Lock Congestion and Its Impact on Grain Barge Rates on the Upper Mississippi River

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ABSTRACT

An anticipated increase in lock delays on the upper Mississippi River has generated concern about its future navigational efficiency. The objective of this paper is to identify selected factors affecting lock delay on the River's busiest locks and to examine the impact of lock delay on grain barge rates. Results show that lock unavailability, traffic level, and delay at nearby locks affect lock delay. Further, barge rates are affected by lock delay, however, the impact is modest.

Key Words: Inland Waterway, Lock Delay, Grain Barge Rates

JEL Classifications: Q13, R41

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The upper Mississippi River (UMR) is the primary transportation artery for moving corn, soybean, and wheat production from the north central U.S. to the lower Mississippi River port area, the principal port area for U.S. grain exports. Lately, producer organizations and farmers have cited unsatisfactory lock performance and increasingly congested traffic on the UMR as sources of inefficiency, affecting U.S. competitiveness in world grain markets (Rich). It is argued that lock delay increases barge rates that link the north central U.S. to lower Mississippi River ports. Higher barge rates result in lower producer grain prices in the hinterland and generate higher prices for importing countries, thus weakening the international competitiveness of U.S. grain markets. The objective of this paper is to explore the factors affecting delay of vessels passing through the UMR's busiest locks and examine the impact of UMR lock delay on barge rates of grain/oilseed products. Conceptually, lock delay will increase the cost of barge activity and this added cost is passed on to grain elevators and producers in the form of higher barge rates. Applying recently developed methodology of directed acyclic graphs, along with regression analysis, we attempt to understand the association between lock delay and selected factors which may cause delay and to measure the impact of lock delay on UMR barge rates.

This paper includes a background section that offers perspective on the UMR. A brief literature review is followed. A description of the methodology and of data used in then analyses is presented. Next, results are offered and, then summary and conclusions are provided.

BACKGROUND

The 663-mile UMR extends from Minneapolis, Minnesota to the juncture of the Missouri River near St Louis, Missouri. It includes twenty-nine locks and dams with most lock chambers 600 feet in length and about 110 feet in width except for three 1,200-foot locks. The average barge is 195 feet long and 35 feet wide. At most, a 600 foot lock can allow eight jumbo barges (plus the towboat) to pass through at one time while a 1,200-foot lock can hold 17 jumbo-barges plus the towboat. When the number of barges pushed by a towboat exceeds eight (typical situation), it becomes necessary to break the tow in order to pass a 600-foot lock chamber. The break-up and reassembly of the tow plus the lock operations take from one hour to ninety minutes (Fuller, Fellin and Grant), while tow passage via a 1,200-foot lock requires about 30 minutes. Therefore, the extension of selected locks in the lower reaches of the UMR has been argued as a solution of reducing lock congestion and associated barge delay.

Tow or vessel delay (wait time) at a lock is defined by the U.S. Army Corps of Engineers (the Corps) as the time elapsed from the arrival of a tow or vessel at a lock to the start of its approach to a lock chamber. Delay includes waiting time experienced while other tows or vessels are being processed and when the lock is stalled or unavailable to perform the locking function. Yu and Fuller found on the lower portion of the upper Mississippi River (locks 18 to 25), that lock 22 had the largest average delay (5.19 hours) per delayed vessel, while five of the remaining six locks experienced average delays of 2.0 to 4.9 hours, except for lock 19. Further, if a grain barge traveling from Minneapolis, Minnesota to near St. Louis, Missouri were to be delayed at each lock it would experience an average of 58 hours of delay, with 55 percent encountered at lock 18 (upper Mississippi) through lock 27 (middle Mississippi) (Figure 1). Further, although the average delay time of delayed vessels at each lock on the lower portion of the UMR is considerable, there is no obvious trend in average delay except at lock 25 which exhibited an upward trend in delay over the 1980-1999 study period.

LITERATURE REVIEW

There have been numerous studies of the UMR waterway and the efficiency of its current 600-foot lock chambers. Fuller and Grant show that lock delay on the upper Mississippi/Illinois

Rivers system will divert grain from barges to other transportation modes. Jack Faucett Associates (JFA) (1997) estimated for the Corps that the tonnage of corn and soybeans will double on the upper Mississippi/Illinois Waterways between 1995 and 2045, therefore, the expansion of some key locks should be considered. More recently, JFA (2000) lowered the projection of grain exports and waterway traffic since their earlier analysis was criticized as over-estimating traffic levels and it failed to include some important dimensions (Bitzan and Tolliver). A National Academy of Science study criticized the Corps for proposing an expensive lock expansion program as the only solution to increased traffic volume and lock delay (Turnew-Lowe). The nonstructural alternatives, such as better-trained deck hands, powered devices to reassemble tows, issuing tradable/transferable permits of passing through locks and scheduling of towboat arrival times were recommended to reduce lock delay rather than the expensive lock expansion projects proposed by the Corps. Gervais et al. conducted a study using a disaggregated linear programming model to evaluate the short-run economic impacts of UMR navigation improvements. They show that expanding critical locks to 1,200 feet on the lower reach of UMR would provide limited benefits, which would not improve the U.S. competitiveness in world grain markets.

Many of the previous studies have focused on the lock delay problem and various aspects of lock expansion on the UMR. Before offering solutions to the delay problem, it seems appropriate to determine what causes this delay. A quantitative estimate of the association between the lock congestion or delay and barge rate is also important. Clearly, knowledge of the effects of lock capacity and lock delay on barge rates is central to carrying out meaningful research into the benefits of the extended lock chambers.

