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Factors Affecting Locking Times at 600 ft. and 1,200 ft. Locks on the Mississippi River with an Examination of Excessive Locking Time Charges

by Seth D. Meyer and John Kruse

This research investigates factors influencing locking time as well as the source of variation in the locking time on the Upper Mississippi River, and includes tow characteristics and environmental conditions over 1992-2004. The newer 1,200 ft. locks reduce both locking time and time variation, improving efficiency on the system as a whole. Importantly, the analysis suggests lock capacity has declined over the 1992 to 2004 period for all locks. After correcting for tow and environmental characteristics, very little of the remaining variation is explained by a unique vessel identification number assigned by the Army Corps of Engineers, indicating that lockage fees based purely on relative locking times would not provide the intended result.

INTRODUCTION

Over the last two decades, there has been considerable debate regarding proposals to upgrade the lock and dam system on the Mississippi River, which was originally constructed to allow for a minimum 9.5 ft. deep navigable channel. The Mississippi River serves as a significant transport artery for bulk commodities, and is the dominant route for corn and soybean exports to Gulf of Mexico ports (USDA 2004). The lock and dam system on the upper Mississippi River, which is operated and maintained by the U.S. Army Corps of Engineers, includes 29 locks, 24 of which were built in the 1930s, and most have a 600 ft. long primary locking chamber. The remaining five locks have been constructed since 1953. Of these five locks, two are the northern-most locks in the system, with the smallest chambers reflecting the size of the river. The three on the lower system have a 1,200 ft. long primary locking chamber, and experience high levels of commercial traffic (Table 1). These lower locks are used by a variety of vessel types for commercial hauling, transportation, governmental, and recreational uses.

Table 1: Characteristics of the Main Locking Chambers on the Mississippi River

Lock No.	River Mile	Year Operational	Width	Length	Lift
			(Feet)		
Upper St. Anthony Falls	853.9	1963	400	56	49
Lower St. Anthony Falls	853.3	1959	400	56	25
Lock & Dam 1	847.6	1930	400	56	38
Lock & Dam 2	815.0	1930	500	110	12
Lock & Dam 3	769.9	1938	110	600	8
Lock & Dam 4	752.8	1935	110	600	7
Lock & Dam 5	738.1	1935	110	600	9
Lock & Dam 5A	728.5	1936	110	600	5
Lock & Dam 6	714.0	1936	110	600	6
Lock & Dam 7	702.0	1937	110	600	8
Lock & Dam 8	679.0	1937	110	600	11
Lock & Dam 9	647.0	1938	110	600	9
Lock & Dam 10	615.0	1936	110	600	8
Lock & Dam 11	583.0	1937	110	600	11
Lock & Dam 12	556.0	1938	110	600	9
Lock & Dam 13	522.0	1938	110	600	11
Lock & Dam 14	493.3	1939	110	600	11
Lock & Dam 15	482.9	1934	110	600	16
Lock & Dam 16	457.2	1937	110	600	9
Lock & Dam 17	437.1	1939	110	600	8
Lock & Dam 18	410.5	1937	110	600	10
Lock & Dam 19	364.2	1957	110	1200	38
Lock & Dam 20	343.2	1936	110	600	10
Lock & Dam 21	324.9	1938	110	600	10
Lock & Dam 22	301.2	1938	110	600	10
Lock & Dam 24	273.4	1940	110	600	15
Lock & Dam 25	241.4	1939	110	600	15
Melvin Price	200.8	1990	110	1200	24
Lock & Dam 27	185.1	1953	110	1200	21

Source: U.S. Army Corps of Engineers, Navigation Data Center,
http://www.iwr.usace.army mil/ndc/lockchar/pdf/lkgenrl.pdf

Congestion on the river, defined as delay or time spent waiting in queue to lock at periods of high traffic volume, has been substantial during certain periods of the year depending in part on grain export volumes or alternative export routing (Table 2). Average delays are longer at the 600 ft. locks on the lower half of the system and are particularly lengthy downstream from where traffic enters and exits the Illinois River. This is a concern as delay increases barge rates (Yu et al. 2006), which, in turn, results in lower prices to commodity producers (McKenzie 2005).

Table 2: Aggregate Commercial Tow Delay in Hours on the Upper Mississippi River

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Lock 3	417	541	591	499	502	559	1,609	1,367	1,837	1,499	1,018	882
Lock 4	279	417	461	452	499	643	1,682	1,226	1,611	1,302	1,005	895
Lock 5	410	458	654	496	496	553	1,655	1,271	1,598	1,251	958	918
Lock 5A	330	483	505	549	525	623	1,771	1,226	1,527	1,257	1,033	880
Lock 6	493	807	977	875	836	975	2,527	2,809	2,386	1,844	1,227	1,261
Lock 7	577	763	914	908	1,054	966	2,667	2,402	2,707	1,820	1,432	1,284
Lock 8	669	1,176	1,322	1,149	1,076	1,253	3,111	2,615	3,165	2,226	1,913	1,602
Lock 9	517	862	870	916	1,075	1,114	3,252	2,346	2,874	2,248	1,725	1,799
Lock 10	524	1,438	1,572	1,548	1,202	1,485	3,707	3,085	3,718	2,846	1,932	2,120
Lock 11	1,090	2,400	1,897	1,719	1,640	2,029	4,655	3,633	4,434	3,353	2,300	2,480
Lock 12	831	1,941	2,291	1,791	1,602	2,261	4,563	4,863	5,688	3,922	2,483	2,668
Lock 13	1,072	2,699	2,592	1,480	1,380	2,138	4,961	3,916	5,121	3,584	2,632	3,085
Lock 14	2,045	4,787	6,570	7,304	7,142	12,257	14,758	11,384	13,887	8,307	5,197	4,368
Lock 15	2,626	6,671	8,648	4,128	4,849	7,858	10,919	12,556	14,271	9,535	6,184	6,098
Lock 16	2,177	4,908	5,117	3,485	4,450	5,591	8,358	10,681	9,168	6,745	3,926	3,891
Lock 17	1,772	6,157	4,971	3,869	5,572	6,343	9,772	9,178	14,717	8,277	5,328	6,630
Lock 18	1,975	8,902	7,075	3,709	3,303	5,370	10,145	11,046	12,942	8,471	4,939	7,824
Lock 19	1,476	2,330	2,443	1,940	1,791	2,174	2,201	1,867	2,360	1,853	1,105	1,304
Lock 20	2,326	7,175	10,314	4,645	4,532	6,542	16,492	12,890	14,333	9,804	5,666	5,504
Lock 21	2,562	9,783	9,335	4,780	4,637	6,108	14,564	15,109	11,958	9,343	5,652	5,751
Lock 22	4,327	20,583	25,284	9,328	7,767	11,680	22,216	27,680	18,844	13,074	7,851	7,209
Lock 24	3,862	16,302	14,853	8,192	12,362	8,959	17,518	22,856	29,798	14,941	7,201	5,938
Lock 25	6,910	18,573	12,244	8,269	12,943	11,746	20,502	31,592	18,264	12,842	6,943	6,788
Melvin Price	9,189	4,188	3,763	2,908	3,640	3,625	4,795	4,554	4,733	3,951	3,757	3,510
Lock 27	6,688	9,541	6,841	9,430	4,673	7,208	5,936	5,953	7,265	6,603	6,135	5,312

Source: Corps of Engineers, Lock Perfromance Management System, Lock Summary Statistics
http://www.iwr.usace.army.mil/ndc/lpms/lpms.htm

In an effort to shorten locking times, and thus reduce congestion and tow queue times at locks, recent legislative initiatives have proposed constructing 1,200 ft. locks beside several of the older 600 ft. locks (18 and 20 through 25) that experience high traffic volumes and delays after harvest. The goal of a reduction in locking times is not exclusively to reduce the time spent traversing the lock, but to reduce the time spent in line by the waiting vessels in queue. Nauss and Ronen (2004) highlight the non-linear shape of the delay curve, and indicate that when delay is significant, reductions in locking times, among other measures, can have substantive impact on reducing aggregate delay across all vessels. A reduction in locking times increases system capacity, or the number of vessels that can traverse the locks over a given period of time.

