Approximate Delays Caused by Lock Service Interruptions

VENKATESH RAMANATHAN AND PAUL SCHONFELD

The lock structures in the inland waterway system have become major constraints to navigation as a result of increased traffic and facility deterioration, leading to costly delays. Most of the locks have exceeded their design life, and service interruptions occur quite frequently, causing increasing delays to traffic. Hence, a reliable model is necessary to estimate the delay caused by lock service interruptions. In this paper, a model is developed in the form of one relatively simple equation to estimate tow delays caused by a single lock service interruption. A basic equation is derived on the basis of continuous flow theory. Because the waterway flows consist of discrete vessels, an appropriate discrete adjustment factor is developed. To account for the stochastic characteristics of actual waterway operations, an adjustment factor is estimated statistically from simulation results. The resulting model provides accurate estimates of delays far more quickly and inexpensively than simulation. The simple model developed in this paper should be useful in future studies of capacities, delays, service reliability, maintenance policies, and general waterway economics.

Inland waterways are an important part of the transportation network in the United States. They provide low-cost, energy-efficient and safe transportation of heavy or bulky commodities. The National Waterways Study (*1*) identified the structural reliability of the inland waterway system as a major constraint in the system's ability to handle commercial waterborne traffic. More than 100 locks will have exceeded their 50-year design life by 2003 (*1*). Locks and dams are essential for creating stepped navigational pools with reliable depth for navigation. However, many of these facilities have become major constraints to inland navigation because of increased traffic and facility deterioration, leading to costly delays.

The objective of this paper is to develop a model that estimates the delay caused by a single lock service interruption (i.e., a "stall"). An equation is derived using the principles of continuous flow theory. Because the flow in real waterways consists of discrete tows or other vessels, an adjustment factor is developed on the basis of the assumption that the flow is discrete and uniform. Furthermore, the arrival and service distributions at waterway locks are probabilistic. Hence the equation developed using continuous flow is combined with an adjustment factor estimated statistically from the simulation results. This equation provides accurate estimates of delay caused by a lock service interruption.

LITERATURE REVIEW

Prediction of lock delays is essential for evaluating and scheduling waterway investments. Two models based on queueing theory have been found for estimating lock delays. DeSalvo and Lave (*2*) model lock operation as a simple single server queueing process with Poisson distributed arrivals and exponentially distributed service time. The assumption of Poisson distributed arrival and exponentially distributed service time does not fit every lock in the waterway system. Wilson's model (*3*) extends DeSalvo's model by treating the service processes as general distributions. Both models are designed for analyzing single lock delays. Neither of these models explicitly accounts for stalls. Also, the delays estimated with these models did not consider the interdependence between locks, which is highly significant in waterway locks.

Kelejian's (*4*) efforts to model stall frequencies and duration have not yet yielded strong results despite the rigorous statistical method employed. Dai and Schonfeld (*5*) developed a microscopic simulation model that accounts for generally distributed arrivals and service times and interdependence between locks and stalls. As usual with microscopic simulation models, a significant amount of computer time is required for variance reduction to obtain reliable delay estimates. May and Keller (*6*) used the continuous flow theory to estimate the effects of road capacity changes at bottlenecks on delays to users. The continuous flow theory has also been used for various other highway applications.

In this paper, a simple model is developed to estimate delay caused by a lock service interruption using continuous flow theory and an adjustment factor estimated from simulation results. The model is a reliable substitute for expensive simulation.

PROPOSED MODEL

In this section, a general equation is derived that provides a good estimate of the delay caused by a single lock service interruption based on the assumption that the arrival and service rates are uniform and continuous.

The effect of a single stall, assuming uniform continuous flow, is shown in Figure 1. The service interruption would reduce the normal lock capacity (tows/day) c to a partial lock capacity (tows/day) p in a lock with multiple chambers. If the lock has a single chamber, the partial capacity will probably drop to zero. If the service interruption occurs for stall duration (days) d, then the maximum queue length (tows) L formed during this period will be the duration d multiplied by the difference between the tow volume (tows/day) v and partial capacity p.

$$L = d(v - p) \quad (1)$$

After the end of the stall, the queue will start decreasing at a rate equal to the difference between the volume v and capacity c, and would finally become zero. The time s required to dissipate

V. Ramanathan and P. Schonfeld, Transportation Studies Center, University of Maryland, College Park, Md. 20742.

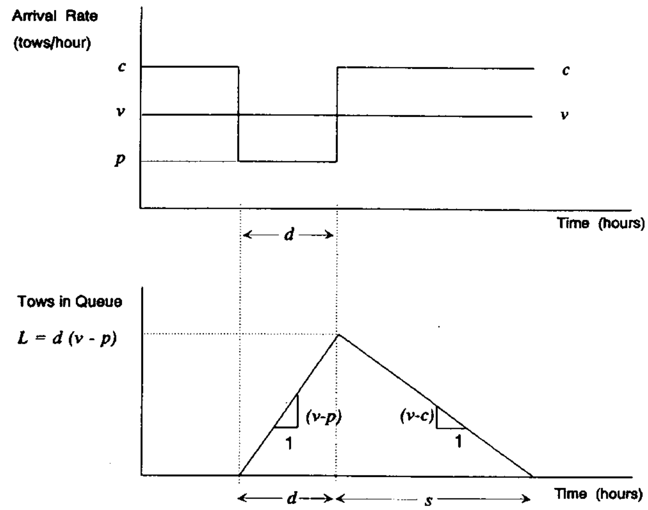

FIGURE 1 Effect of one stall based on uniform continuous flow.