METHODOLOGY TO DETERMINE CAUSALITY

To determine the causal relationship between various factors and lock delay as well as lock delay and grain barge rates, a newly developed methodology referred to as directed acyclic graphs is employed. The tool originates from the field of artificial intelligence and computer science. A directed graph is a picture representing causal flow among variables that have been suggested by prior study or theory to be related (Bessler and Loper). Sprites, Glymour and Scheines developed a PC algorithm to infer causal relations when these variables are measured as observational data. PC algorithm utilizes a step-wise procedure beginning with a general unrestricted set of relationships among variables. It removes connections or edges between variables based on zero correlations or conditional correlations. Remaining connections or edges between variables are directed using the notion of a "sepset". The conditioning variable(s) on removed lines between two variables is called the sepset of the variables whose edge has been removed (for vanishing zero-order conditioning information the sepset is the empty set). Directed edges between triples O – P – Q appear as O → P ← Q if P is not in the sepset of O and Q. If O → P, P and Q are adjacent, O and Q are not adjacent, and there is no arrowhead at P, then P – Q is oriented as P → Q. If there is a directed path from O to P and an edge between O and P, then orient O – P as O → P.

Fisher's z is used to test whether conditional correlations are significantly different from zero, where $z[\rho(i, j|k)n] = ½(n - |k| - 3)^{1/2} \times \ln[|1+ \rho(i, j|k)| \times (|1 - \rho(i, j|k)^{-1}]$ and, n is the number of observations, $\rho(i, j|k)$ is the population correlation between series i and j conditional on series k, and $|k|$ is the number of variables in k (that we condition on). If i, j and k are normally distributed and $r(i, j|k)$ is the sample conditional correlation of i and j given k, then the distribution of $z[\rho(i, j|k)n] - z[r(i, j|k)n]$ is standard normal. The software TETRAD II is developed to process the PC algorithm and its extensions.

Traditional regression-based procedures for specifying causal structure on observational data require experimental randomization in application. However, the assumption of randomization does not hold in the real world. Therefore, for a policy analysis, we need to understand the causal mechanism among all variables we study (Bessler). The graphical methods applied here can achieve this purpose.

Likewise, the directed graph methodology is superior to "Granger" causality (Granger) for purposes of carrying out this study. Granger causality is limited to forecasting a variable based on the past information of itself and other variables. Griffiths, Hill and Judge (p. 696) wrote "Granger's concept of causality does not imply a cause-effect relationship, but rather is based only on "predictability." As an example, Granger causality would be appropriate to estimate a model with lagged relationships between variables: $x_{t1} = a_{11} + a_{12}\, x_{t-1,1} + a_{13}\, x_{t-1,2} + e_{t1}$. However, Granger causality is not appropriate when the dependent variable and the independent variables have a contemporaneous relationship. In contrast, the directed graph methodology applies to both contemporaneous and lagged relationships (Akleman, Bessler and Burton). In this study, a contemporaneous relationship may exist among the various forces being evaluated. The directed graph method, as mentioned above, uses artificial intelligence and computer technology to proceed in a step-wise comparison so as to remove edges between variables and to direct "causal flow."

Directed acyclic graph analysis provides the causality analysis between selected factors and lock delay, and between lock delay and barge rate on the UMR. The resulting graphs are recursive. Accordingly, we can employ ordinary least squares regression to summarize the quantitative relationship between variables found using the directed acyclic graphs.

DATA

In this analysis we discuss the data used to investigate various factors causing lock delay as well as the data used to examine the relationship between lock delay and barge rates.

Factors Causing Lock Delay

Lock delay occurs while one or more vessels are waiting and the lock is in operation. Monthly average delay of delayed tow vessels for locks located on the lower reach of the UMR is employed in the analysis. When increasing levels of traffic enter a lock's pool, it is expected that the queue of vessels or tows that require locking service will increase. Any factors reflecting traffic level, such as tonnage, number of loaded barges, number of empty barges, number of commercial lockages, or level of hardware operations would be a candidate to influence lock delay. In addition to traffic related factors, the unavailable time (stalls), frequency, and duration of stalls may also contribute to lock delays. If the stalls occur because of an unanticipated condition (accident, tow malfunction, or locks and/or tow staff occupied with other duties) and the shippers have no option of diverting shipments to other modes, then lock delay will result. An increase in the duration of stalls is expected to increase lock delays. Another factor that may cause lock delay is recreational lockage. In the summer season, recreational vessels use the waterways, thus competing with commercial navigation. Recreational vessels have a priority, authorized by the Lockmaster's Blue book, to pass through locks after every third commercial cut. In addition, the recreational vessels usually require separate lockages due to their relatively fragile body, it is expected that they increase the number of lock operations as well as lock delays (USACE, 2002).

The data in our analysis is collected through the Corp's Lock Performance Monitoring System (LPMS) (USACE, 1992). The factors included in the analyses are defined in Table 1. Included in the analysis are monthly data on loaded barges; unloaded barges; commercial lockages; hardware operations; tonnage; recreational lockages; the frequency of stalls; the average and total duration of stalls; seasonality of tonnage; and average delay at other locks.

