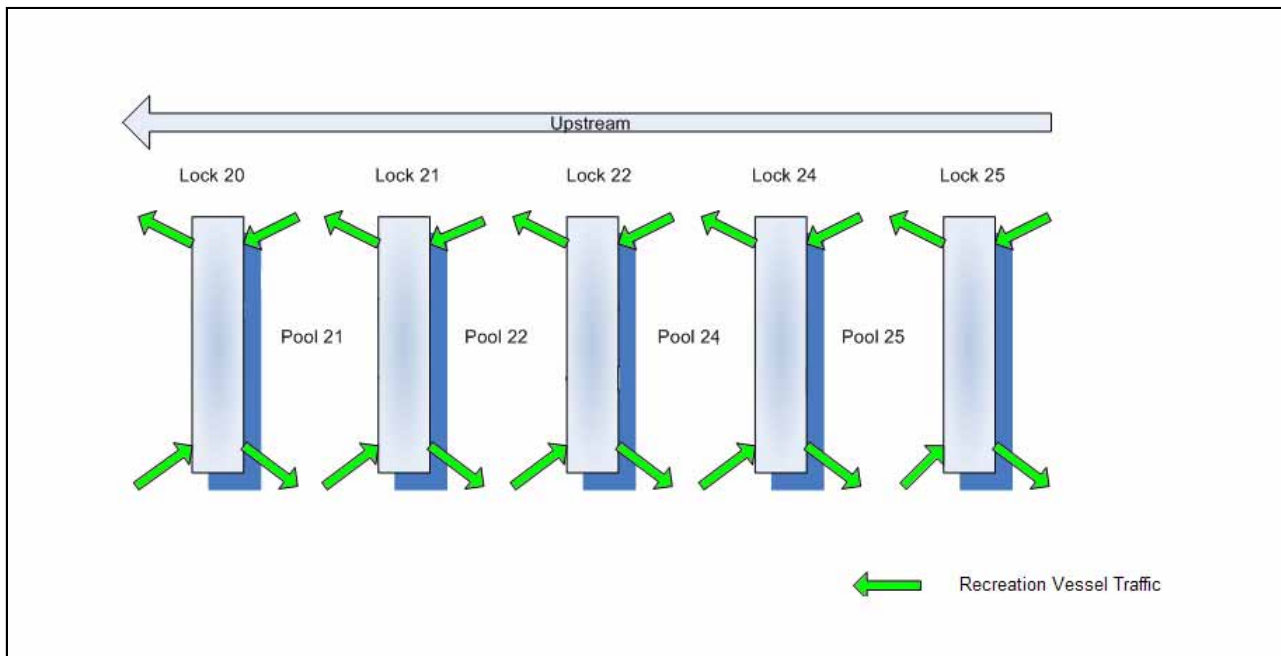


Figure 14. The UMR simulation model schematic diagram–recreation vessels

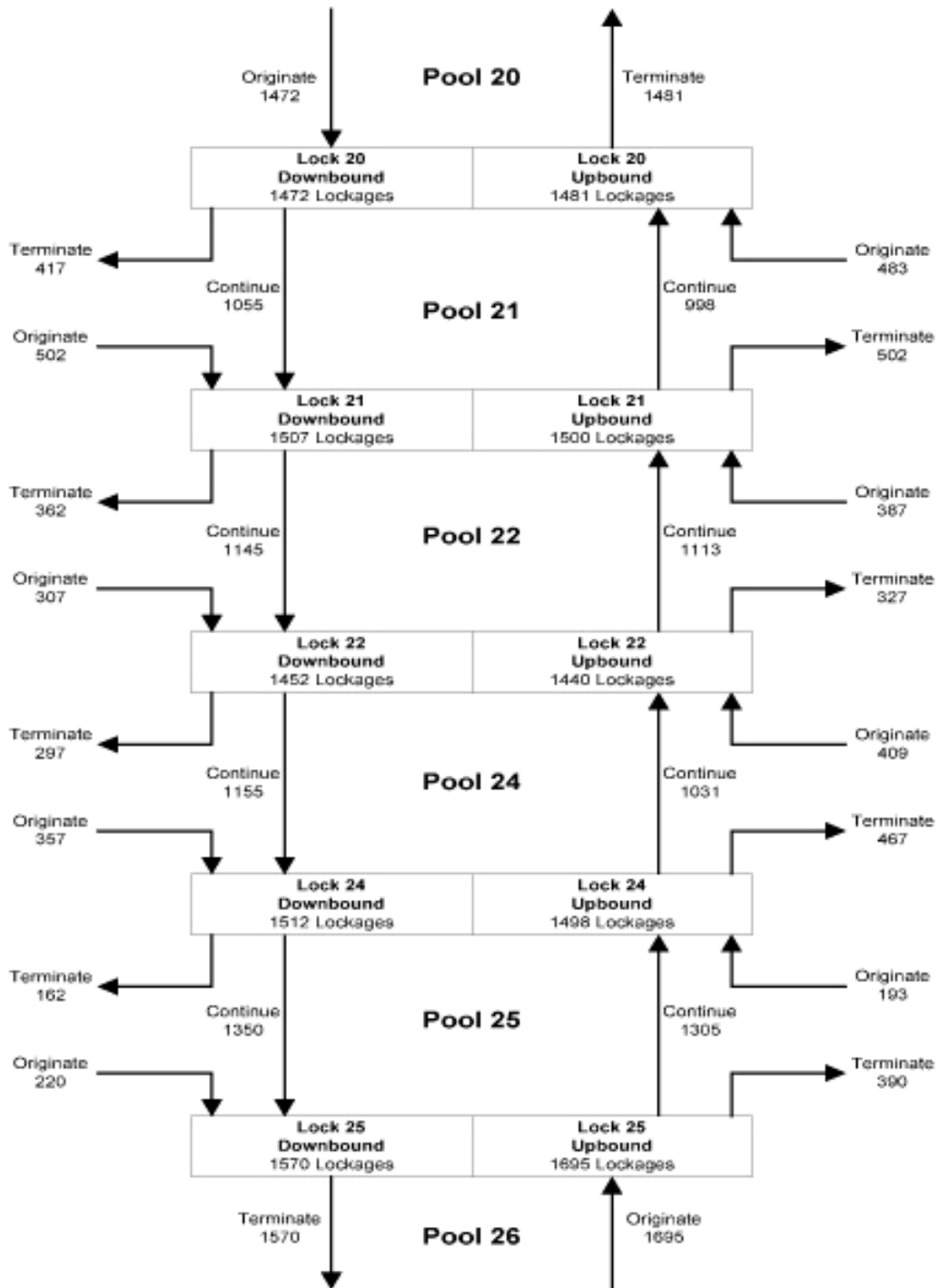


Figure 15. Average annual tow flows at UMR locks 20 through 25, 2000-2003

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 entire system, but rather only transit a single lock.

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 20 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 20. Vessel lockages, wait times, and lockage times at UMR locks compiled from OMNI data, 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 21 presents some selected summary statistics compiled from the results of 100 independent simulations of the annual operation of the five lock system completed by the UMR simulation model.

Table 21. Selected summary statistics compiled from 100 UMR simulation model runs

	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 22 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 0.7% 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% 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% of the observed average annual wait for lockage time and the simulated mean total lockage time of all vessels is within 1.3% of the observed average annual total lockage time of all vessels.

Table 22, panels A, B, C, and D further indicate 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% 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% of the OMNI statistic for all lock pools. Finally the mean simulated transit time through the pools connecting the locks is within 2.4% of the corresponding OMNI statistic for all four of the lock pools.

Table 22a. Selected details of the results of 100 UMR simulations and comparison with the 2000-2003 OMNI data

	Lock 20	Lock 21	Lock 22	Lock 24	Lock 25	Totals	%
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

Table 22b. 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 22c. Mean annual number of 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%

Table 22d. 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%

Figures 16 and 17 explore some important dynamic properties of the simulated UMR system. Each figure presents a graphic in which the simulated year is portioned into thirty-six 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 16 presents the average percentage of total time in each of these intervals that is utilized by vessels completing lockages in the system. Figure 17 presents the total number of vessels in lock queues at the end of each 240-hour interval.