a queue (tows) of length L is

$$s = \frac{L}{-(v - c)} = \frac{d(v - p)}{-(v - c)} = \frac{d(v - p)}{(c - v)} \tag{2}$$

The total delay to tows D_c [small delay assuming continuous deterministic flow (tow days)] caused by interruption in service for duration d would be the area of the triangle or "wedge" shown in Figure 1.

$$D_c = \frac{L(d + s)}{2} \tag{3}$$

Substituting the values of the maximum queue length L and queue dissipation time s from Equations 1 and 2, Equation 3 can be written as

$$D_c = \left[\frac{d(v - p)}{2}\right]\left[\frac{d(v - p)}{(c - v)} + d\right] \tag{4}$$

If the partial capacity p is zero, then the delay D_c in Equation 4 simplifies to

$$D_c = \frac{dv}{2}\left[\frac{dv}{(c - v)} + d\right] \tag{5}$$

For example, if $v = 3$ tows/hr, $c = 4$ tows/hr, $d = 2$ hr and $p = 1$ tow/hr, then the delay D_c using Equation 4 will be

$$D_c = \left[\frac{2(3 - 1)}{2}\right]\left[\frac{2(3 - 1)}{(4 - 3)} + 2\right] = 12 \text{ tow hours}$$

Equations 4 and 5 are general enough to apply to one- or two-way traffic and to single or multiple chamber locks.

DISCRETE ADJUSTMENT FACTOR

At waterway locks, arrival and service distributions are discrete and probabilistic. However, Equations 4 and 5 were derived by assuming uniform continuous flow. In this section, an equation is derived that accounts for the difference in delay between uniform continuous and uniform discrete flows.

A comparison of the probabilistic and deterministic discrete flow patterns is shown in Figure 2. This figure corresponds to the continuous deterministic wedge in the lower part of Figure 1. It can be seen that when the flow is deterministic, arrivals and departures occur at uniform intervals. If the tow volume is v tows/hr and the lock capacity is c tows/hr, then the interarrival time between tows is $1/v$ hr and the service time is $1/c$ hr/tow. However, when the flow is stochastic, interarrival and service times are not uniform. The effect of a single lock service interruption on uniform discrete flow is shown in Figure 3. The delay caused by a single lock service interruption in case of discrete and deterministic flow depends on the stall duration d and tow size (tows/tow) z. As the step size is higher for bigger than for smaller tows, the deviation of the discrete uniform flow from the continuous uniform flow is higher for bigger than for smaller tow arrivals for the same stall duration d. This can be clearly seen from Figure 3. The delay caused by a single lock service interruption can be

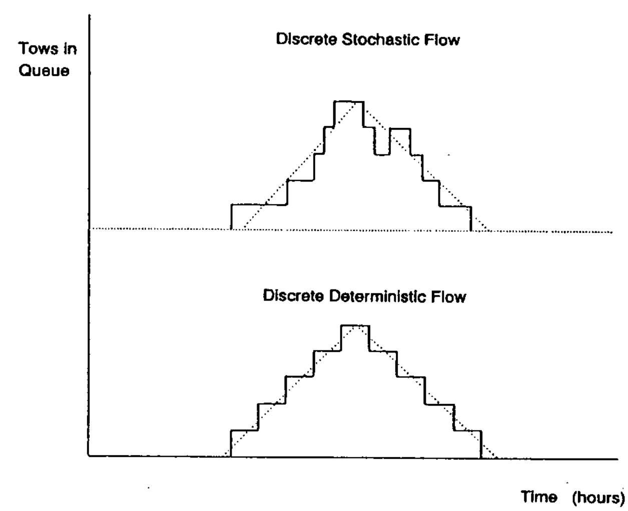

FIGURE 2 Comparison of deterministic and stochastic flow patterns.