Lock Delay and Barge Rates

It is argued that lock delay increases the shipper's transportation costs. Tows must wait for extended periods at selected locks with operating costs of towboats ranging from $400 to $500 per hour, increasing barge rates (USACE, 1992). Intuitively, the greater the accumulated lock delay that a tow experiences while moving on the UMR, the higher the transport cost and ultimately the higher the barge rate.

Here, the UMR is divided into three geographic segments. They include the Upper St. Anthony's Falls Lock to Lock 8 (L1-L8), Lock 9 to 17 (L9-L17) and Lock 18 to 27 (L18-L27). To obtain a better understanding of the relationship between lock delay and barge rates, the monthly barge rate for southern Minnesota (BRSM) and northern Iowa (BRNI) grain shipments to lower Mississippi River ports were obtained for the 1980 to 1999 period. Southern Minnesota includes the St. Paul, Minnesota to McGregor, Iowa segment while northern Iowa includes the segment extending from McGregor, Iowa to Clinton, Iowa. Monthly rates are not evaluated during the frozen season (December, January and February) and periods of flooding in July 1993. A total of 179 monthly barge rates were collected for each river segment. Barge rates were provided by USDA Agricultural Marketing Service (AMS) (USDA), which collects the spot rates from mid-west barge companies (or brokers). The spot rate is the current barge rate for shipping grain from river origins to export facilities located on the lower Mississippi River. The spot rate does not reflect any discounts, promotions, or contracted services (Marathon). Data on the monthly average delay time, in hours, at UMR locks was obtained from the Corp's LPMS (USACE, 1992). Table 2 summarizes the two barge rates and accumulated delay time for the three segments.

RESULTS AND ANALYSES

Factors causing lock delay and the effort to determine the affect of lock delay on barge rates are presented in the results of the investigation. Once the causal relationships are identified with the directed acyclic graphs, regression analysis is used to formalize the discovered relationships.

Analysis of Factors Causing Lock Delay

Directed acyclic graph methodology is employed on a lock-by-lock basis to determine factors affecting lock delay on the lower portion of the UMR. On the lower portion of the River, six 600-foot Locks 18, 20, 21, 22, 24, and 25 are selected for analysis. Figure 2 is the estimated graph for Lock 18. Since the number of observations on each lock is about 200, a 5 percent significance level was selected. For Lock 18, average delay (ADELDV) is caused by frequency of stalls (NUMUN) and average delay at Lock 21. The analysis shows that an increased frequency of stalls will cause an increase in delay at Lock 18, as will delay at Lock 21. The analysis did not find traffic level to cause delay at Lock 18. The traffic level variables included in the analysis were loaded barges (BRGL), unloaded or empty barges (BRGU), commercial lockages (COML), total hardware operations (TOTOP), and recreational lockages (RECL). All traffic level variables were highly correlated. Interestingly, delay time at locks in the lower portion of the UMR causes delays at adjacent or nearby locks. For example, a delay at Lock 25 creates a delay at Lock 24, and a delay at Lock 24 causes a delay at Lock 22.

The directed acyclic graph analyses for the remaining five locks are summarized in Table 3. None of the evaluated factors appear to cause delay at Lock 20, at the 5 percent significance level. However, a delay at Lock 20 has an impact on delays at Locks 19 and 22. Similar to Lock 20, delay at Lock 21 is not explained by any evaluated factors. In contrast, the delay at Lock 21 influences delays at Locks 22 and 19. The average duration of stalls (AVGUN) and delay at

Locks 21 and 24 affect the delay at Lock 22. Neither traffic level nor the frequency of stalls causes delays at Lock 22. Delay at Lock 24 is caused by total hardware operations (TOTOP), frequency of stalls (NUMUN), total duration of stalls (TOTUN), and delays at Lock 25. Hardware operations are closely related to traffic volume since they are related to commercial lockages (COML) and loaded barges (BRGL). The frequency of stalls and duration of stalls appear to cause delay. The number of loaded barges (BRGL) and total stall time (TOTUN) affect delay at Lock 25. The delay at Lock 25 causes delay at Lock 24, which parallels the findings in the directed acyclic graph of Lock 24. The delay at Locks 26 and 27 do not cause any delays at those five locks.

Selected barge companies operating on the UMR were contacted to explain how delay at one lock could cause delay at a nearby lock. The most feasible explanation centered on the occurrence of stalls. In particular, once a stall has occurred at a lock, this information is transmitted to other tow operators on the affected segment of the river. Since fleeting capacity in the affected lock's pool may be limited or because the barge company has no fleeting capacity in the affected pool, tow operators may fleet in a nearby lock. Thus, stalls at a particular lock may increase fleeting in a nearby lock's pool. And, once the stall at the affected lock has been remedied and traffic commences, the delay time at nearby locks may increase as a result of the accumulated traffic that must be locked. Hence, a stall and associated barge delay at a particular lock may cause an increase in delay at a nearby lock.

Based on the findings from the directed acyclic graph analyses, we regress monthly average delay time on those identified factors (direct causes) which cause lock delay in order to determine the association between monthly average delay and those factors causing delay. The statistical description of causal factors and average delay time for individual locks is presented in Table 4. Each lock is represented by monthly data over a 20-year period, however, non-operational periods such as winter months are excluded. Delay at Locks 20 and 21 are not explained by any of the factors at the 5 percent significance level. All six locks experienced at least an average delay per vessel of 2.7 hours.