However, the capital expense for such a large project has drawn considerable attention, with others suggesting that the capital improvement costs are not justified by the anticipated gains and that congestion could be reduced by less costly small scale structural or non-structural methods, including fining or otherwise providing economic incentives to slower operators.

THE LOCKING PROCESS

The majority of vessels passing through the locks on the upper Mississippi River system are commercial tow operators carrying a variety of commodities such as coal, gravel, agricultural commodities, fertilizers, and petroleum products in barges. Barges are mostly uniform in size, with the exception of liquid cargo barges, which can be considerably larger in length and width. A full flotilla of standard covered hopper barges, such as those used to haul corn and soybeans to the Gulf of Mexico port facilities, normally consists of 15 barges, each 195 ft. long by 35 ft. wide, arranged three across and five barges long held together with riggings of cables or ropes. This gives the flotilla an approximate width of 105 ft. and a length of 975 ft., plus the length of the towboat, which together is referred to as a tow. With 600 ft. long locking chambers, it becomes necessary to divide the flotilla with the first cut consisting of nine barges in a three by three configuration and the second cut being a two by three set of barges with the tow. The 1,200 ft. locks are able to hold a full flotilla without disassembly and, thus, only need one locking phase.

Tows approach the lock from both sides and proceed through the lock on a first-come, first-served basis. Tows enter the locking queue upon contacting the lock, give notice of their arrival time, and wait for notification of their turn to lock. Once notified, the tow begins the approach, entering into the open gates of the lock. When the entry is complete, the gates are closed and the tow is raised or lowered depending upon the direction of travel. The opposite gates then open and the vessel begins its exit. The next cut or next waiting vessel then begins the locking process. For tows requiring more than one cut, such as a flotilla of 15 barges at a 600 ft. lock, in the entry phase the towboat pushes the barges into the locking chamber, the lashings between cuts are undone, and the towboat pulls back with the remaining half. The un-powered barges are locked, extracted with a cable winch system, and lashed to the guide wall. The chamber is closed, raised or lowered empty, and the opposite gates opened for the locking of the powered half of the tow. When the power half exits, all the barges in the tow are lashed back together and continue on, and the next tow in queue begins its approach.

OPTIONS TO REDUCE CONGESTION

A number of studies have investigated the impact of significant structural changes in the locking system, such as extending several of the 600 ft. locks to 1,200 ft. or the construction of guide walls at 600 ft. locks, to increase the system's capacity and reduce locking time. Fellin et al. (2001) employed a spatial quadratic programming model to evaluate the impact of lock and guide wall extensions, taking forecasted tow volume and delay from the Army Corps of Engineers estimates and simulating the reduction in delay; therefore, the reduction in tow cost that occurs from various capital improvement schemes. Gervais et al. (2001) used a linear programming model, maximizing profits, to compare costs to benefits of lock extensions, but took issue with the Corps of Engineers forecasted tow volume used by Fellin et al. (2001) and used a much lower anticipated volume of traffic. In both studies, future commodity volume and the shape of the transit curve for barge transport remains a significant unknown in evaluating significant capital investment in lengthening lock chambers and has directed attention towards less costly alternatives.

The Corps of Engineers has screened (1995) and examined (1999) numerous small scale or non-structural alternatives to lengthening of lock chambers. Dyer et al. (2003) took a proposed scheduling system further and described a system of tradable permits, but did not include a cost benefit analysis of a specific proposal. Specific locking times at each lock would be assigned throughout the year, and assignments would be tradable among the operators, establishing a market for the most desirable locking times and seasons. The impact would be to increase shipping costs during the fall shipping season and spread traffic more evenly throughout the year.

Nauss and Ronen (2004) proposed an appointment system, based on technology advancements, as a way to reduce demand variability and thus aggregate delay. Smith et al. (2007) explored scheduling and queue re-sequencing alternatives through a simulation model of Mississippi River locks 20, 21, 22, 24, and 25 for evaluation. Alternatives included re-sequencing the waiting tows to minimize the expected time to clear the queue by placing the tows with the fastest expected locking time, based on coarse groupings of tow characteristics, at the front of the queue. Re-sequencing results indicated a modest savings of 5% of the time that vessels spend at locks, and the authors raised potential concerns about the equity of the process.

Another alternative non-structural proposal explored by Dyer et al. (2003) was to charge a fee for locking times deemed excessive. Additional fees or lower locking priority would increase the tow operators' cost and provide incentives to improve locking times through investment in equipment and training. Such equipment may include winches to speed the extraction of the un-powered tows or pay incentives for trained pilots and deck hands. While Dyer et al. (2003) found the potential time savings to be substantial, they anticipated the savings would be achieved through the purchase and installation of new line handling equipment, like winches, making the cost-benefit ratio unfavorable.

To evaluate the potential impacts of structural or non-structural improvements to the locks, the factors affecting locking time must first be determined. Wilson (2004) took select tow characteristics and a unique vessel identifier and quantified the impact on locking times, but did not address a specific non-structural alternative or present locking time distributions.

As a contribution to existing research, this study provides a more in-depth analysis by using individual locking observations over a number of years, and a more complete set of factors impacting locking times are quantified in the first step of the analysis. Focusing specifically on excessive lockage time fees, the remaining unexplained variation in locking time is then used to compare a vessel's average locking time to the population as a whole, corrected for the factors from the first step, to characterize relative vessel efficiency and address the potential time savings of this non-structural proposal. While the directional impact of several of the locking factors could be anticipated by experienced tow captains, the quantification of each factor is necessary for an appropriate congestion fee structure and possible gains to lock performance as well as unanticipated information on annual trends in lock capacity

DATA

The data used in the analysis contains locking observations from 1992 through early 2004, and was obtained from the Army Corps of Engineers' Lock Performance Monitoring System (LPMS). The LPMS data are a summary of the lockage logs recorded for each vessel traversing a Corps of Engineers operated lock. The dataset was trimmed to include only primary chambers for locks 3 through 27 on the Mississippi River, which are either 110 ft. by 600 ft. or 110 ft. by 1,200 ft., and includes only commercial tow operations, removing such observations as recreational boats and Corps of Engineers vessels. As a condition of releasing the data, the Corps of Engineers removed proprietary or confidential information from the dataset, eliminating variables not observable from shore, such as the commodity transported or if the barges were loaded or unloaded.

The lockage logs record a number of variables, including location, direction of travel, and vessel type. The logs also indicate the date and time of arrival, time of entry into the lockage queue, time from the beginning of locking through to the final phase of the locking process, and a number of stages in between. Information on lockage style is recorded, which includes information on a reconfiguration of a tow for locking, the transfer of a barge through the lock by two separate tows, or a simple straight lockage, which, in this data, may include a cut between sections of the flotilla, but no repositioning of the towboat relative to the position of the barges. Entry and exit type is also recorded. Variables describing the flotilla, such as number and type of barges are also provided. The data was checked for consistency and the limited number of observations that failed logical checks in the recorded times were eliminated as were observations where a lock failure occurred that was not attributable to the tow operator. The final data set contained 709,734 usable observations.