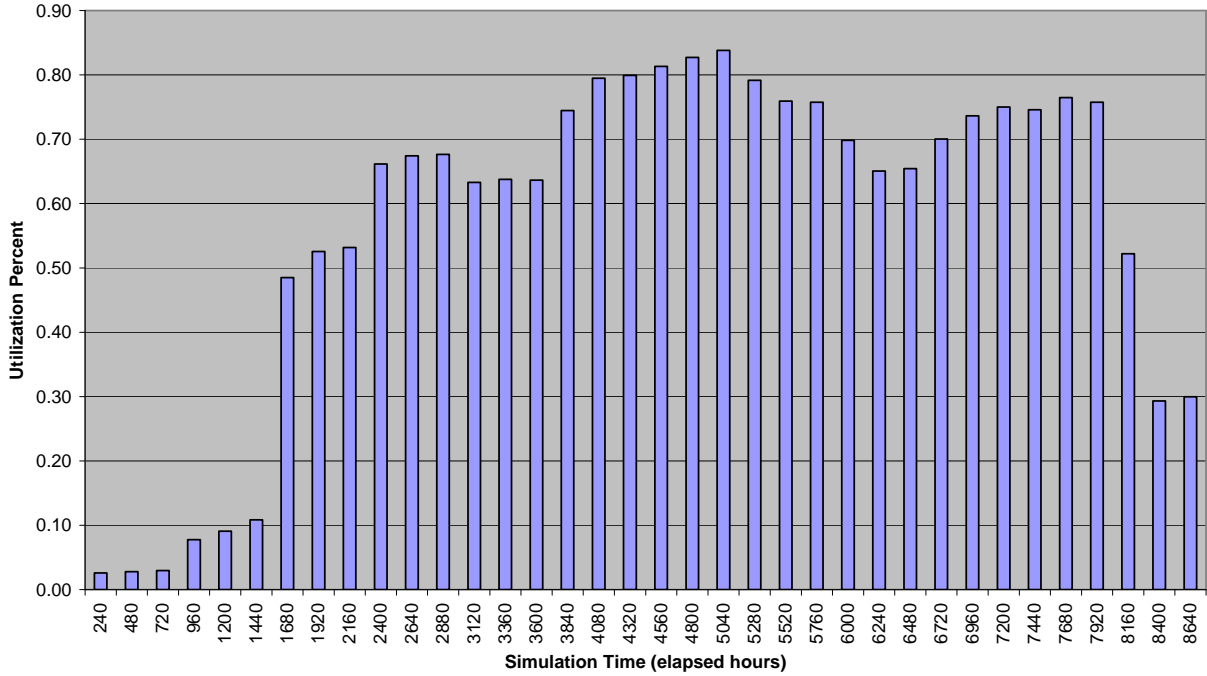


Figure 16. Mean simulated values of the total lock utilization percentages for UMR locks 20 through 25 for consecutive ten-day periods