Table 5 includes the estimated delay equations for each lock and the associated statistics. Average duration of stalls (AVGUN) and delay at Locks 21 and 24 directly cause delay at Lock 22. The estimated coefficient on the AVGUN variable, 0.002, informs that a one minute increase in the average duration of stalls increases delay by 0.002 hours at Lock 22, or 0.12 minutes. Further, a one-hour increase in delay at Lock 21 increases delay by 0.127 hours at Lock 22. The large t-ratio (28.58) associated with L21 indicates the importance of this factor. In addition, one additional hour of delay at Lock 24 will cause 0.23 hours of delay at Lock 22. The adjusted R-square value of 0.812 implies the estimated equation has considerable explanatory ability for delay at Lock 22. The D-W statistic of 2.047 suggests no autocorrelation problem with this equation.

The t-statistics suggest that delay at Lock 24 is positively affected by total hardware operations (TOTOP), frequency of stalls (NUMUN), total duration of stalls (TOTUN), and delay at Lock 25. The calculated elasticity shows a one-percent increase in total hardware operations will increase vessel delay at Lock 24 by about 0.6 percent. A one-percent increase in frequency and duration of stalls will increase the delay at Lock 24 by 0.193 and 0.126 percent, respectively. In addition, a one-percent increase in delays at Lock 25 will cause delays at Lock 24 to increase by 0.216 percent. Modest explanatory power (R-square value of 0.299) is offered by the estimated equation. There is no significant autocorrelation found according to the D-W statistic.

For Lock 25, the number of loaded barges transiting the lock (BRGL) and total duration of stalls (TOTUN) are the factors causing delay. The magnitude of the estimated coefficient on the BRGL variable is very small, 0.0013, however, its estimated elasticity shows that a one-percent increase in loaded barges will increase average delays 0.873 percent. The total duration of stalls has a relatively small impact on delays with an elasticity of 0.133. The adjusted R-square indicates BRGL and TOTUN explain about 25 percent of the variation in delay at Lock 25. The D-W statistics, 1.640, is inconclusive regarding the presence of autocorrelation.

The directed acyclic graphs and regression results show that traffic level has an important impact on delay at Locks 24 and 25. Delay at Locks 20 and 21 is not caused by any factor included in the LPMS dataset. Seasonal tonnages and recreational vessels do not directly cause lock delays. Interestingly, most locks are affected by delay at nearby locks. Further, stalls contribute to delay problems for most of the examined locks. Although the explanatory power of the identified variables is limited in the estimated equations, they provide insight regarding the association between lock delay and various factors in the Corps' LPMS (USACE, 2002) database.

Analysis of Lock Delay and Barge Rates

Similar to the previous section, the directed acyclic graphs and regression analyses are employed to assess the relationship between lock delay and barge rate for the UMR. For southern Minnesota barge rates (BRSM), the accumulated monthly lock delay for three segments of the UMR (L1-L8, L9-L17 and L18-L27) is included in the directed acyclic graph analysis. In addition, the past information (lag) on barge rate (LBRSM, LLBRSM) is added to prevent overestimating the contemporaneous impact of lock delay. The length of lag (2) was determined by the Schwarz criteria (Schwarz). The directed acyclic graph analysis shows that accumulated lock delay at Locks 18 to 27 along with the lag of barge rates affects the current southern Minnesota barge rate (Figure 3). This implies that the delay incurred at Locks 18-27 increase the southern Minnesota barge rate. Accumulated delay associated with Locks 18 to 27, as well as past information on barge rate (LBRNI, LLBRNI), were found to affect northern Iowa (BRNI) barge rates at the 20 percent significance level (Figure 4).

Based on the directed acyclic graph analysis, barge rate equations were estimated for southern Minnesota and northern Iowa segments. Several specifications are estimated and presented. The top portion of Table 6 includes a regression that reflects the impact of accumulated lock delay in the segment of locks 18 to 27 on southern Minnesota grain barge rates while the lower portion shows the influence of aggregated lock delays on north Iowa barge rates. The magnitude of the coefficient associated with L18-L27 is 0.021, indicating that an additional hour of accumulated delay from Locks 18 to 27 will increase the barge rate 2.1 cents per ton (1.9 cents/mg). The average delay time per delayed tow vessel in this segment is 32.06 hours (see Table 3); therefore, the cost of delay to shippers is about $0.67 per ton (32.06 hours x 2.1 cents/ton) or about $1005/barge, assuming each barge carries 1,500 tons and the barge is delayed at each lock on this river segment. This explanatory variable is statistically significant at the 5 percent level. The associated elasticity of 0.059 was calculated at the means and it shows that a one-percent increase in delay will increase southern Minnesota barge rate 0.059 percent. The adjusted R-square of 0.622 shows the lagged barge rate and accumulated delays at L18-L27 explains 62.2 percent of the monthly variation in the southern Minnesota barge rate. The D-W statistic of 1.668 indicates autocorrelation is averted by including the lagged dependent variable.

The northern Iowa barge rate is affected by accumulated delays associated with Locks 18 to 27 at the 20 percent significance level (Table 3). However, the impact of delay is very moderate: an additional hour of accumulated delays from Locks 18 to 27 will only increase the barge rate 1.10 cents per ton (1 cent/mg), that is, $0.35 of delay costs or about $525/barge if barges are delayed at all locks will be added to the barge rate given an average delay of 32.06 hours. About 55 percent of the variation in the northern Iowa barge rate is explained by lagged barge rate and accumulated delays at L18-L27. The D-W test of 2.009 shows no autocorrelation.