MODEL SPECIFICATION

To determine which variables in the LPMS dataset to include and establish expectations of their impacts, a review of technical documents as well as conversations with port captains and barge industry participants were conducted. As part of its charge to evaluate alternative proposals for lock and dam improvements, the Corps has produced or commissioned several studies of which the U.S. Army Corps of Engineers (2004) and Dyer et al. (2003) provided background information on the locking process in support of their analyses. These studies include information on how various factors may influence locking time, however, the list is not comprehensive and fails to quantify many of those impacts. Consultations with tow operators proved invaluable in refining the model specification and interpreting features of the data. These discussions supplemented Corps of Engineers' documents and supplied information on the locking process from a tow operator's perspective. As a result of these documents and discussions, a generalized model for factors impacting locking time was specified as (1):

$$
\begin{aligned}
(1)\quad \mathit{Lockage\ Time}_i = {} & \alpha + B_1 \times \mathrm{D1200} + B_2 \times \mathrm{D600C1} + \sum_{g=1}^{23}\left[B_{3g} \times lock_g\right] + \sum_{h=1}^{12}\left[B_{4h} \times year_h\right] \\
& + B_5 \times bgnums + B_6 \times bgnums \times \mathrm{D1200} + B_7 \times bgnums \times \mathrm{D600C1} \\
& + \sum_{i=1}^{12}\left[B_{8i} \times bgtype_i + B_{9i} \times bgtype_i \times \mathrm{D1200} + B_{10i} \times bgtype_i \times \mathrm{D600C1}\right] \\
& + \sum_{i=1}^{12}\left[B_{11i} \times bgtype_i \times bgnums + B_{12i} \times bgtype_i \times bgnums \times \mathrm{D1200} + B_{13i} \times bgtype_i \times bgnums \times \mathrm{D600C1}\right] \\
& + \sum_{j=1}^{11}\left[B_{14j} \times month_j + B_{15j} \times month_j \times \mathrm{D1200} + B_{16j} \times month_j \times \mathrm{D600C1}\right] \\
& + \sum_{k=1}^{23}\left[B_{17k} \times hour_k + B_{18k} \times hour_k \times \mathrm{D1200} + B_{19k} \times hour_k \times \mathrm{D600C1}\right] \\
& + \sum_{l=1}^{2}\left[B_{20l} \times entryt_k + B_{21l} \times entryt_l \times \mathrm{D1200} + B_{22l} \times entryt_l \times \mathrm{D600C1}\right] \\
& + \sum_{m=1}^{2}\left[B_{23m} \times exitt_m + B_{24m} \times exitt_m \times \mathrm{D1200} + B_{25m} \times exitt_m \times \mathrm{D600C1}\right] \\
& + \sum_{n=1}^{6}\left[B_{26n} \times locksty_n + B_{27n} \times locksty_n \times \mathrm{D1200} + B_{28n} \times locksty_n \times \mathrm{D600C1}\right] \\
& + \sum_{o=1}^{25}\left[B_{29o} \times trend \times lock_o\right] + B_{30} \times trend + B_{31} \times trend \times \mathrm{D1200} + B_{32} \times trend \times \mathrm{D600C1} \\
& + B_{33} \times direction + B_{34} \times direction \times \mathrm{D1200} + B_{35} \times direction \times \mathrm{D600C1} + \varepsilon_i .,
\end{aligned}
$$

where:

$\mathrm{D1200}$: Dummy variable=1 for 1200' locks, 0 otherwise,

$\mathrm{D600}C1$: Dummy variable=1 for 600' locks with one cut, 0 otherwise,

$lock_g$: Lock dummy variables, locks 3 through 27,

$year_h$: Year dummy variables, years 1992 through 2004,

$bgnums$: Number of barges in the flotilla,

$bgtype_i$: Dummy variable for each barge type: open hopper, covered hopper, etc.,

$month_j$: Monthly dummy variables, January through December,

$hour_k$: Hour dummy variable, 0:00 through 23:00,

$entryt_k$: Lockage entry type dummy variable: exchange, turnback or fly,

$exitt_m$: Lockage exit type dummy variable: exchange, turnback or fly,

$locksty_n$: Lockage style dummy variable,

$trend$: Annual trend variable 1992=1, 2004=13,

$direction$: Direction dummy variable=1 if downbound, 0 if upbound, and

ε_i : Locking time that remains unexplained.

To investigate seasonality and time impacts, the continuous time variables were converted to a set of binary shift variables. As an example, DJUN=1 if the locking occurred in the month of June and DJUN=0 if it did not. Further, TSOL22=1 if the tow began locking in the 22:00 hour or TSOL22=0 if it began locking at some other hour of the day. Additional groupings of binary variables were created for lockage style, entry type, exit type, and type of barges in the flotilla. Additional binary variables were created indicating the three lockage types: a 1,200 ft. lock, a 600 ft. lock with one cut, and a 600 ft. lock requiring two cuts. Two of the three variables are then multiplied by other appropriate groups of variables to create interaction terms and allow for differences among lockage types. Discrete variables for the number of barges were also included in the model to determine the marginal impact on lockage time of an additional barge as well as a linear trend growth to investigate changes in lock capacity over time.

In the second step, the unexplained variation, ε_i, is retained as a dependent variable and regressed against dummy variables for each unique Corps of Engineer vessel identification number as a way to proxy relative towboat efficiency. Use of the vessel number is only a proxy as the number is tied to the towboat, but may change with changes in ownership and is not tied to the specific captain and crew. Use of the error terms from the prior estimation corrects for the given factors, putting each locking on an even footing with the resulting parameters, β_v, indicating each towboat's corrected average locking time in comparison to the overall average for all lockings, or its relative efficiency.

$$(2) \qquad \varepsilon_i = \sum_{v=1}^{1008} \beta_v \times DummyVessel_v$$

ESTIMATION TECHNIQUE

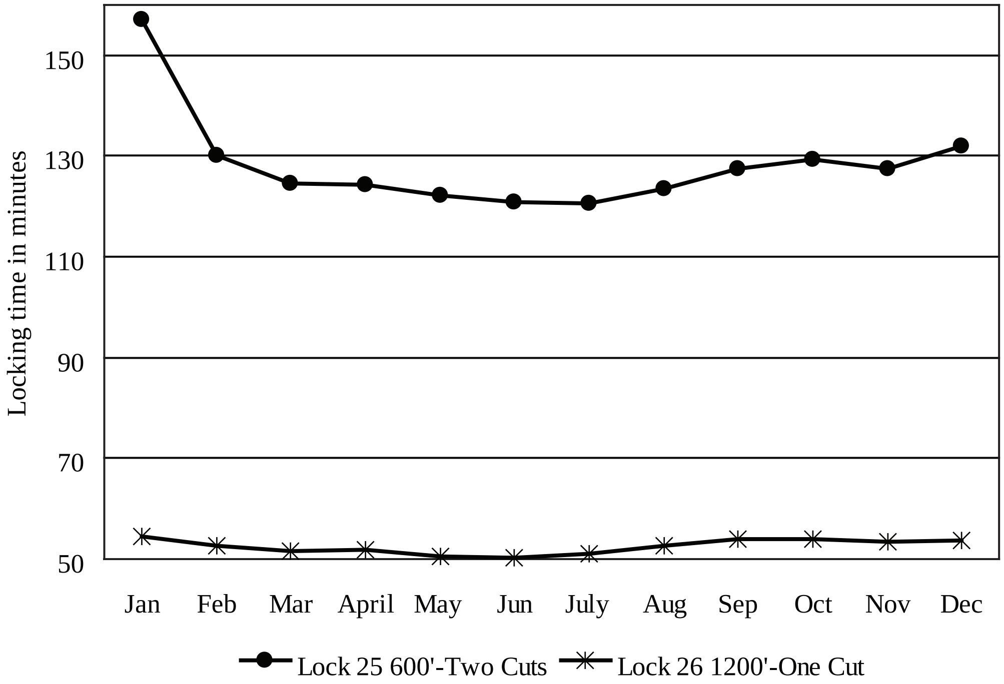
Using the specification from Equation (1), the model is estimated using simple OLS regression. The residuals from the specified model estimating locking time are retained and then regressed against dummy variables for all of the available vessel numbers also using OLS, in this case with no intercept term. The resulting parameters are the vessel's average deviation from normal lockage time by vessel, corrected for the characteristics in Equation (1), and indicate which vessels are quicker or slower than average. These deviations from average are due to factors not included in Equation (1) and could include captain and crew experience, towboat characteristics, such as engine power, unfavorable weather conditions that do not result in a lock closure, river flows, and tow loads among other possible factors. Because the regression is a calculation of mean locking times by vessel number, significance levels only illustrate the variability of individual vessel's locking times.