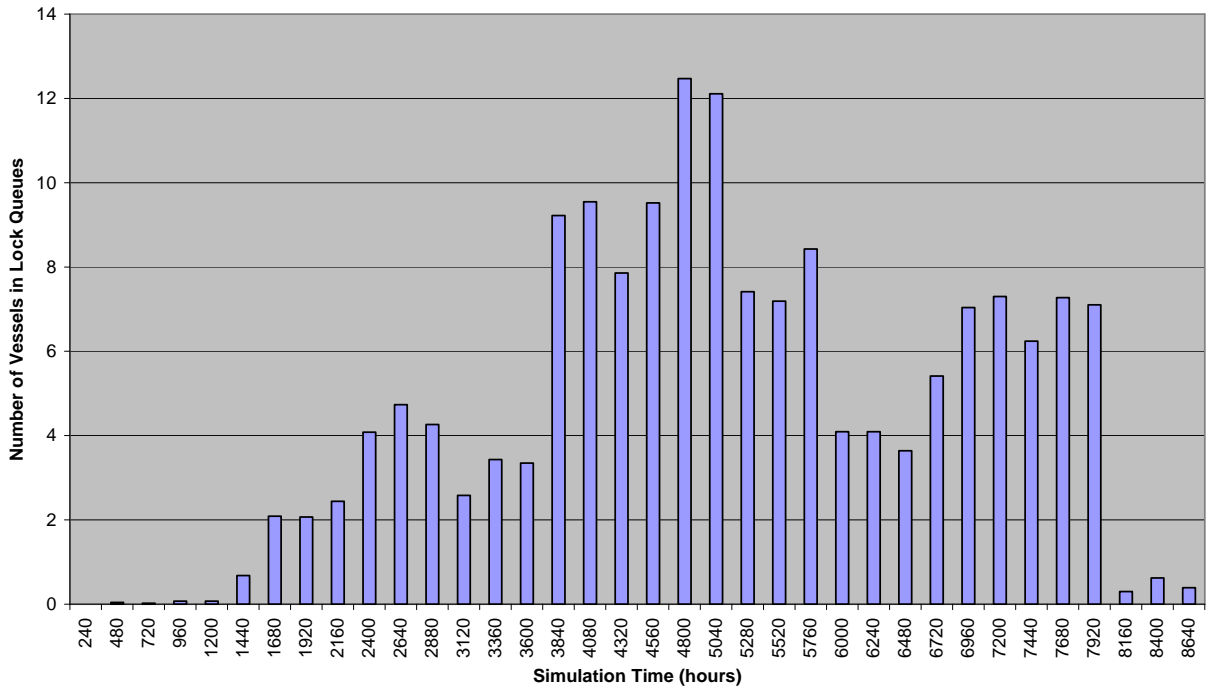


Figure 17. Total number of vessels waiting for lockage at selected times compiled from 100 runs of the UMR system simulation model

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 eight. 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 warrants 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. While there were significant delays from time to time in locking vessels in this congested segment of the river, the delays at Locks 20-25 constitute a small percentage of the total annual operational times for the tows. During the entire period 2000 through 2003, commercial tows spent approximately 0.7% of their time waiting for lockage and 0.4% of their time undergoing lockage at Locks 20-25. This fact implies that approximately 98.9% of the total time tows operate in the UMR-IW is spent in activities that will not benefit from relieving periodic lock congestion or improving lock efficiency. Clearly, this observation suggests that there is only a limited potential of increasing the existing utilization of inland navigation resources by employing traffic management policies, unless the volume of river traffic increases substantially above the recent historic levels evident in our data. 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 and costs of tows operating in the UMR system.

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 as follows: (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 earlier, 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 23 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 20.

Table 23. 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	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 24 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 24. Selected summary results of changes in selected variables resulting from employing 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 24 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 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 24 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.

For this reason, the tow re-sequencing policy would be somewhat disruptive to existing water transportation markets; however the disruption would yield a small increase in overall market efficiency. To put the size of the efficiency gain in perspective, Table 7 indicates that tows spent a total of 23,044,006 hours operating in the UMR-IW navigation system from 200 through 2003, which represents an average of approximately 5,761,000 tow hours per year devoted to operations in the UMR-IW. A decrease of some 4,300 hours in the total tow wait for lock service time represents an increase of approximately 0.07% in overall productivity for these tows. This is indeed a very small increase in tow productivity.

Figure 18 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 18 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.