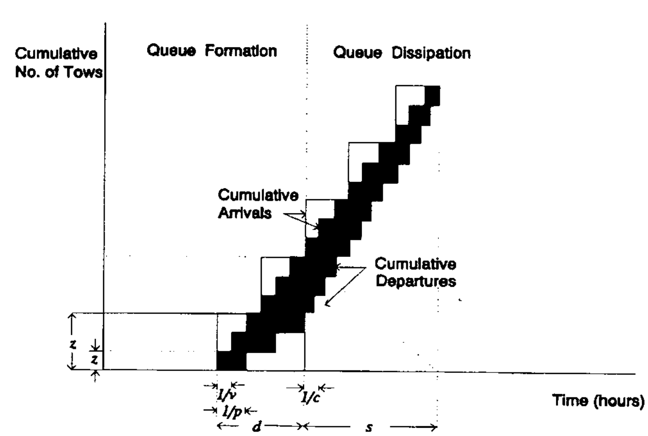

FIGURE 3 Effect of one stall on discrete uniform flow.

determined by expressing the arrivals and departures as the sum of a geometric series. If the tow volume is v, the tow size is z, the partial capacity is p, and the interruption occurs for duration d, then the delay caused by discrete deterministic flow, D_I, during the queue formation period is the difference between the area under the arrival and the departure steps (i.e., the area marked I in Figure 3). Because the interarrival time between tows is $1/v$ and the size of each step is equal to the tow size z, the area under the arrival steps is the sum of the areas of the rectangles, the area of each rectangle being the tow size z multiplied by the difference betweeen the duration d and arrival time of the tow ($1/v$, $2/v$, etc.). Similarly, the area under the departure steps can be determined by summing the areas of each rectangle. The area of each rectangle is the tow size z multiplied by the difference between duration d and departure time $1/p$, $2/p$, and so on. Thus, the delay D_I on the queue formation side can be written as follows:

$$D_I = \left\{d + \left[d - \frac{1}{v}\right] + \left[d - \frac{2}{v}\right] + \ldots + \left[d - \frac{(dv-1)}{v}\right]\right\}z - \left\{\left[d - \frac{1}{p}\right] + \left[d - \frac{2}{p}\right] + \ldots + \left[d - \frac{(dp-1)}{p}\right]\right\}z \quad (6)$$

Because Equation 6 is a sum of a geometric series, the delay D_I can be simplified as follows:

$$D_I = \left(\frac{d^2v + d}{2}\right)z - \left(\frac{d^2p - d}{2}\right)z \quad (7)$$

After the end of the stall, because the queue takes s hours to dissipate to zero length, the delay caused by discrete deterministic flow during the queue dissipation period (tow/days), D_{II}, is the shaded area marked II in Figure 3. Because the departure time of the tows is now $1/c$, $2/c$, and so on, the delay D_{II} can be expressed as

$$D_{II} = \left(\frac{1}{c} + \frac{2}{c} + \ldots + \frac{cs}{c}\right)z + \left(\frac{1}{v} + \frac{2}{v} + \ldots + \frac{vs}{v}\right)z \quad (8)$$

Equation 8 can be simplified as follows:

$$D_{II} = \left[\frac{s(cs + 1)}{2}\right]z - \left[\frac{s(vs + 1)}{2}\right]z \quad (9)$$

The total stall delay D_r assuming discrete deterministic flow (tow days) caused by a service interruption for duration d when the arrival and service rates are discrete is the sum of delays D_I and D_{II}:

$$D_r = \left[\frac{d^2v + d}{2}\right]z - \left[\frac{d^2p + d}{2}\right]z + \left[\frac{s(cs + 1)}{2}\right]z - \left[\frac{s(vs + 1)}{2}\right]z \quad (10)$$

Thus, Equation 10 gives the total delay D_r caused by discrete flow and Equation 4 gives the total delay D_c caused by continuous flow. The ratio of the delay D_r to the delay D_c may be defined as the discrete adjustment factor F_r:

$$F_r = \frac{D_r}{D_c} \quad (11)$$

Assuming the interdeparture time $1/p$ in the partial capacity condition to be less thant the stall duration d and substituting Equations 4 and 10 into Equation 11, the discrete adjustment factor F_r can be written as

$$F_r = 1 + \frac{dz}{D_c} \quad (12)$$

Thus the delay caused by discrete uniform flow D_r from Equations 11 and 12 can be written as

$$D_r = D_c\left(1 + \frac{dz}{D_c}\right) \quad (13)$$

Equation 13 is therefore a good approximation for a waterway with discrete arrival and service times. The discrete adjustment factor depends on tow size z and stall duration d. Thus for the same stall duration d, the factor F_r is larger when tows are larger because the steps in Figure 3 are larger. It is also worth noting that, because D_c is approximately proportional to d^2 (in Equations 4 or 5) the factor F_r (Equation 12) decreases asymptotically toward 1.0 as the stall duration increases. Therefore, Equations 4 or 5 based on the continuous flow assumption provide good approximations of the delay, if (*a*) tows are small or (*b*) service interruptions are long. Even with a discrete adjustment factor, Equation 13 is only an approximation for real waterways with probabilistic arrival and service times.

SIMULATION EXPERIMENT

A microscopic simulation model to estimate delays caused by lock service interruptions has been developed by Dai and Schonfeld (*5*). The actual data, including the stall-related data from real waterway locks, were used for calibrating and then validating the simulation model. As usual with microscopic simulation models, a significant amount of computer time is required for variance reduction purposes to obtain reliable delay estimates. In order to estimate the delay caused by a single stall, it is necessary to compute delays by running the simulation with and without that stall. The delay caused by a single stall is the difference between those two delays.