Step 1: Quantifying Factors Influencing Locking Times

The generalized Equation (1) produces a model with 229 significant parameter estimates. Due to the large number of variables and interaction terms used to explain lockage times, a standard listing of parameter results would be voluminous, so the results are presented in summary tables and graphics that, because of the complexity of the estimated equation and the numerous interaction terms, are shown by varying the variable of interest for a standardized tow. The standardized tow is a 15 covered hopper barge flotilla heading downstream on October, 2003, at 12:00 pm. The lockage type is a straight lockage with a fly type exit and entry. The comparison will often focus on lock 25, an older 600 ft. lock proposed for an upgrade, and lock 26, a newer 1,200 ft. lock of the length proposed.

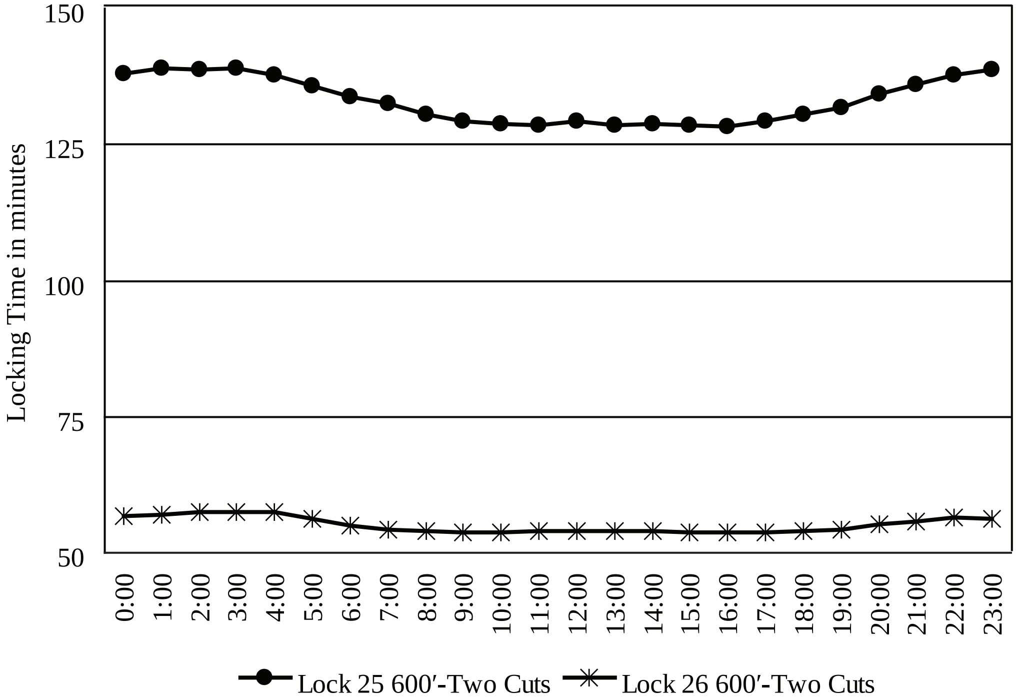
The seasonal effect on locking times at lock 25 and lock 26 are shown in Figure 1. The values are varying months on the standardized tow, and results indicate that summer months allow for faster locking time for both locks. The greater seasonal impact is at 600 ft. locks where two cuts are needed to traverse the lock. The increased locking times during early spring and late fall for double cut lockages on the 600 ft. locks may be due to the need to manually lash and unlash the barges under adverse weather conditions when separating the cuts, but could include other factors. If we set aside the January extreme, which has a very small number of observations because portions of the river are un-navigable, the difference between the quickest and slowest month for 600 ft. locks requiring two cuts is 11 minutes while the difference for 1,200 ft. locks is four minutes, indicating that the longer locks are less impacted by seasonal factors.

Figure 1: Seasonal Effect on Locking Times



The effect that the hour of the day at the start of locking has on locking time also proved to be important as seen in Figure 2. The lockage times are shorter during daylight hours, and the effect of available light is larger for the 600 ft. locks than the 1,200 ft. locks. For lockages requiring two cuts, the difference in locking time is 10.4 minutes over the course of the day. The 1,200 ft. locks are less impacted by the availability of daylight with a difference in locking time of less than four minutes. The increased locking time at night was anticipated from conversations with tow operators as low light conditions slow operations, including the approach and separation of cuts.

Figure 2: Daylight Effect on Locking Times



In order to investigate changes in lockage times, therefore, lock capacity through time, trend variables and interaction terms by lockage type and individual lock number were constructed. In all but one case (single-cut lockings at lock 6), lockage times showed positive trend growth. The results indicate, *ceteris paribus*, with one exception it took longer to lock in 2004 than it did in 1992; and in a few cases, lockage times increased by nearly 20 minutes from 1992 to 2004 (Table 3). As the model corrects for a number of environmental, tow/flotilla characteristics, and other factors, changes in the norm of tow configurations are corrected for and, therefore, do not influence the trend variable. The results indicate a consistent and significant reduction in the locks' operating capacity over the analyzed time period with the most significant impacts occurring at the locks receiving the majority of traffic, locks 14 through 27. Two cut lockages at the 600 ft. locks show the greatest increase in locking times, while those for 1,200 ft. locks show smaller increases.

Table 3: Trend Change in Locking Times from 1992 to 2004 by Lock, in Minutes

Lock 3–One Cut	1.29	Lock 10–One Cut	3.40	Lock 18–One Cut	4.77
Lock 3–Two Cut	6.81	Lock 10–Two Cut	8.55	Lock 18–Two Cut	8.86
Lock 4–One Cut	4.38	Lock 11–One Cut	0.94	Lock 19	8.99
Lock 4–Two Cut	10.31	Lock 11–Two Cut	5.89	Lock 20–One Cut	2.57
Lock 5–One Cut	0.16	Lock 12–One Cut	3.99	Lock 20–Two Cut	9.12
Lock 5–Two Cut	8.54	Lock 12–Two Cut	9.42	Lock 21–One Cut	6.89
Lock 5a–One Cut	3.84	Lock 13–One Cut	3.04	Lock 21–Two Cut	13.35
Lock 5a–Two Cut	5.94	Lock 13–Two Cut	8.70	Lock 22–One Cut	5.87
Lock 6–One Cut	-0.22	Lock 14–One Cut	9.07	Lock 22–Two Cut	10.29
Lock 6–Two Cut	10.63	Lock 14–Two Cut	19.27	Lock 24–One Cut	8.58
Lock 7–One Cut	3.58	Lock 15–One Cut	3.07	Lock 24–Two Cut	12.67
Lock 7–Two Cut	5.90	Lock 15–Two Cut	16.03	Lock 25–One Cut	6.65
Lock 8–One Cut	3.11	Lock 16–One Cut	1.80	Lock 25–Two Cut	14.03
Lock 8–Two Cut	8.69	Lock 16–Two Cut	6.15	Lock 26	8.43
Lock 9–One Cut	3.65	Lock 17–One Cut	7.43	Lock 27	7.28
Lock 9–Two Cut	11.38	Lock 17–Two Cut	15.65		