The analyses of lock delays and grain barge rates on the UMR show the grain barge rate is somewhat affected by delays at several locks. Southern Minnesota and northern Iowa barge rates are affected by the accumulated delays from Locks 18 to 27, the most congested portion of the UMR. Even though the relationship between the barge rates and lock delays is statistically significant, the influence of lock delays on those barge rates is very modest.

SUMMARY AND CONCLUSIONS

The UMR is the primary transportation artery for moving grain/oilseed production from the north central U.S. to the lower Mississippi River port area. However, the unsatisfactory lock performance and increasingly congested traffic on the UMR have been cited as a source of inefficiency and a factor affecting U.S. competitiveness in world grain markets. The objective of this study is to explore the factors that affect lock delay and measure the relationship between lock delay and barge rates. Clearly, knowledge of the effects of lock delay on barge rates is central to carrying out meaningful research of the benefits of the extended lock chambers.

The directed acyclic graphs and regression results show that traffic level has an important impact on delay at Locks 24 and 25 on the UMR. Interestingly, most of the locks are affected by delay at nearby locks. Further, stalls contribute to delay problems for most of the examined locks. In the analysis of causal relationship between lock delays and barge rates, the directed acyclic graphs analysis shows that barge rates linking southern Minnesota and northern Iowa to lower Mississippi River ports are partially caused by the accumulated delay from Locks 18 to 27, the most congested portion of the UMR. Estimated rate equations show a 1 percent increase in accumulated lock delay at locks 18 through 27 will increase the south Minnesota and north Iowa rates to lower Mississippi River ports by 0.059 and 0.038 percent, respectively. Based on historic average delay at locks 18 through 27 (32.06 hours), the barge rate linking south Minnesota to lower Mississippi River ports is increased about $1005/barge as a result of this delay, if the grain barge experiences delay at all involved locks. Likewise, the north Iowa rate is increased about $525/barge.

Further research into the identification of factors on lock delay could be insightful. With additional details on lock delays, evaluating the effect of factors on delays associated with up-bound and down-bound traffic would offer more perspective. Similarly, with additional information on other potential factors, such as weather or commercial processing time, it would make more definitive statements about factors influencing delays. Also, it would be interesting to exploring how other forces in combination with lock delay impact on barge rates.

FOOTNOTES

[1] Additional analysis was carried out to determine the effect of average lock delay of all vessels on grain barge rates. This is in contrast to the reported analysis that examines the effect of average lock delay of delayed vessels on grain barge rates. The directed graph analysis shows accumulated average delay of all vessels passing lock 18 to lock 27 (L18 - L27) to be a partial cause of south Minnesota barge rates. When the L18 – L27 variable is included with four additional variables in the barge rate equation it was found to be significant at the 1 percent level. The estimated coefficient on the accumulated lock delay variable (L18 - L27) was $0.025/ton and its estimated elasticity was 0.066, indicating a 1 percent increase in the average delay of all vessels would increase the north Minnesota grain barge rate about 0.066 percent. Further, since the historic accumulated average delay of all vessels passing locks 18 to 27 was 29.08 hours, the delay at these locks increase barge rates on all passing grain tows an estimated $0.727/ton or about $1090/barge. Interestingly, the estimated affect of lock delay on south Minnesota grain barge rates is only modestly impacted by whether analysis focuses on delay of delayed vessels or delay of all vessels.

REFERENCES

Akleman, D.G., D.A. Bessler, and D.M. Burton. "Modeling Corn Exports and Exchange Rates with Directed Graphs and Statistical Loss Functions." *Consumption, Causation, and Discovery*. C. Glymour and G.F. Cooper, eds. Menlo Park, CA: American Association for Artificial Intelligence Press, 1998.

Bessler, D. A. "On World Poverty: Its Causes and Effects" Food and Agricultural Organization of the United Nations Research Bulletin, 2003 (forthcoming).

Bessler, D. A. and N. Loper. "Economic Development: Evidence from Directed Acyclic Graphs." *The Manchester School* 69, Vol. 69, No. 4, Sept. 2001, pp. 457-476.

Bitzan, J.D. and D..D. Tolliver. *Review of Waterway Grain Traffic Forecasts for the Upper Mississippi River Basin*. Aug. 2000. http://www.mvr.usace.army.mil/pdw/nav_study/JFAreport.pdf. [Accessed Feb. 12, 2002].

Fuller, S., L. Fellin, and W. Grant. *The Upper Mississippi/Illinois Rivers and Grain/Soybean Transportation: An Analysis of Transportation Capacities.* Research Report CM 1-98. TAMRC, Dept. of Agricultural Economics, Texas A&M University, 1998.

Fuller, S. and W. Grant. "Effect of Lock Delay on Grain Marketing Costs: An Examination of the Upper Mississippi and Illinois Waterways." *Logistics and Transportation Review* Vol. 29, No. 1, Mar. 1993, pp. 81-95.

Gervais, J-P, T. Misawa, M.J. McVey, and C.P. Baumel. "Evaluating the Logistic and Economic Impacts of Extending 600-Foot Locks on the Upper Mississippi River: A Linear programming Approach." *Journal of the Transportation Research Forum* Vol. 40, No. 4, Fall 2001, pp. 83-103.

Granger, C.W.J. "Investigating Causal Relations by Econometric Models and Cross-spectral Methods." *Econometrica*. Vol. 37, No. 3, Aug., 1969, pp. 424-438.

