Determinants of Lock Delays on the Upper Mississippi River: A Spatial Econometrics Approach

T. Edward Yu, Associate Professor, University of Tennessee, tyu1@utk.edu
Bijay Sharma, Graduate Research Assistant, University of Tennessee, bsharma3@utk.edu
Burton C. English, Professor, University of Tennessee, benglish@utk.edu

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Abstract: The 28 lock and dams sites on the upper Mississippi River is currently central to transporting U.S. agricultural commodities to the world market. This aging lock and dam system and slow double lockage process at the 600-foot locks have generated concern about its navigational efficiency. The objective of this study is to examine the determinants of delay occurred at the lock and dam system on the River. The focus is on the impact of lockage processing time (lock capacity issue) and unscheduled outages/stalls (system management issue) on lock delay. Results suggest that reduction in processing time reduces lock delay considerably. In addition, increases in the number of unscheduled outage cause by weather issue result in more delay hours. Delays at a given lock is also affected by lockage duration, the average duration of unscheduled stalls caused by weather, the unscheduled outage related to the occurrence of mechanical and vessel issues at nearby locks.

Keywords: Mississippi River, Lock Delay, Spillovers, Spatial and Dynamic Panel

1. INTRODUCTION

The inland waterway system in the United States is central to transportation of low-valued agricultural commodities such as grain/oilseed and animal feed, and selected agricultural inputs (e.g., fertilizer, petroleum products). Barge transportation is of great importance to U.S. agriculture because of its comparatively low transport charges as compared to overland modes. An estimate by the Iowa Department of Transportation (IDOT, 2014) shows that barge cost on the upper Mississippi River, on average, is $11/ton less than the cost of truck and rail. The transport costs that link two trading regions (e.g., north central U.S. and lower Mississippi River ports) have a direct influence on commodity prices in both origin and destination markets. Thus, improvement in navigation efficiency on the inland waterway would enhance the U.S.'s competitiveness in world grain markets.

The upper Mississippi River is currently the primary carrier of agricultural commodities for export ports in the United States. Grain/oilseeds are the principal commodities transported on the River, comprising more than half of the tonnage transported on the River. Central to navigation on the upper Mississippi River are 28 locks sites that are managed and maintained by the U.S. Army Corps of Engineers (USACE). Most locks have a chamber of 600 feet long and 110 feet wide, except for lock 19, Melvin Price lock and lock 27 (1,200×100 chamber). The size of lock chamber has direct impact on lockage process since a 600-foot (ft) lock can process at most nine jumbo-barges (plus the towboat) in a single lockage, while a 1,200-ft lock can accommodate up to 18 jumbo-barges in addition to the towboat. Currently, an average of 15-16 barges are in a tow on the upper Mississippi River. Therefore, the tows will need to be re-coupled when passing a 600-ft long lock chamber (i.e. *double lockage*) and reassembled after exiting the chamber. The average duration of double lockage plus related operations at 600-ft locks took almost two hours, while a single lockage of towboat and barges at a 1,200-ft lock typically requires about half of an hour to 45 minutes (Campbell et al., 2009).

This aging lock and dam system, primarily built during World War II, and the slow double lockage process at 600-ft locks have raised concern about the navigational efficiency of these transport arteries. The greatest concern centers on the constrained lock capacity in the lower portions of these rivers where comparatively high traffic generates extended delays for barges/tows. Grain producers argue that the lock delay on the upper Mississippi River unfavorably influences the competitiveness of U.S. grain in the international market (Yu et al., 2006). The American Society of Civil Engineering (ASCE) projects a loss of $3.6 billion in agricultural exports in the next decade if waterway infrastructure continues to deteriorate (ASCE, 2013). Thus, the U.S. Army Corps of Engineers, barge industry, and agricultural commodity groups have advocated the construction of new lock and dam systems for decades. However, the expensive capital investment and potential environmental distortions associated with the modernization of lock and dam systems have drawn considerable debates (Meyer and Kruse, 2007). Instead, less costly non-structural methods, e.g. scheduling, maintenance management, etc., have been suggested to be considered as means to control congestion and delay on the River (Transportation Research Board, 2015).