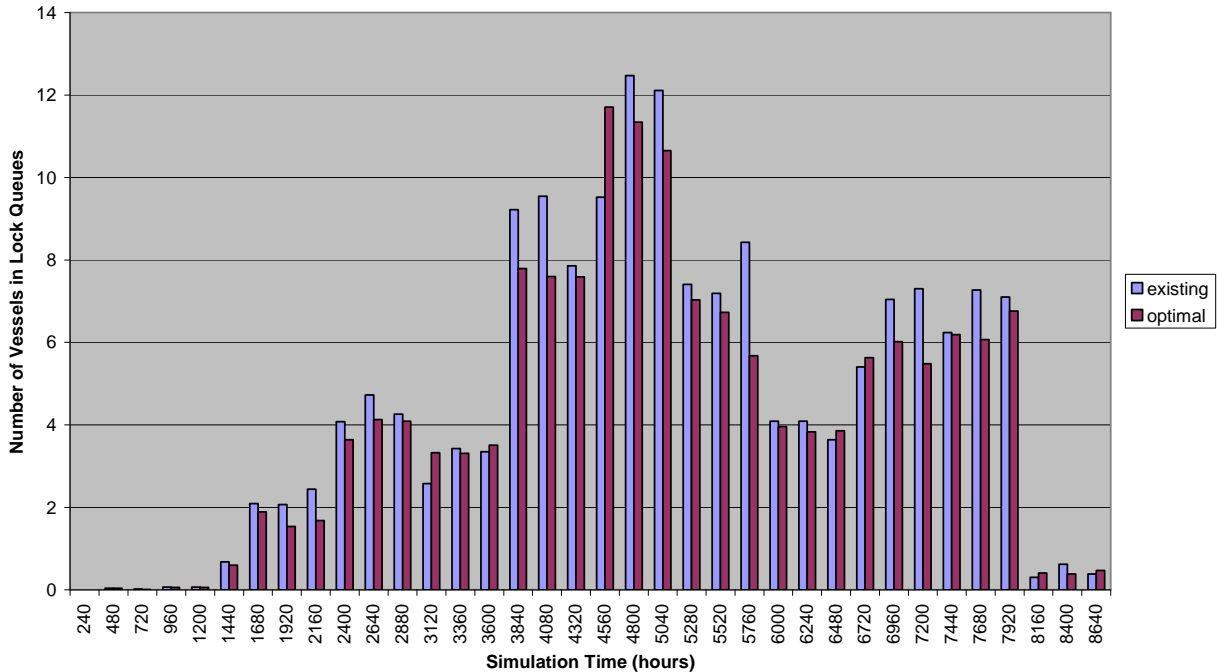


Figure 18. Comparison of the total number of vessels waiting for lockage at selected times with the existing and a locally optimal queue dispatch policy compiled from 100 runs each of the UMR system simulation model

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% 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 be only 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 annual 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 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 afforded by the average of 4,400 tow hours made available for productive re-use by the implementation of the tow re-sequencing policy. Assuming costless re-use of the freed up tow time and tow sizes evident on the Upper Mississippi River, Sweeney (2003)

estimates a market value of approximately \$170 per freed up tow hour (2002 price levels) which yields a total economic value averaging approximately \$750,000 per year resulting from the implementation of the tow re-sequencing policy.

To view this annual benefit estimate in context, the U.S. Army Corps of Engineers (2004) estimates the total annual economic benefits of the current operations of the UMR-IW navigation system to be between \$700 million and \$1.1 billion (2002 price levels). A \$750,000 average annual increase in the economic benefits of the operation of the system created by this tow re-sequencing policy represents approximately a 0.1% increase in the value of the output of this portion of the inland navigation system.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

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 first-come, first-served policy, first come first served, tow processing policy for this segment of the UMR navigation system. The implementation of this traffic management policy has a very small beneficial 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 very small amount by reducing the expected level and variability of lock delays in the simulated system. The traffic management policy also creates differential winners and losers relative to the existing FCFS policy which in turn will create disruptions in the operation of the existing UMR water transportation market.

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 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 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 and, consequently, other sources of data will be needed to extend the model in this direction. 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.

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 will improve the representation of tow activities. 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 UMR 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.

Conclusions

At current traffic levels evident on the UMR, the economic benefits of new traffic management policies will be very 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 19 summarizes the last five years of congestion data for these five UMR locks.