Griffiths, W.E., R.C. Hill and G.G. Judge. *Learning and Practicing Econometrics.*John Wiley & Sons, New York, 1993.

Jack Faucett Associates. *Waterway Traffic Forecasts for the Upper Mississippi River Basin. vol. I Summary and vol. II grain*, 1997. http://www.mvr.usace.army.mil/pdw/nav_study/JFAreport.pdf. [Accessed Feb. 12, 2002.]

Jack Faucett Associates. *Review of Historic and Projected Grain Traffic on the Upper Mississippi River and Illinois Waterway: An Addendum.* September 20, 2000 http://www.mvr.usace.army.mil/pdw/nav_study/JFAreport.pdf. (Accessed Feb. 12, 2002)

Rich, J. L. "Soy Growers in Brazil Shadow U.S. Farmers." *NYTimes*, July 10, 2001. http://www.nytimes.com/2001/07/10/business/10SOY.html?ex=995769069&ei=1&en=4c6213a83c50fbd7. [Accessed July 11, 2001].

Roh, J., D.A. Bessler, and R.F. Gilbert. "Traffic Fatalities, Peltzmans Model, and Directed Graphs" *Accident Analysis and Prevention.* Vol. 31, 1999, pp. 55-61

Schwarz, G. "Estimating the Dimension of a Model." *Annals of Statistics* 6:461-464. 1978.

Sprites, P., C. Glymour, and R. Scheines. *Causation, Prediction, and Search.* Springer-Verlag, New York, 1993.

Turner-Lowe, S. "Unlocking Congestion on the Heartland's Main Waterway." *The National Academies in Focus* Spring 2001, 15-16.

U.S. Army Corps of Engineers, Lock Performance Monitoring System data. Various issues. http://www.wrsc.usace.army.mil/ndc/lpms.htm. [Accessed Apr. 23, 2002].

U.S. Army Corps of Engineers, Water Resource Support Center *The 1992 Inland Waterway Review*. IWR Report 92-R-7, October 1992.

U.S. Department of Agriculture-Agricultural Marketing Service, Grain Transportation Report. Various issues. http://www.ams.usda.gov/tmd/grain/index.htm. [Accessed Sept. 15, 2001].

Yu, T. and S. Fuller. *Factors Affecting Lock Delay on the Upper Mississippi and Illinois Rivers and The Effect of Lock Delay on Barge Rates.* Texas Agricultural Market Research Center. Research Report CP 2-02, Department of Agricultural Economics, Texas A&M University, 2002.

TABLE 1 Definition of Variables Included in Directed Graphs Featured in Figure 2, and Equations in Tables 3, 4, 5 and 6.

Variable	Definition
ADELDV	Average delay time of delayed vessels in hours for lock *i,* month *j*
BRGL	Number of loaded barges at lock *i*, month *j*
BRGU	Number of empty barges at lock *i*, month *j*
COML	Number of commercial lockages at lock *i*, month *j*
RECL	Number of recreational lockages at lock *i*, month *j*
TOTOP	Number of total hardware operations at lock *i,* month *j*
NUMUN	Frequency of stalls in minutes at lock *i,* month *j*
AVGUN	Average duration of stalls in minutes at lock *i,* month *j*
TOTUN	Total duration of stalls in minutes at lock *i,* month *j*
SPRING	Number of tons locked in spring at lock *i,* month *j*
SUMMER	Number of tons locked in summer at lock *i,* month *j*
FALL	Number of tons locked in fall at lock *i,* month *j*
WINTER	Number of tons locked in winter at lock *i,* month *j*
L18	Average delay at lock 18 in hours in month *j,*
L19	Average delay at lock 19 in hours in month *j*
L20	Average delay at lock 20 in hours in month *j*
L21	Average delay at lock 21 in hours in month *j*
L22	Average delay at lock 22 in hours in month *j*
L24	Average delay at lock 24 in hours in month *j*
L25	Average delay at lock 25 in hours in month *j*

TABLE 2 Statistical Summaries of Accumulated Barge Delays and Barge Rates on Upper Mississippi River

	Mean	Standard Deviation	Variance	Minimum	Maximum
Geographic Segment (Hours)					
L1-L8	6.95	3.090	9.548	1.18	26.17
L9-L17	18.93	8.358	69.856	8.56	58.08
L18-L27	32.06	18.206	331.458	11.35	123.57
Barge Rate ($/mg)					
BRSM	10.19	3.577	12.795	4.73	21.16
BRNI	8.52	2.891	8.358	4.59	17.35

TABLE 3 Summary of Factors Causing upper Mississippi River Lock Delay as Determined by Directed Acyclic Graphs Analysis

Lock Delay	Is Caused by:	Is Causing:
L20	------*	L19, L22
L21	------*	L19, L22
L22	NUMUN, L21, L24	------*
L24	TOTOP, NUMUN, TOTUN, L25	L22
L25	BRGL, TOTUN	L24