Commodities on the Mississippi River move in a wide variety of barge types, with covered hopper barges the dominant container for agricultural commodity transportation. Without explicit information on barge dimensions to compare the lockage times for different barge types, additional sources must be drawn upon to determine standard configurations. Recall that a full flotilla of hopper barges (covered, open, or liquid hopper) normally consists of 15 barges that are 195 ft. long by 35 ft. wide and arranged three across and five barges long. Alternatively, a modern configuration of liquid cargo barges, which differ from liquid hopper barges, may be the standard 195 ft. long by 35 ft. wide or longer double hulled barges, but much of new liquid cargo barge construction is in excess of 250 ft. long by 50 ft. wide (USACE 2005b) and are normally configured with three to four barges in single file. The difference in locking speed between the two flotilla types may be due to the smaller overall flotilla dimensions for the liquid cargo configuration and that, when cut, requires a break between only one set of barges while a covered hopper flotilla would require a break between three sets of barges and all their associated lashings (Figure 3). This hypothesis was supported in conversations with tow captains.

The type and number of barges also impacts lockage time. While the Corps of Engineers was able to provide information on the number and type of barges, confidentiality issues prevented them from including data on whether the barges were loaded or unloaded as well as their dimensions. As additional barges of all types are added to a flotilla, the lockage times increase. With all else constant, the increase in lockage time with additional barges was assumed to be linear (Figure 4). Lockage time on a per-barge basis can be seen in Figure 5. The results indicate there is a significant time savings between 1,200 ft. and 600 ft. locks when the flotilla consists of more than six barges. On a per-barge basis, at a 1,200 ft. lock, times are minimized by having the maximum flotilla size. At 600 ft. locks, the time per barge is minimized by having six barges in the flotilla. Although there is an individual lockage time difference, this does not suggest that capacity could be increased by limiting tows to six barges.

Figure 3: Differences in Locking Times by Barge Type

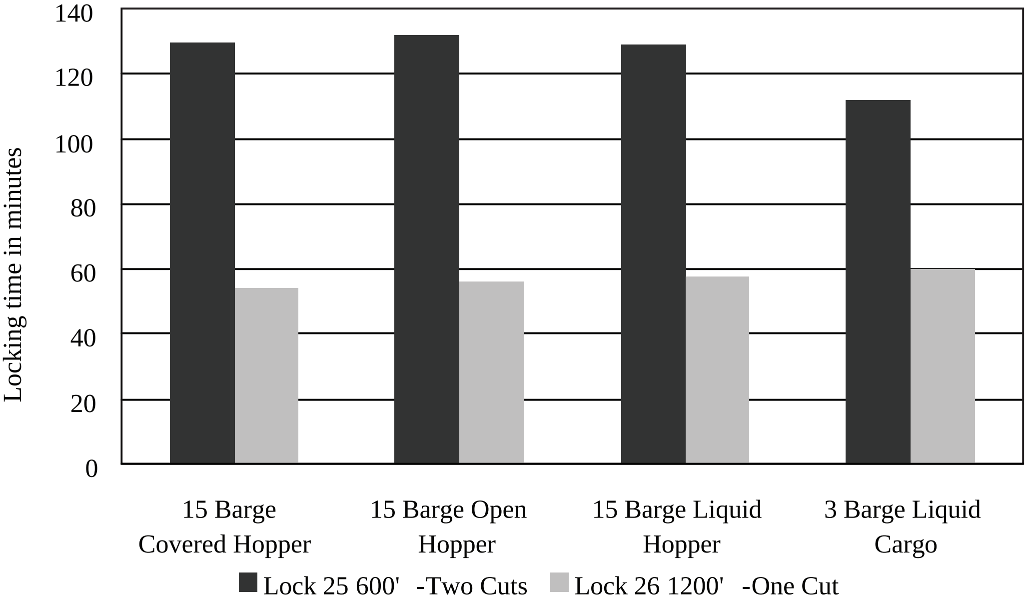


Figure 4: Average Locking Time by Number of Barges in the Flotilla

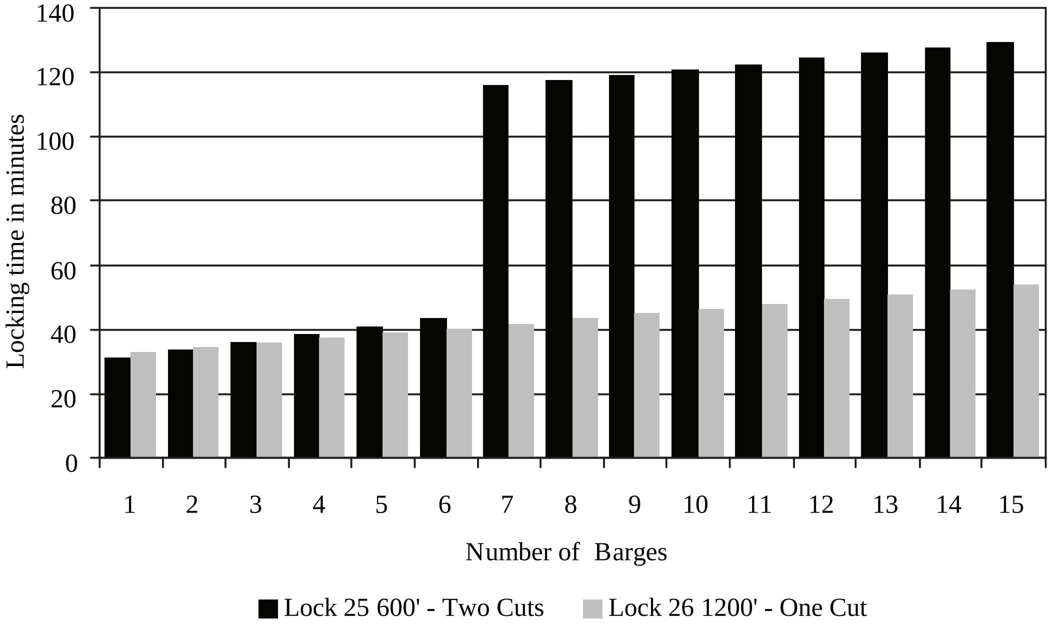
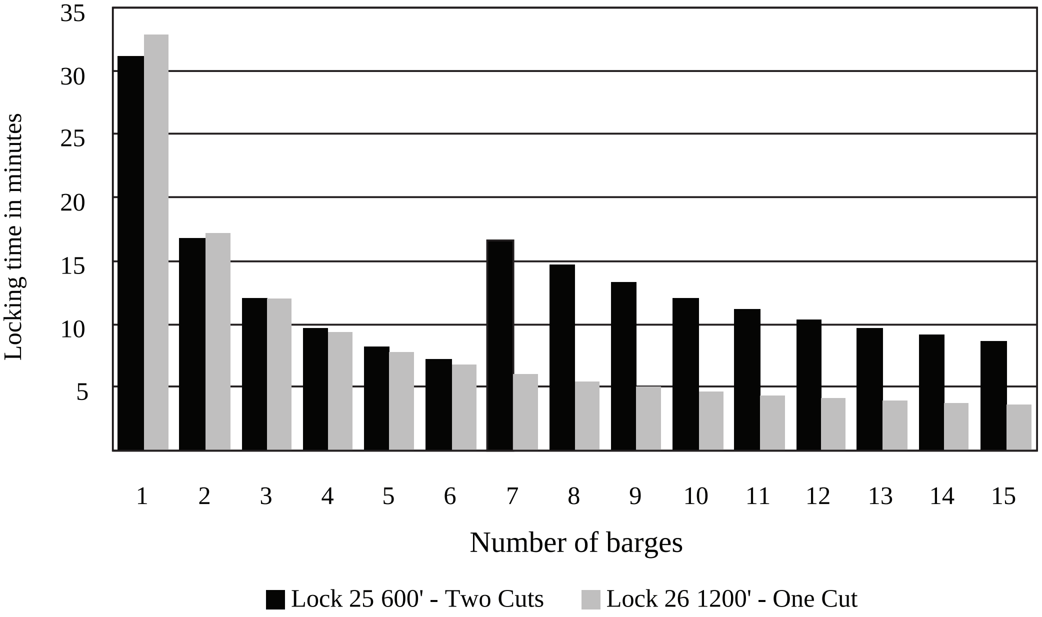