Due to the importance of the upper Mississippi River to agricultural and bulk commodities, numerous studies have been done to examine the lock delays issue on the River. Some have simulated the improvement of the River's lock and dam systems and found positive economic benefits to U.S. agricultural sector (e.g. Gervais et al., 2001; Fellin et al., 2001; Wilson et al., 2010). Alternatively, several scholars investigate the economic impact of impediments to barge transportation on the River and suggest adverse economic consequences due to lock delay or failure (e.g. Fuller and Grant, 1993; Yu et al., 2006; Fellin et al., 2008). Another group of scholars have explored the strategies of improving lockage process or management to mitigate the congestion issue at locks (e.g. Nauss and Ronen, 2004; Cook and Plott, 2005; Meyer and Kruse, 2007; Campbell et al., 2009).

Despite the aforementioned studies related to lock efficiency on the upper Mississippi River in the literature, little attention has been given to assessing the impact of potential factors on lock delays. Particularly, spatial dependency of locks on the River is generally overlooked in the previous studies although the whole river should be evaluated as a whole system. Thus, *the objective of this study is to examine the potential influences to delays occurred at the lock and dam system, incorporating potential spatial interaction among locks and dams, on the upper Mississippi River*. A spatial modeling framework that considers the spatial dependence of both depend and explanatory variables was used to achievement the study objectives. The analysis can help decision makers better understand the lock delays issues and make related investment or adjustment on the inland waterway system that will ultimately benefit U.S. agricultural sector.

2. ANALYTICAL METHOD

Tow or vessel delay at a given lock is defined as the waiting time between the point of tow/vessel arrival and the time of beginning the lockage process at the lock chamber (Yu et al. 2006). Congestion related delays can be related to various factors, such as seasonal commercial traffic, adverse operating conditions, the process of double lockage, and periodic significant use by recreational craft. The focus in this study will be on the impact of lockage processing time and unscheduled lock outages/stalls on lock delay based on the report of Transportation Research Board (2015). The lockage processing time is related to lock capacity (hardware), while unscheduled outages are the issues of system maintenance (management). Unscheduled stalls can be typically categorized as weather-related (e.g. fog, flood), mechanical-related (e.g. lock equipment malfunction, lock inspection), vessel-related (tow accident or breakdown) and others. In this analysis, the impact of lockage processing time, frequency of unscheduled stalls at lock, and average duration of unscheduled stalls at lock by category on lock delay time was evaluated.

2.1 Spatial Econometrics Analysis

To estimate the impact of lockage processing time and unscheduled outages/stalls by category (i.e. mechanical, vessel, weather and others) on lock congestion and delays on the upper Mississippi River, a spatial econometrics approach is adopted to capture the potential spatial spillover effects of these variables (LeSage and Pace 2009; Vega and Elhorst 2015). Since the inland waterway on the upper Mississippi River includes multiple locks, and the barge traffic is both north- and south-bound, the delays occurred at a given lock will presumably affect the nearby locks and also be influenced the delays at those locks. Similarly, the spatial autocorrelation issue could also be found in the independent variables (lockage processing time, unscheduled outages) and the error terms from a regression model.

Following Elhorst (2010), a spatial Durbin model (SDM) that addresses the spatial interaction effect from both dependent and explanatory variables was employed in the analysis. The SDM framework can be expressed as:

$$\mathbf{Y} = \alpha\mathbf{I} + \delta\mathbf{WY} + \mathbf{WX}\boldsymbol{\theta} + \mathbf{X}\boldsymbol{\beta} + \mathbf{u}; \qquad (1)$$

where I is the N × N identity matrix, W is the N × N spatial weight matrix, WY denotes the endogenous interaction effects among the dependent variables, WX is the exogenous interaction effects among the explanatory variables, δ includes the scalar parameters measuring the strength of spatial dependence between units, and θ and β are the $K \times 1$ vector of response parameters.

The SDM mitigates omitted variables issue and produces an unbiased estimator (LeSage and Pace 2009).

2.2 Direct and Indirect/Spillover Effects

The estimated parameters of spatial lag variables, i.e. δ and θ in equation (1), cannot be directly interpreted as a marginal effect of the explanatory variables (LeSage and Pace 2009). In fact, the total marginal effect can be decomposed into direct and indirect effects to better represent marginal effect given the spatial interaction framework. Direct effect is the effect of changing a given explanatory variable in one location on the dependent variable of that location. Indirect or spillover effect is the effect of a change in a particular explanatory variable in one location on the dependent variable of all other locations on average.