An alternative to direct application of microsimulation is to employ the simulation model in an experiment to obtain a functional simplification that can be used to estimate the delay caused by a lock service interruption. An experiment was conducted to explore the extent to which the probabilistic nature of arrival and service rates in a real waterway affects the delay caused by one stall predicted by Equation 4. The observed data (1987) from Lock 22 on the Mississippi river was used for the experiment. The variables chosen for the simulation experiment were stall duration d and volume/capacity ratio v/c.

The experiment simulated the lock for various combinations of volume/capacity ratio v/c and stall duration d. To achieve different values for volume/capacity ratio, the volume v was fixed at 10 tows/day and the capacity c was adjusted to yield the desired v/c. For example, to achieve a v/c of 0.4, the capacity c used in simulation was 25 tows/day, because $10/25 = 0.4$. In the existing simulation model (*5*), stalls of various durations were randomly generated based on average stall duration and frequency of occurrence. Hence, the model was modified to estimate the delay caused by a single stall of variable duration starting at some specified time. To reduce the variance of the simulated delay, the final result used for comparison was obtained by averaging the output from 40 independent simulation runs. To ensure that the system reaches steady state before the stall occurs, the first 12,000 tow waiting times are discarded from each simulation run. The results were recorded for a sufficiently long period to ensure that the full effects of the stall were captured. The results from the simulation experiment were then compared with those obtained using Equation 5.

EXPERIMENT RESULTS

The results from the simulation and the values calculated using Equation 5 for volume/capacity ratios ranging from 0.4 to 0.95 are provided in Table 1. The average delay caused by a single stall obtained from simulation and the delay obtained using Equation 5 are shown for various stall durations and volume/capacity ratios. Also shown are the standard deviation of the average delay from the simulation, standard error, and the t-test value for 95 percent confidence interval. The ratio of the simulated and the deterministic delay is also computed. This ratio is defined here to be the stochastic adjustment factor F_s:

$$F_s = \frac{D_s}{D_c} \tag{14}$$

This stochastic adjustment factor F_s accounts for the probabilistic arrival and service rates in a real waterway. Thus, the results obtained using Equations 4 or 5, when multiplied by this factor F_s, give the simulated delay. The stochastic adjustment factor is plotted in Figure 4 with stall duration on the horizontal axis and the delay caused by stall on the vertical axis for different volume to capacity ratios. Shown in Figure 5 is the variation of stochastic adjustment factor F_s with simulated delay D_s. Each point in these plots represents the average of 40 independent simulation runs. These plots are helpful in the assessment of the functional form of the stochastic adjustment factor F_s. It appears from these plots that the factor decreases at a decreasing rate with the stall duration d and the simulated delay D_s. The factor increases with the volume/capacity ratio v/c.

The comparison of simulated and deterministic delay suggests that the results are consistent with the basic principles of queueing theory. The deterministic delay was calculated on the basis of the assumption of uniform continuous flow. However, in a real waterway the arrival and service are probabilistic and discrete. It can be seen from Equations 4 and 5 that the delay D_c varies roughly with the square of the stall duration. Thus it is expected that the deviations between the deterministic delay D_c and the simulated delay D_s are higher at smaller stall durations than at longer ones. Hence, the stochastic adjustment factor F_s is larger at smaller stall durations and smaller for the longer (and costlier) stalls.

TABLE 1 Comparison of Simulated Delay with Deterministic Queueing Delay

a) v = 10 tows/day; c = 25 tows/day; v/c = 0.4

Stall Duration (days)	Delay (D_s)[1] (tow days)	Delay (D_c)[2] (tow days)	Factor (F_s)[3]	Simulation Estimates (1)[4]	(2)[5]	(3)[6]
0.3	0.99	0.75	1.313	0.41	0.07	3.63
1	9.59	8.33	1.152	2.25	0.36	3.56
2	36.63	33.33	1.099	9.31	1.47	2.24
3	79.74	75.00	1.063	12.34	1.95	2.43
4	138.40	133.33	1.038	21.26	3.36	1.51
6	306.16	300.00	1.020	39.85	6.30	0.98
8	541.92	533.33	1.016	71.21	11.26	0.76
10	843.50	833.33	1.012	86.50	13.68	0.75
12	1208.40	1200.00	1.007	116.23	18.38	0.46

b) v = 10 tows/day; c = 12.5 tows/day; v/c = 0.8

Stall Duration (days)	Delay (D_s)[1] (tow days)	Delay (D_c)[2] (tow days)	Factor (F_s)[3]	Simulation Estimates (1)[4]	(2)[5]	(3)[6]
0.3	3.25	2.25	1.445	1.71	0.27	3.70
1	31.92	25.00	1.270	12.28	1.94	3.56
2	117.89	100.00	1.179	28.06	4.44	4.07
3	252.95	225.00	1.124	51.21	8.09	3.45
4	437.90	400.00	1.094	69.29	10.95	3.45
6	956.10	900.00	1.062	110.40	17.46	3.21
8	1672.11	1600.00	1.045	199.29	31.51	2.28
10	2586.61	2500.00	1.034	300.90	47.58	1.82
12	3682.85	3600.00	1.023	348.40	55.09	1.50