Figure 5: 1-15 Barge Flotillas, Locking Time per Barge



While it minimizes the time per barge for a single tow, the standardized 15 barge tow would require three separate tow boats to traverse the lock without a cut, increasing the total time to get the 15 barges through the lock and adding congestion to the river system. It is important to recall that the return to service phase, where a lock is raised or lowered when emptied to serve the next cut, is not directly attributed to the locking times of single cuts or subsequent vessels. However, for the calculation of total time of a flotilla requiring a cut, it includes the time to close the gates, lower or raise the water level, and open the opposite gates between cuts of the same tow.

Information on exit and entry type provides information on the direction of travel of the previous and subsequent vessel, relative to the current tow. A fly entry indicates the lock was idle when the vessel began locking and a fly exit indicates the lock became idle after the tow's exit. An exchange entry (exit) indicates the previous (subsequent) lockage was in the opposite direction. The largest impact on lockage time for entry or exit type in the presence of another vessel is the time savings from a turnback entry, where the next vessel locked is heading the same direction as the previous vessel. This type of entry is recorded when the vessel locks in the same direction as the previous tow. It is current Corps of Engineers policy to switch from the first-come, first-served operation to the N-up/N-down operation in the presence of congestion. In N-up/N-down operation, a number of vessels going the same direction are locked, then the locking direction is reversed and several vessels are locked in the opposite direction.

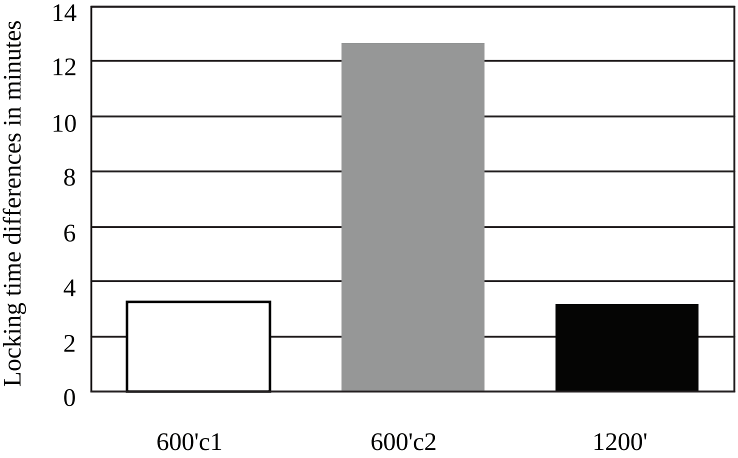
The Corps of Engineers states N-up/N-down improves efficiency as tows traveling in opposite direction must navigate past each other, and during this time the lock is idle (USACE 2004). As the lockage time includes approach and lock exit, the efficiency difference between an exchange entry or exit in which the prior or subsequent vessel is traveling in the opposite direction and a turnback entry or exit in which the prior or subsequent vessel is traveling in the same direction shows a bigger time savings (negative) or smaller time loss (positive) for a turnback entry or exit relative to a fly lockage than does an exchange entry or exit (Table 4). This supports the Corps of Engineers conclusion that locking several vessels in the same direction during periods of congestion reduces aggregate tow wait times.

Table 4: Differences in Locking Times by Entry and Exit Type vs. a Fly Entry or Exit (minutes)

	600′ One Cut	600′ Two Cut	1200′
Entry-Exchange	-3.09145	-4.30933	1.50026
Entry-Turnback	-10.42688	-16.37311	-11.19086
Exit-Exchange	1.85018	5.36440	7.39899
Exit-Turnback	-0.85232	0.96113	0.87312

Direction of travel was also included as an explanatory variable with the estimation results shown in Figure 6, and indicates that it takes a greater amount of time to lock when headed downstream than when headed upstream. The approach portion of the lockage procedure is more difficult when downward bound. When the towboat slows, water movement across the rudder also declines, reducing maneuverability. On an upward bound locking the boat slows, but the current moving in the opposite direction maintains water speed at the rudder, thus maintaining maneuverability (USACE 2004). The downward bound time increase is greatest for lockages requiring a cut.

Figure 6: Additional Locking Time Required Going Down-Stream vs. Up-Stream



The impact of direction of approach is not the only factor; there is also an effect in the extraction phase due to barge loading, and it should be noted that a greater proportion of the barges moving downstream are loaded than those going upstream (USACE 2005a). In addition, the Corp of Engineers has concluded that during the extraction phase, increased draft and mass have larger impacts on downward bound locking times than upward bound locking times (USACE 2004). The exclusion of information on barge loads in the data likely results in an over estimation of the impact of locking times based solely on direction of travel, but probably underestimates the impact of direction of travel and barge loads in total. Explanatory power could be increased with the separation of these two variables if data were available.

The overall explanatory power of the model is indicated by an R^2 value of .78, or 78% of the variation in locking time for the set of commercial tows from 1992 to early 2004 is explained by the resulting model. This leaves 22% of the variation in lockage times unexplained, which is explored in the second phase of the analysis.

Step 2: Corrected Towboat Locking Time Distribution

The congestion fees at 600 ft. locks recommended to the Corps of Engineers were to be imposed in instances where maneuver time, time not including that necessary to raise and lower the lock, was in excess of a historic third quartile of locking times for a double cut straight lockage (Dyer et al. 2003). It is further asserted that the penalties must be substantial in order to induce the tow upgrades desired. The time standard would be fixed to avoid continued pressure to improve locking times and, thus, jeopardize safety. The fees were recommended based upon the large variation in lockage times and potential efficiency gains by motivating the historically slowest quartile of tow operators to improve locking times. The proposal only considers the distribution of double cut lockages, but fails to consider other factors that may be impacting locking time and ignores the variation in lockage times by operators other than those using a double cut straight lockage.

By imposing fees based upon a long-run historical average and only on double cut straight lockages, the intended incentives appear to be largely diluted (Table 5). By imposing fees only on the historic average of a specific tow setup, such as lockages with two cuts, which has appeared in Corps of Engineers proposals, there is a loss of potential efficiency gain. Lockages with two cuts, which represented 56.18% of lockages in the sample, and such a proposal would ignore the potential gains from speeding up the other 43.82% of configurations as the variation in their speed is not considered.