The matrix of partial derivatives of the expectation of **Y**, E(**Y**), with respect to the k^{th} explanatory variable of **X** is given by:

$$\frac{\partial E(\mathbf{Y})}{\partial \mathrm{X}_{\mathrm{k}}} = (\mathbf{I} - \delta\mathbf{W})^{-1}(\beta_{\mathrm{k}}\mathbf{I} + \mathbf{W}\theta_{\mathrm{k}}) \tag{2}$$

Specifically, the direct effect is obtained by averaging the diagonal elements of the N × N marginal effect matrix (2) whereas the spillover impact is obtained by averaging all non-diagonal elements of the above obtained marginal effect matrix.

The quarterly data for locks 11 through 27 on the upper Mississippi River during 2004-2013, a balanced panel including a total of 640 observations, was used in the estimation. The locks above Lock 11 are not included since they are not operated during winter season so data is not available for both dependent and explanatory variables. Data of average lock delays for all vessels was used for the dependent variable (delay). The average lockage processing time for all vessels, unscheduled lock outages frequency and average outages duration by category at locks were the explanatory variables. All data was obtained from the U.S. Army Corps of Engineers' Lock Performance Monitoring System and USDA. Proprietary information was removed from the dataset by The Corps of Engineers. The descriptive statistics of selected variables are summarized in Table 1. The spatial weight matrix **W** used in the study was the inverse distance matrix obtained using the distance between all the locks.

3. PRELIMINARY RESULTS AND DISCUSSIONS

A specification tests on the SDM model was tested prior to the estimation. The robust LM lag and error tests results rejected the null of no spatial autocorrelation from the OLS model. The Wald test on the specification of the spatial model rejected the alternative spatial lag model and spatial error model, which confirmed the SDM is appropriate for the analyses (see Table 2). In addition, the Hausman test statistic of 33.64 (p-value 0.02) suggested that combined (two-way) fixed effects model is appropriate compared to random effects specification

The average direct, indirect and total effect of those factors included in the two-way fixed effects SDM are summarized in Table 3. Average lockage processing time was very influential to lock delays: a one-hour increase in the lockage time per vessel resulted in more than 1.7 hours of delay considering both direct and indirect/spillover effect. When the number of lock stalls increased due to bad weather, the delay hours at a given lock was decreased. This may be because the pilot of tows slowed down their speed on the river or parked in the barge fleeting area to wait instead of getting to the lock site, hence the shorter queue at locks. Similar findings were observed for the stalls related to number of mechanical issues and the number of vessel issues. The pilots learned the lock outage through radio and then likely adjusted their pace. Presumably, the negative effect of those lock stalls reflects the operation strategies of pilots to handle the unexpected stalls.

Figure 1 and Table 4 show the spillover effect from an hour increase in lockage time at each individual lock separately based on the estimated parameters. The spillover effect of Lock 14 and Lock 15 are the largest, suggesting the better capacity management at those two locks can mitigate the delay in other locks. Lockage time at locks on the lower reach of the River (Lock 16, 17, 18, 20, 21, 22 and 24) also contributed to the delays in neighboring locks. Those locks are included in the 2007 Navigation and ecosystem Sustainability Program (NESP). Improving the lock capacity or efficiency of those locks can potentially mitigate the delay issue on the upper Mississippi River.

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Table 1: Descriptive Statistics of Evaluated Variables for Lock 11 through 27 on Upper Mississippi River, 2004-2013

Variable*	Unit	Observation	Mean	Std. Deviation	Minimum	Maximum
delay	Hour	640	1.20	1.399	0.00	18.06
process	Hour	640	1.48	0.448	0.63	5.73
mechanical	Hour	640	4.20	4.433	0.00	12.98
vessel	Hour	640	3.77	4.906	0.00	12.98
weather	Hour	640	5.18	3.873	0.00	12.98
other	Hour	640	4.69	4.994	0.00	12.98
fmechanical	Number	640	3.81	7.149	0.00	43.00
fvessel	Number	640	1.08	1.728	0.00	14.00
fweather	Number	640	4.50	7.896	0.00	90.00
fother	Number	640	2.58	5.876	0.00	65.00