[1]Simulated Delay
[2]Delay due to Continuous flow
[3]Stochastic Adjustment Factor
[4]Standard Deviation of Simulated Delay
[5]Standard Error of Simulated Delay
[6]t-test value of Simulated Delay

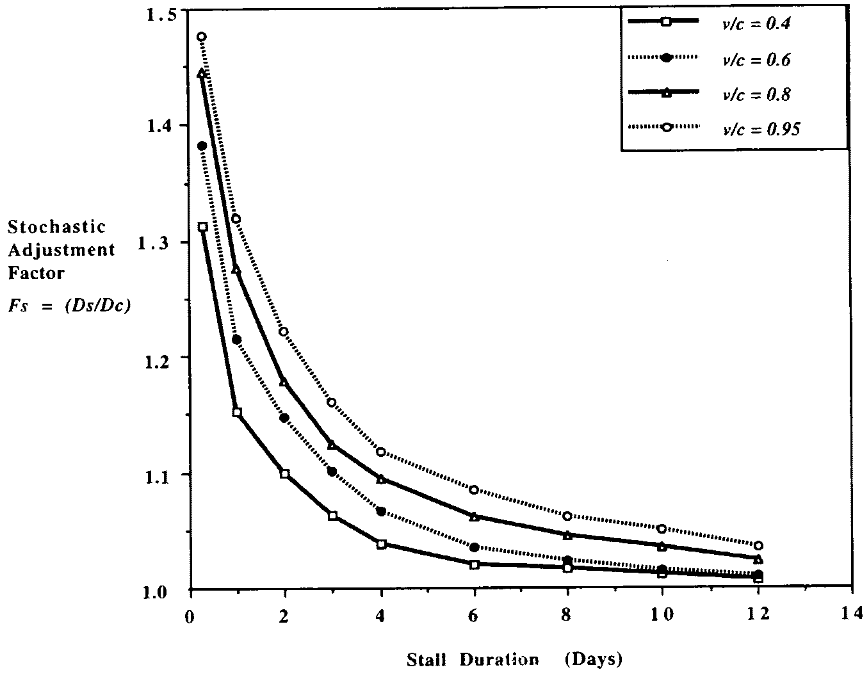

FIGURE 4 Variation of stochastic delay adjustment factor with stall duration.

ESTIMATION OF STOCHASTIC DELAY ADJUSTMENT FACTOR

In this section, a mathematical function that reasonably fits the observed stochastic adjustment factor F_s is derived. The experimental results suggest that the functional form of the stochastic adjustment factor is nonlinear with respect to the stall duration and linear with respect to the volume/capacity ratio. A functional form that increases linearly with the volume/capacity ratio v/c and decreases exponentially with the stall duration d appears to closely fit the data. One tractable mathematical form expressing such a relation is the following:

$$F_s = 1 + a\left(\frac{v}{c}\right) e^{bd} \tag{15}$$

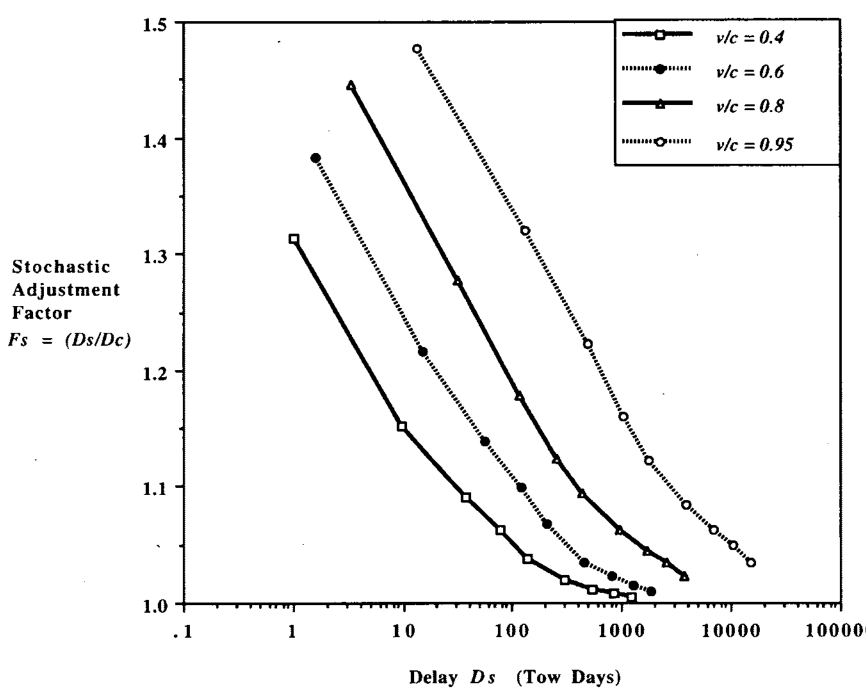

FIGURE 5 Variation of stochastic delay adjustment factor with simulated delay.