[1] *not applicable*

TABLE 4. Statistical Summaries of Variables Included in Lock Delay Equations

	Unit	Obs (N)	Mean	Standard Deviation	Minimum	Maximum
Lock 18		213				
ADELDV*	Hours		2.70	2.64	0.00	30.65
NUMUN	Number		4.27	3.28	0.00	19.00
L21	Hours		2.68	1.92	0.00	17.54
Lock 20		230				
ADELDV*	Hours		6.32	44.72	0.00	677.33
Lock 21		230				
ADELDV*	Hours		5.24	40.25	0.19	612.32
Lock 22		231				
ADELDV*	Hours		4.79	6.18	0.32	83.03
AVGUN	Number		246.52	403.58	0.00	4,239.90
L21	Hours		1.97	4.80	0.00	48.00
L24	Hours		3.91	4.17	0.00	33.32
Lock 24		234				
ADELDV*	Hours		3.86	4.17	0.00	33.32
TOTOP	Number		907.32	429.31	12.00	1,627.00
NUMUN	Number		5.68	4.05	0.00	27.00
TOTUN	Number		1,365.20	3,305.60	0.00	30,668.00
L25	Hours		3.16	3.44	0.70E-01	24.30
Lock 25		234				
ADELDV*	Hours		3.16	3.44	0.00	24.30
BRGL	Number		1,996.10	1,007.30	29.00	3,657.00
TOTUN	Number		1,989.10	5,495.60	0.00	46,103.00

* dependent variable.

TABLE 5. Estimated Barge Delay Equations for Upper Mississippi River Locks

	Variables	Coefficient	Standard Error	t-ratio	Elasticity
Lock 18	NUMUN	0.146	0.048	3.026	0.232
	L21	0.614	0.083	7.421	0.611
	INTERCEPT	0.425	0.331	1.283	
	Obs (N)	213			
	Adj. R-Square	0.238			
	Durbin-Watson	1.908			
Lock 22	AVGUN	0.234E-02	0.427E-03	5.482	0.120
	L21	0.127	0.446E-02	28.58	0.139
	L24	0.229	0.447E-01	5.118	0.187
	INTERCEPT	2.652	0.324	8.193	
	Obs (N)	231			
	Adj. R-Square	0.812			
	Durbin-Watson	2.047			
Lock 24	TOTOP	0.249E-02	0.660E-03	3.766	0.585
	NUMUN	0.131	0.585E-01	2.240	0.193
	TOTUN	0.357E-03	0.708E-04	5.041	0.126
	L25	0.265	0.739E-01	3.580	0.216
	INTERCEPT	-0.464	0.687	-0.675	
	Obs (N)	234			
	Adj. R-Square	0.299			
	Durbin-Watson	2.003			
Lock 25	BRGL	0.138E-02	0.195E-03	7.090	0.873
	TOTUN	0.212E-03	0.357E-04	5.930	0.133
	INTERCEPT	-0.202E-01	0.446	-0.453 E-01	
	Obs (N)	234			
	Adj. R-Square	0.248			
	Durbin-Watson	1.640			

TABLE 6. Regression Analyses of Southern Minnesota and North Iowa Barge Rates on Lock Delay

Southern Minnesota

Variables	Coefficient	Standard Error	t-ratio	Elasticity
LBRSM	0.907	0.751E-01	12.09*	0.906
LLBRSM	-0.191	0.754E-01	-2.53*	-0.190
L18-L27	0.210E-01	0.927E-02	2.27*	0.059
INTERCEPT	2.512	0.633	3.97*	
Obs (N)	179			
Adj. R-Square	0.622			
Durbin-Watson	1.981			

North Iowa

Variables	Coefficient	Standard Error	t-ratio	Elasticity
LBRNI	0.880	0.752E-01	11.71*	0.879
LLBRNI	-0.228	0.752E-01	-3.04*	-0.228
L18-L27	0.110E-01	0.819E-02	1.35***	0.038
INTERCEPT	2.918	0.581	5.03*	
Obs (N)	179			
Adj. R-Square	0.548			
Durbin-Watson	2.009			

** Significant at 5% level , ** significant at10% level , *** significant at 20% level*

Upper Mississippi River and Illinois Waterway Navigation Systems.

Figure 1. Map of Upper Mississippi and Illinois Rivers with Locks and Dams.