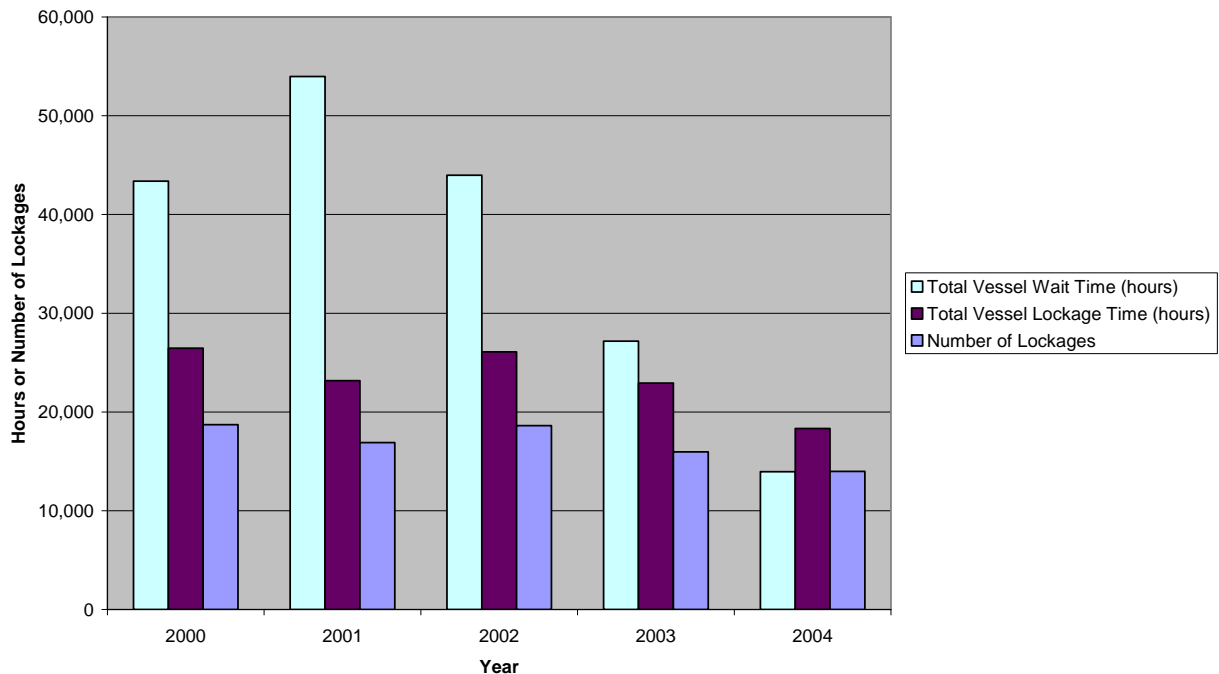


Figure 19. Total annual wait for lock service time and total lockage time, locks 20 through 25, all vessels, 2000–2004

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 are always locked first, then companies operating multi-cut tows could expect a negative economic impact on their operations.

Recommendations

1. Therefore, 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. Table 25 presents a summary of our evaluation of alternative traffic management policies. However, if traffic levels dramatically increase or lock performance and reliability dramatically degrade, implementing new traffic management policies could yield significant economic benefits that potentially outweigh the costs of disruptions in existing water transportation markets served by the UMR.
2. We recommend that alternative traffic management policies be evaluated under conditions of both significantly increased traffic levels and conditions of decreased lock performance and reliability to ascertain their effects and desirability in those circumstances.

Table 25. Summary of evaluations of alternative traffic management policies

Alternative	Incremental Benefits¹	Incremental Costs²	Market Disruption³
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	intermediate	significant
6. System-wide traffic management using enhanced vessel tracking	small	large	extensive

¹ These incremental benefits are reported relative to the existing economic benefits generated by water transportation through the UMR-IW navigation system. The U.S. Army Corps of Engineers (2004, pages Econ-152 to Econ-166) estimates the existing economic benefits of the entire UMR-IW navigation system to be between \$700 million and \$1.1 billion per year. The UMR segment contributes approximately one-half of these total economic benefits. “Very small” here means incremental annual benefits less than \$750,000. “Small” here means between \$750,000 and \$1,000,000.

² These qualitative descriptions of incremental costs are not directly comparable to the incremental costs. See Volume 2 for details.