As may be expected, the number of up and downstream movements in the LPMS dataset are roughly equal (Table 5). However, under a fee system based simply on the slowest 25% of lockages or the slowest 25% of double cut lockages, the share of those penalized who are headed downstream rises to 63.35% and 65.94%, respectively. Other potential distortions can be readily observed in Table 5.

Using the distribution of all lockage times overstates the variability in lockage times that could be influenced without modifying tow configuration and behavior in potentially undesirable ways, therefore, overstates the potential gain of the congestion fees by not correcting for direction of travel, time of day, number of barges, and weather. When corrected, the variance, and thus the potential time savings, is reduced. As seen in Step 1, the difference between locking during the early morning and early afternoon averages 10 minutes, making those locking in the dark appear less efficient. Add to that the differences in barge numbers and type, direction of travel, and other factors from Step 1, it is easy to see that uncorrected locking times potentially penalize tow operators not on their relative efficiency, but upon factors beyond their control or tow configuration factors. The penalties may potentially distort behavior in unintended ways, such as inducing tow operators to attempt to time arrivals to lock during the day or reducing the number of barges below the most efficient number, 15, increasing congestion on the river.

An alternative measure is to use the results of the corrected model from Step 1 to identify the slowest locking times. One must, however, still consider the remaining unidentified factors as it is conceivable that under adverse weather and river current conditions on any given day, a large number of the tows could have locking times beyond the historical third quartile, again fining the tow operators for things other than inefficiency. Therefore, it may be more appropriate to identify tows by looking at corrected locking time averages and identifying tow operators who are consistently slower than average. This can be approximated by using vessel identification numbers and computing the average error for corrected locking times by vessel ID using Equation (2).

Table 5: Select Population Characteristics Under Alternative Fee Recipient Regimes

		Alternative Ways to Identify Excessive Lockage Time Fee Recipients		
	All Tows (Population)[1]	Slowest 25% of All Tows	Slowest 25% of Double Cut Tows[2]	Slowest 25% of All Tows Corrected for Characteristics in Step 1[3]
Number of Tows (obs.)	709,734	177,334	99,624	117,334
Avg. Number of Barges in Tow	11.15	13.89	14.03	11.76
Avg. Number of Lockings	3685	4141	40.72	3591
	Percentage with the Following Characteristic of Environment			
At Lock 14	4.54	6.06	6.11	4.63
At Lock 18	4.46	5.73	5.17	4.76
At Lock 19	4.45	0.40	NA	4.38
At Lock 20	4.70	6.51	5.55	5.07
At Lock 21	4.87	7.52	7.64	5.50
At Lock 22	4.73	9.89	12.29	5.72
At Lock 24	4.80	8.54	8.61	5.11
At Lock 25	4.85	7.59	7.96	5.22
At Lock 26	9.56	0.02	NA	7.14
At Lock 27	11.46	0.02	NA	8.14
600′ Lock Single Cut	18.38	0.62	NA	14.47
600′ Lock Double Cut	56.18	98.94	100.00	65.88
1200′ Lock Single Cut	25.47	0.44	NA	19.65
Locked in year 1992	8.86	7.25	6.70	9.12
Locked in year 1998	8.29	8.20	8.26	8.01
Locked in year 2003	7.47	8.88	9.50	7.95
Locked in May	11.51	10.95	10.39	11.71
Locked in October	10.56	12.61	13.38	10.68
Locked in November	10.18	11.75	12.36	9.34
Traveling Downstream	50.30	63.35	65.94	50.14
Started Locking at 1am-2am	3.98	4.92	5.37	4.08
Started Locking at 12pm-1pm	4.27	3.66	3.38	4.25
Started Locking at 9pm-10pm	4.32	4.72	4.93	4.32
Straight Lockage Style[4]	95.18	99.11	99.72	95.09
Primarily Covered Hopper Barges	68.06	77.86	78.17	69.83
Primarily Open Hopper Barges	2.78	2.54	2.57	3.07
Primarily Tank Barges	9.87	3.11	2.67	8.80

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[1] Lock Performance Management System data used in the analysis.

[2] Corps of Engineers suggests selecting only Double Cut Straight Lockages, but it is not clear if each lock would have its own distribution (USACE 2004).

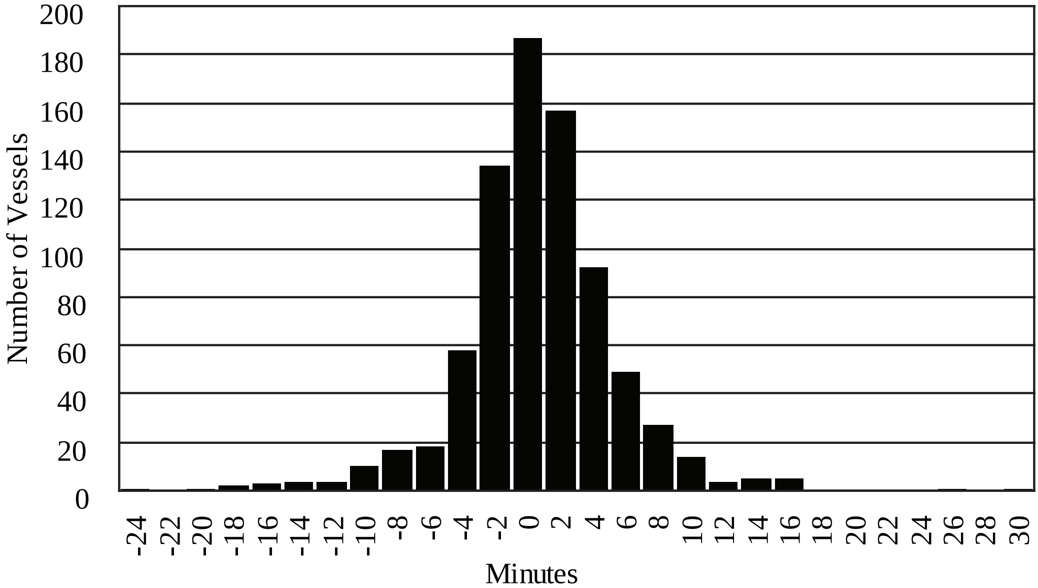
[3] Represents the characteristics of the largest 25% of residuals obtained from the estimation in step 1 of the analysis.

[4] Straight Lockage in this data set refers to a lockage through a chamber where the configuration of the tow does not change but a cut may occur.

In the dataset used in the first step for estimating locking times, there were 1,009 unique vessel identification numbers. The errors, ε_i, retained from the estimation in Step 1 are used as the dependent variable in Equation 2. The errors are the portion of the locking time not explained by the estimated model and are, in part, hypothesized to be the result of factors, such as towboat characteristics, equipment compliments, such as available winches on the barges, and crew experience as well as weather conditions, prevailing currents, and other factors. The resulting parameters are the corrected average locking time differential for the identified towboat. It is not estimation, but simply a calculation of the mean difference. Positive values indicate a towboat whose corrected average locking time was slower than the model would indicate. It is these towboats which could be targeted by congestion fees.