Note:
delay: average delay hours of all vessels;
process: average processing hours of all vessels;
mechanical: average hours of mechanical-related unscheduled stalls;
vessel: average hours of vessel-related unscheduled stalls;
weather: average hours of weather-related unscheduled stalls;
other: average hours of other unscheduled stalls;
fmechanical: frequency of mechanical-related unscheduled stalls;
fvessel: frequency of vessel-related unscheduled stalls;
fweather: frequency of weather-related unscheduled stalls;
fother: frequency of other unscheduled stalls

Table 2. Panel Data Estimation with SDM specifications

Factors	Spatial and time-period fixed effects bias corrected		Random spatial and fixed time-period effects	
process	1.0478	(5.6112)***	0.9762	(5.5634)
mechanical	-0.0054	(-0.3958)	-0.0044	(-0.3396)
vessel	0.0010	(0.0754)	0.0006	(0.0487)
weather	-0.0222	(-1.4612)	-0.0237	(-1.6185)
other	-0.0127	(-1.0820)	-0.0129	(-1.1357)
fmechanical	0.0018	(0.1951)	0.0014	(0.1527)
fvessel	0.0226	(0.5762)	0.0141	(0.3730)
fweather	0.0238	(3.1442)***	0.0224	(3.0646)
fother	0.0082	(0.6810)	0.0077	(0.6703)
W*process	0.4590	(0.7507)	0.4329	(0.7468)
W*mechanical	-0.0439	(-0.9597)	-0.0308	(-0.7018)
W*vessel	0.0168	(0.3611)	0.0123	(0.2744)
W*weather	-0.0997	(-1.8185)*	-0.0896	(-1.6953)
W*other	-0.0371	(-0.9009)	-0.0402	(-1.0090)
W*fmechanical	-0.0943	(-2.7301)***	-0.0890	(-2.7008)
W*fvessel	-0.4304	(-3.9126)***	-0.3867	(-3.6535)
W*fweather	-0.0225	(-1.1927)	-0.0159	(-0.8780)
W*fother	0.0091	(0.2539)	0.0059	(0.1740)
W*dep.var.	0.1166	(1.6684)*	-0.0871	(-1.1264)
R^2	0.3677		0.2575	
σ^2	1.3399		1.2564	
LogL	-972.88		-1006.31	
Wald test spatial lag	48.5439	[0.0000]	43.6540	[0.0000]
Wald test spatial error	47.2113	[0.0000]	44.2398	[0.0000]
LR test spatial lag	51.3302	[0.0000]	38.5894	[0.0000]
LR test spatial error	51.9287	[0.0000]	40.6807	[0.0000]
Hausman test	33.6443	[0.0202]		

Notes: R^2 includes the spatial and/or time-period fixed effects. Number presented in parentheses is the t-values corresponding to estimated parameters. Number in bracket refers to the p-values of the test statistics.

Table 3. Direct and Indirect Effects from the Two-way fixed Effects SDM

Variables	Direct effect		Indirect effect		Total effect	
process	1.050	(5.678)	0.685	(1.031)	1.735	(2.622)
mechanical	-0.006	(-0.431)	-0.052	(-1.011)	-0.058	(-1.030)
other	-0.013	(-1.079))	-0.041	(-0.892)	-0.054	(-1.041)
vessel	0.001	(0.111)	0.020	(0.387)	0.021	(0.366)
weather	-0.023	(-1.465)	-0.115	(-1.892)	-0.138	(-2.012)
fmechanical	0.000	(-0.008)	-0.106	(-2.716)	-0.106	(-2.566)
fother	0.008	(0.689)	0.010	(0.244)	0.018	(0.389)
fvessel	0.016	(0.406)	-0.479	(-3.705)	-0.464	(-3.161)
fweather	0.024	(3.090)	-0.023	(-1.110)	0.001	(0.055)

Note: t-values in parentheses corresponds to estimated parameters

Table 4 Spillover Effect from an Hour Increase in Lockage Time at a Given Lock on the Upper Mississippi River