³ Market disruptions range from minor changes in the manner that the industry functions and tows currently operate such as sailing at different speeds (negligible market disruption) to extensive market disruption such as the requirement to gain permission from a water traffic controller to begin any movement of any water flotilla.

REFERENCES

- Carroll, J. L. 1972. *Analysis of Waterway Systems*. Final Report. Chicago, IL: U.S. Army Corps of Engineers, North Central Division.
- Carroll, J.L. and M.S. Bronzini. 1973. Waterway transportation simulation models: Development and application. *Water Resources Research* 9(1): 51-63.
- Dai, M.D.M. and P. Schonfeld. 1994. Metamodeling approach for approximating series of G/G/1 queues on congested waterways. *Proceedings of the First ASCE Congress on Computing in Civil Engineering*, Washington, D.C.
- Dai, M.D.M. and P. Schonfeld. 1992. Approximation methods for queuing delays in waterway networks. *Proceedings of the World Transportation Research Conference*, Lyon, France.
- Dai, M. D.M. and P. Schonfeld. 1991 Simulation of waterway transportation reliability. *Transportation Research Record* 1313: 98-105.
- Kim, Y. M., and P. Schonfeld. 1995. Neural network estimation of waterway lock service times. *Transportation Research Record* 1497: 36-43.
- Martinelli, D. and P. Schonfeld. 1995. Approximating delays at interdependent locks. *Journal of Waterway, Port, Coastal and Ocean Engineering* November/December: 300-307.
- Micro Analysis and Design, Inc. 2002. *Micro Saint 4.0 User Guide*. Boulder, CO: Micro Analysis and Design, Inc.
- Ramanathan, V. and P. Schonfeld. 1994. Approximate delays caused by lock service interruptions. *Transportation Research Record* 1430: 41-49.
- Sweeney, D. C. 2003. *Recent Trends in Output, Industrial Organization, and the Willingness to Pay in the United States Inland Waterborne Commercial Transportation Industry*. St. Louis: Center for Transportation Studies, University of Missouri-St. Louis and the U.S. Army Corps of Engineers.
- Sweeney, D. C. 2004. *A Discrete Event Simulation Model of a Congested Segment of the Upper Mississippi River Inland Navigation System*. St. Louis: Center for Transportation Studies, University of Missouri-St. Louis and the U.S. Army Corps of Engineers.
- Ting, C. J. and P. Schonfeld. 2001a. Efficiency versus fairness in priority control: waterway lock case. *Journal of Waterway, Port, Coastal and Ocean Engineering* March/April: 82-88.
- Ting, C.J. and P. Schonfeld P. 2001b. Control alternatives at a waterway lock. *Journal of Waterway, Port, Coastal and Ocean Engineering*. March/April: 89-96.
- Ting, C. J. and P. Schonfeld. 1999. Effects of speed control on tow travel costs. *Journal of*

Waterway, Port, Coastal and Ocean Engineering. July/August: 203-206.

Ting, C. J. and P. Schonfeld. 1998a. Optimization through simulation of waterway transportation investments. *Transportation Research Record* 1620: 11-16.

Ting, C. J., and P. Schonfeld. 1998b. Integrated control for series of waterway locks. *Journal of Waterway, Port, Coastal and Ocean Engineering* July/August: 199-206.

Ting, C.J. and P. Schonfeld. 1996. Effects of tow sequencing on capacity and delay at a waterway lock. *Journal of Waterway, Port, Coastal and Ocean Engineering* January/February: 16-26.

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

Wang, S. L. and P. Schonfeld. 2002. Development of generalized waterway simulation model for waterway operation. Presented at Transportation Research Board 2002 Annual Meeting, Washington, D. C.

Wei, C.H., Dai, M.D.M. and P. Schonfeld, P. 1992. Computational characteristics of a numerical model for series of waterway queues. *Transportation Research Record* 1333: 45-54.

Zhu, L, Schonfeld, P., Kim, Y. M. Flood, I. and C. J. Ting. November 1999. Queuing network analysis for waterways with artificial neural networks. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* 13 (5): 365-375.