where a is a magnitude parameter and b is an exponential decay parameter. This relation may be interpreted to have a lower bound of 1.0, with the second term representing a quantity accounting for the stochastic effects. The parameters a and b were statistically estimated using ordinary least-squares linear regression. Hence Equation 15 becomes

$$F_s = 1 + 0.6 \left(\frac{v}{c}\right) e^{-0.432d}, \quad R^2 = 0.93 \tag{16}$$

The stochastic adjustment factor F_s together with Equation 4 may be used to commute the total delay caused by a single stall, D_e:

$$D_e = [F_s]\,[D_c] \tag{17}$$

Substituting Equation 16 for the stochastic adjustment factor F_s and Equation 4 for D_c in Equation 17, a complete expression for the stall delay can be obtained, as follows:

$$D_e = \left\{1 + \left[0.6 \left(\frac{v}{c}\right) e^{-0.432d}\right]\right\} \left\{\left[\frac{d(v-p)}{2}\right]\left[\frac{d(v-p)}{(c-v)} + d\right]\right\}, \quad R^2 = 0.93 \tag{18}$$

The basic linear regression procedure used to estimate the parameters 0.6 and −0.432 in Equation 15 assumes that the data are homoscedastically distributed; that is, that the variance of the dependent variable does not vary with the independent variable. However, the simulation results (shown in Figures 4 and 5) indicate otherwise. To eliminate this problem of heteroscedasticity, the parameters were re-estimated with a logarithmic transformation (7,8) of Equation 15. Converting the transformed variables back to their original form yielded the following transformed model for the stochastic adjustment factor:

$$F_s = 1 + 0.42 \left(\frac{v}{c}\right) e^{-0.259d}, \quad R^2 = 0.92 \tag{19}$$

Substituting Equations 19 and 4 into Equation 17, the estimated total delay caused by single stall is found to be

$$D_e = \left\{1 + \left[0.42 \left(\frac{v}{c}\right) e^{-0.259d}\right]\right\} \left\{\left[\frac{d(v-p)}{2}\right]\left[\frac{d(v-p)}{(c-v)} + d\right]\right\}, \quad R^2 = 0.92 \tag{20}$$

A comparison of the simulated delay D_s and estimated stall delay (tow days) D_e obtained using Equations 18 and 20 is given in Table 2. Shown in Figures 6 and 7 is the variation of the es-

TABLE 2 Comparison of Simulated Delay with Estimated Delay

a) v = 10 tows/day; c = 25 tows/day; v/c = 0.4

Stall Duration (d) (Days)	Simulated Delay (D_s) (tow-days)	Estimated Delay (D_e) (tow-days)		% Deviation 100 x (D_e-D_s)/D_s	
		Before[1]	After[2]	Before[3]	After[4]
0.3	0.98	0.91	0.87	-7.80	-12.02
1	9.59	9.63	9.41	0.32	- 1.95
2	36.63	36.70	36.67	0.19	0.09
3	79.74	79.93	80.79	0.23	1.32
4	138.40	139.01	141.28	0.44	2.08
6	306.16	305.39	310.66	-0.25	1.47
8	541.92	537.37	544.61	-0.84	0.49
10	843.50	835.99	843.83	-0.89	0.04
12	1208.40	1201.61	1209.01	-0.56	0.05

b) v = 10 tows/day; c = 12.5 tows/day; v/c = 0.8

Stall Duration (d) (Days)	Simulated Delay (D_s) (tow-days)	Estimated Delay (D_e) (tow-days)		% Deviation 100 x (D_e-D_s)/D_s	
		Before[1]	After[2]	Before[3]	After[4]
0.3	3.25	3.19	2.95	-1.67	-9.33
1	31.92	32.79	31.48	2.73	-1.37
2	117.89	120.23	120.02	1.99	1.80
3	252.95	254.55	259.76	0.63	2.69
4	437.90	434.11	447.69	-0.87	2.24
6	956.10	931.34	963.93	-2.49	0.82
8	1672.11	1624.24	1667.70	-2.86	-0.26
10	2586.61	2515.96	2563.02	-2.73	-0.91
12	3682.85	3609.69	3654.06	-1.99	-0.78

[1]Estimated Delay before Transformation
[2]Estimated Delay after Transformation
[3]% Deviation before Transformation
[4]% Deviation after Transformation