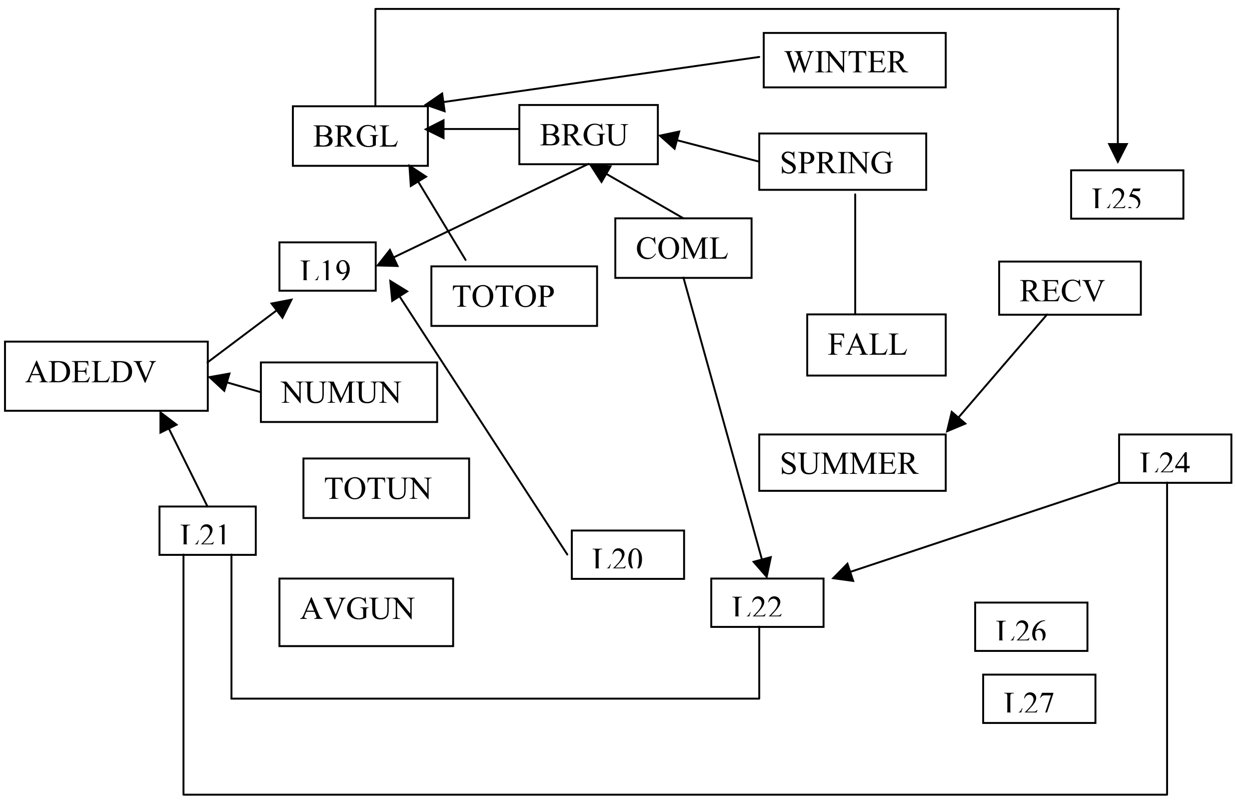

Figure 2. Directed Graph of Lock 18 on the Upper Mississippi River.

(Variables are indicated by rectangle. Lines without arrowheads indicate an association, without a clear causal ordering. Line with an arrowhead indicates a causal relationship)

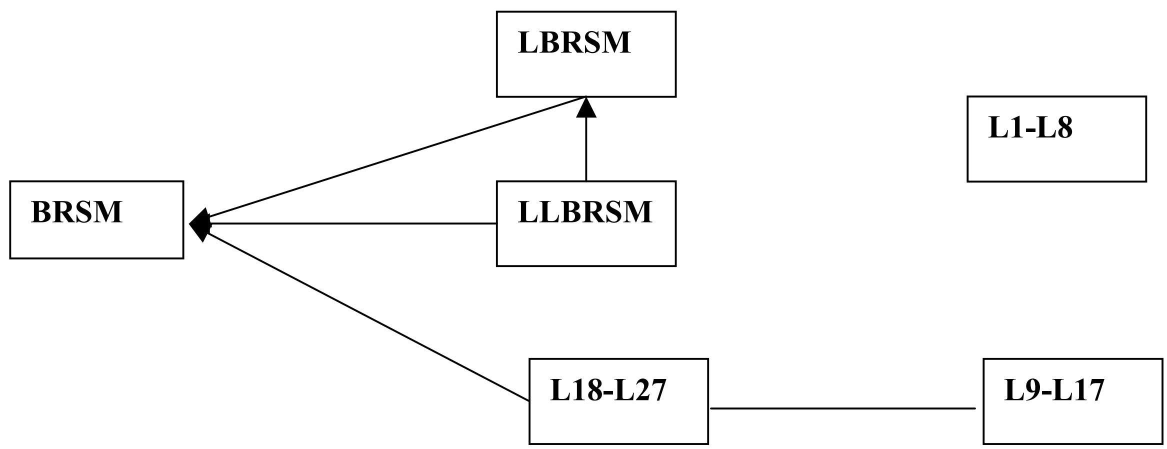

Figure 3. Directed Graph of Southern Minnesota Barge Rate and Accumulated Upper Mississippi River Lock Delays

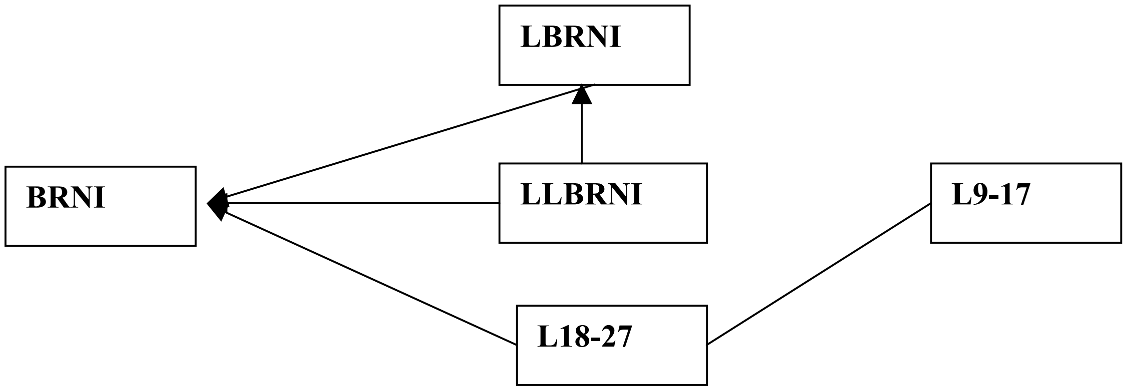

Figure 4. Directed Graph of Northern Iowa Barge Rate and Accumulated Upper Mississippi River Lock Delays.