Range	Lock
0.80-0.85	L14, L15
0.75-0.80	L20
0.70-0.75	L16, L21
0.65-0.70	L17, L22
0.60-0.65	L18, L19, L24, Melvin Price
0.55-0.60	L12, L13, L25
0.50-0.55	L27
0.45-0.50	--
0.40-0.45	L11

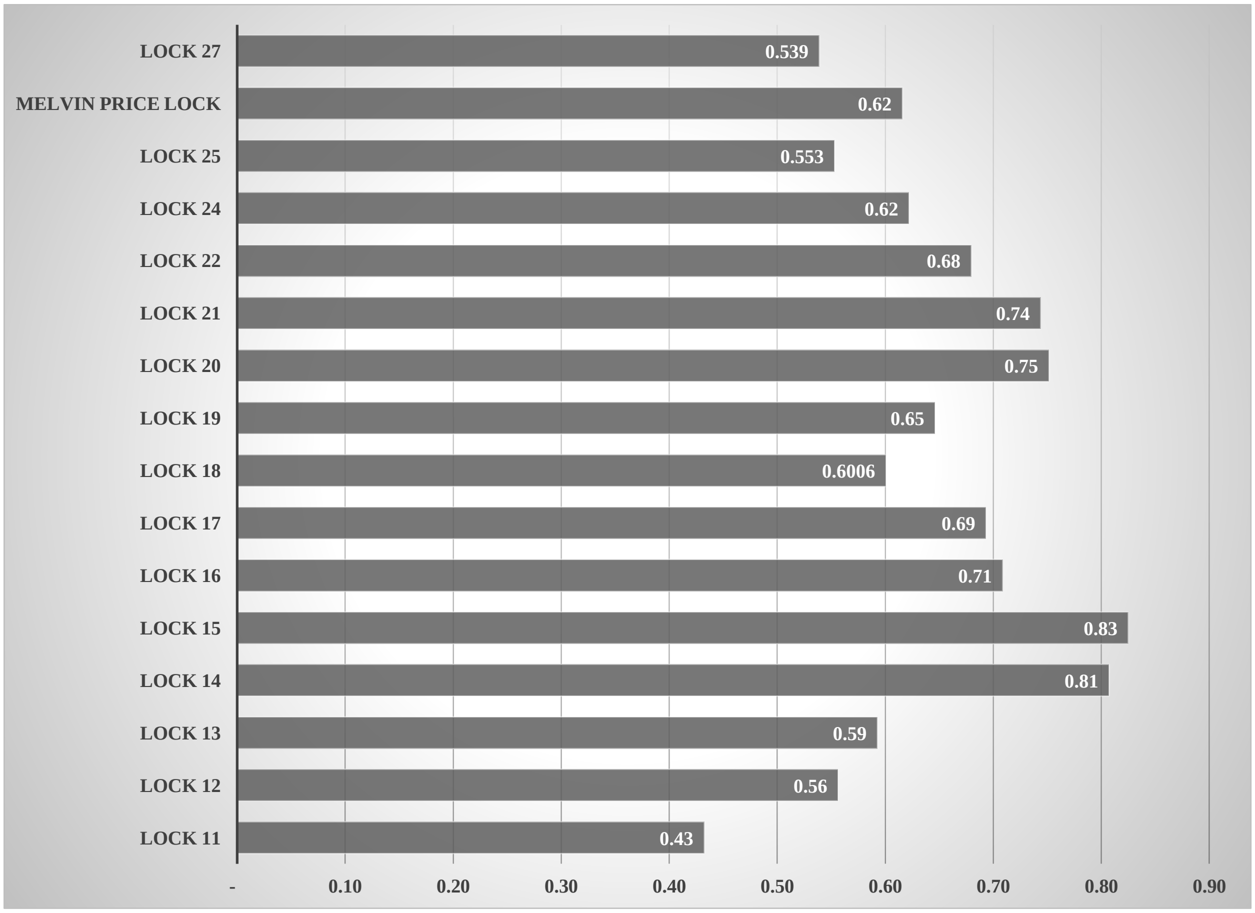

Figure 1 Spillover effect from an hour increase in lockage time at a lock from Lock 11 to Lock 27 on the upper Mississippi River