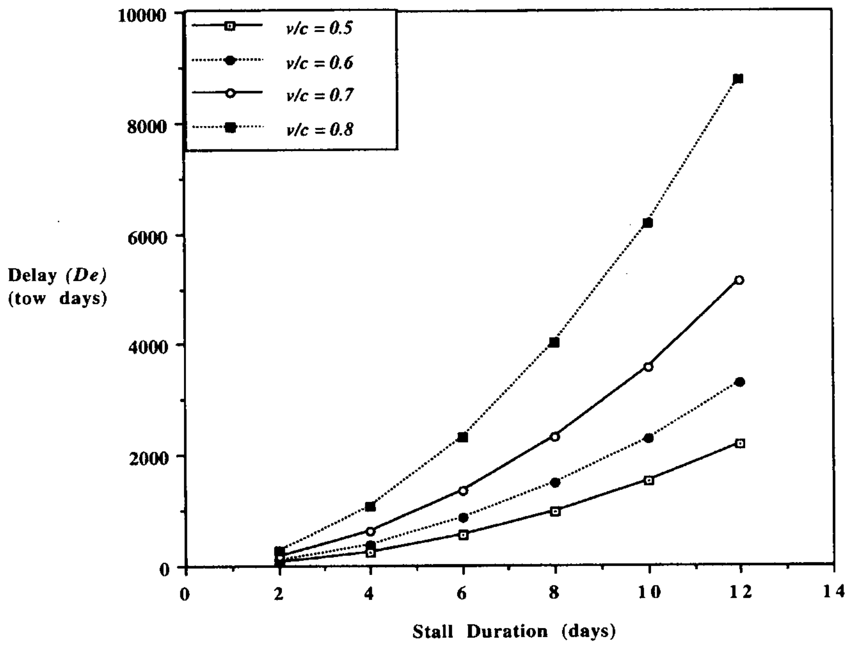

FIGURE 6 Variation of delay caused by a single lock service interruption with stall duration.

timated delay D_e, with stall duration and v/c, respectively. A comparison of the stochastic adjustment factor F_s obtained using Equations 16 and 19 is shown in Figure 8. It is observed that the deviation between the simulated delay D_s and the estimated delay D_e obtained using Equations 18 or 20 is less than 2 percent for stall durations exceeding 2 days and volume/capacity ratios below 0.6. Equations 18 and 20 both provide accurate delay estimates. Although Equation 18 provides slightly more accurate estimates when stall durations are less than 2 days, the transformed model in Equation 20 should be preferred in all cases because of its greater theoretical soundness and in order to have a single general model.

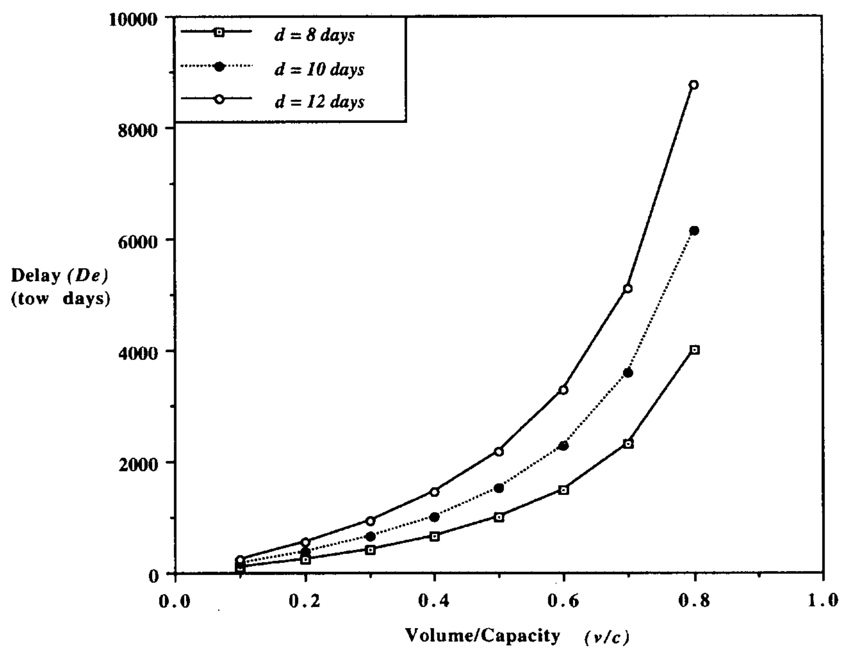

FIGURE 7 Variation of delay caused by a single lock service interruption with volume/capacity.