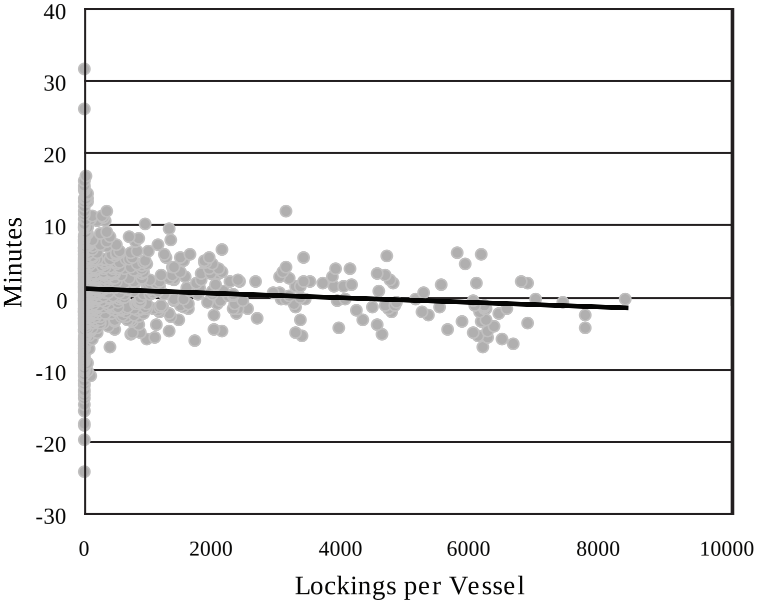
The distribution of vessel average lockage time differentials is presented in Figure 7. The distribution of vessel locking time averages appears close to a normal distribution with a standard deviation of less than five minutes, indicating that 68% of the towboat averages are within five minutes of the mean, which is less than the time difference between locking a 15 barge tow at noon versus midnight on a 600 ft. lock. The R^2 for the equation, which uses the average corrected locking efficiency by vessel number, was .034, indicating a large variation in locking times for each towboat, and also supports the conclusion that imposition of congestion fees, even on a corrected locking time, is likely to be punishing operators for factors not included in the analysis and beyond the control of the operator, such as currents and weather. The low R^2 calculation indicates that the variation in locking times for a particular vessel ID is substantial, and that consistency in locking times may be low. While the congestion fee seeks to reduce average locking time, the non-linear shape of delay times means some consideration should be given to potential benefits from the reduction in variation of individual vessel locking times (Nauss and Ronen 2004).

Figure 7: Distribution of Average Corrected Locking Time Differentials by Towboat



To investigate what impact experience may have on locking times, each towboat's average locking time differential is plotted against the number of lockings in the dataset (Figure 8). While an imperfect measure, as the identification number follows the vessel under specific ownership, it may proxy other factors, such as captain and crew experiences. Figure 8 shows a very slight downward sloping trend, indicating that increased experience in locking modestly improves average locking times. An analysis of the reduction of delay obtained from the modest change in locking times requires an advanced simulation system similar to that employed by Campbell et al. (2007) and Smith et al. (2007). However, the lack of information about the unexplained variation from Step 1, the vast majority of which remains unexplained by inclusion of the vessel number in Step 2, makes it difficult to determine if financial penalties are appropriately targeted or the result of the misfortune of locking during inclement weather or unfavorable currents.

Figure 8: Deviation of Vessel Average Locking Time from Population Average by Number of Lockings

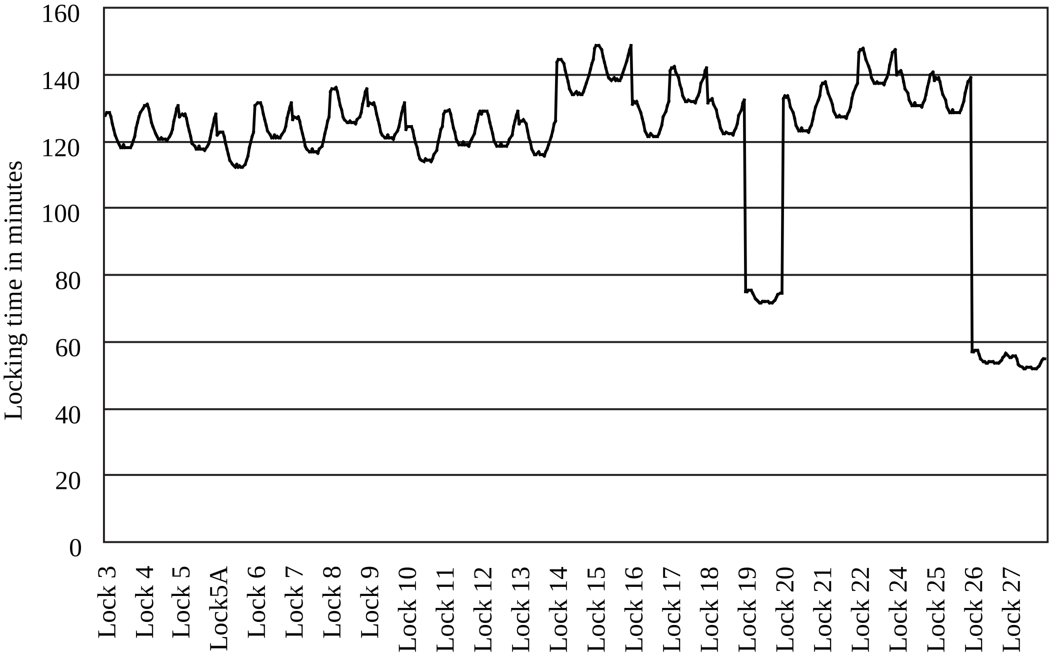


CONCLUSIONS

In determining the sources of lockage time variation, several operational differences between 1,200 ft. and 600 ft. locks were shown. For a given flotilla, it is clear that the tows are able to traverse a 1,200 ft. lock much more quickly than a 600′ lock, and such a result is expected and observable (Figure 9). Additionally, the results for locking entry and exit type as well as direction of travel also support prior expectations about the signs of impacts and quantifies them.

Under the given results, imposition of congestion fees based solely on raw lockage time appears to be arbitrary as flotilla characteristics and environmental impacts beyond the control of the operator explained 78% of the variation in lockage time, leaving 22% unexplained. In the second step, it was found that only 3.4% of the unexplained variation could be explained by vessel ID. Imposing a naive congestion fee, if sufficiently large, could have a negative impact by distorting behavior of the operators, which may cause an increase in congestion. Imposition of congestion fees based on the corrected locking time would be less arbitrary, but may still include impacts beyond the tow operator’s control. A portion of the unexplained variation may be due to factors such as prevailing currents and adverse weather conditions. Other potential variables, such as towboat type and captain and crew experience, are captured in this unexplained variation, but the ability of congestion fees to substantially impact mean locking time is limited by the fact that the standard deviation of average tow locking times is under five minutes and may not consist solely of factors under the control of operators, leaving little room for congestion fees to have the desired impact.

Figure 9: Comparison of Locking Time by Lock and Time of Day, 2003



More surprising may be the significant differences between the lockage types due to environmental factors, such as time at the start of locking and seasonal impacts. The results indicate that the 600 ft. locks, which take longer to process a tow, are also more sensitive to environmental factors. The locks operate as a system and should not be considered individually, therefore, delays at any individual lock may impact the system as a whole (Martinelli and Schonfeld 1995).

Of considerable concern is the significant upward trend in lockage time, which has a direct negative impact on lock capacity throughout the Mississippi River navigation system. In all but one case, the trend in corrected locking times showed positive growth, and the growth was most significant at the older 600 ft. locks, 14 through 18 and 20 through 24, that experience the most traffic. The variables could be capturing maintenance and operational issues on the aging lock system and, if the trends continue, would further reduce the system's capacity.

It is clear that many of the factors influencing locking times are determined by the size and makeup of the flotilla and are not under the direct control of the tow operator. The older 600 ft. locks are slower, more impacted by tow characteristics and environmental factors, and have a greater variation in locking time. Consequently, this increases aggregate delay and, therefore, impacts the operating costs for tows and increases the overall transportation costs for shippers using the Mississippi River to transport their goods.

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