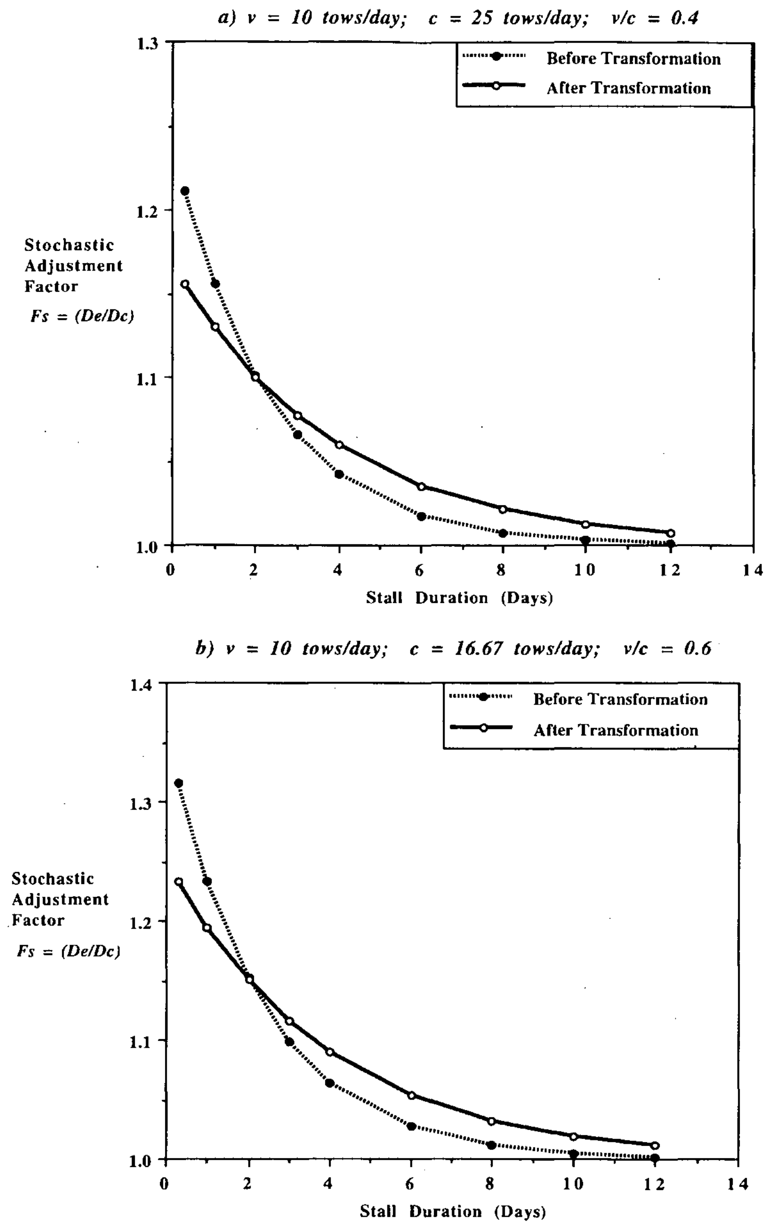

FIGURE 8 Comparison of stochastic delay adjustment factor.

SUMMARY AND CONCLUSIONS

With many inland water locks now becoming older than 50 years, it is important to have reliable and efficient means of modeling the delays at locks for evaluation, reliability analysis, and maintenance and investment planning. Presented in this paper has been the development of a quick and simple model that approximates simulation results in estimating lock delays caused by a single stall.

An equation was developed on the basis of continuous flow theory. This equation is a close approximation for stalls producing large delays but not for those producing small delays. Because this equation was derived on the basis of uniform flow, it is only an approximation for a real waterway with discrete arrival and service rates. To account for discrete arrival and service times at locks, a discrete adjustment factor was derived assuming uniform discrete flow. This model has some explanatory value but is superseded in this paper by a probabilistic model. Because the vessel flows are probabilistic in real waterways, a simulation experiment was conducted to estimate the delay caused by a single stall. A single general "metamodel," combining a structural form obtained from queueing theory with the stochastic adjustment factor statistically estimated from simulation results, fits the simulated delays quite well and constitutes an accurate, quick, and simple substitute for simulation.

The model was further improved with a logarithmic transformation that compensates for heteroscedasticity in the data. Although the transformed model (Equation 20) is slightly less accurate than the untransformed model (Equation 18) when stall durations are low, it is slightly more accurate for longer durations, which are more significant in economic evaluations. Henceforth it is recommended that only the transformed model be used, because it is more justified theoretically and provides a single general model. For an even better approximation of the model, the stochastic adjustment factor may be re-estimated when the chamber configurations or arrival and service distributions change significantly.

ACKNOWLEDGMENTS

The authors wish to thank the anonymous reviewers and L. George Antle for their very helpful advice. They also thank the Institute of Water Resources of the U.S. Army Corps of Engineers for financially supporting this work.

REFERENCES

1. *National Waterways Study.* Institute of Water Resources, U.S. Army Corps of Engineers, Sept. 1987.
2. DeSalvo, J. S., and L. B. Lave. An Analysis of Towboat Delays. *Journal of Transportation Economic Policy 2*, 1968, pp. 232–241.
3. Wilson, H. G. On the Applicability of Queueing Theory to Lock Capacity Analysis. *Transportation Research*, Vol. 12, 1978, pp. 175–180.
4. Kelejian, H. H. Probability Model of Lockage Stalls and Interferences. In *Transportation Research Record 1313*, TRB, National Research Council, Washington, D.C., 1991, pp. 111–116.
5. Dai, M. D. M., and P. Schonfeld. Simulation of Waterway Transportation Reliability. In *Transportation Research Record 1313*, TRB, National Research Council, Washington, D.C., 1991, pp 98–105.
6. May, A. D., and H. E. M. Keller. A Deterministic Queueing Model. *Transportation Research*, Vol. 1, No. 2, 1967, pp. 117–128.
7. Bowerman, B. L., and T. O. Richard. *Linear Statistical Models: An Applied Approach.* PWS Kent Publishing Co., Boston, Mass., 1990.
8. Carroll, J. R., and D. Ruppert. *Transformation and Weighting in Regression.* Chapman and Hall, New York, N.Y., 1988.

Publication of this paper sponsored by Committee on Inland Water Transportation.