PROCEEDINGS—

Twenty-fifth Annual Meeting

Volume XXV • Number 1 1984

T R F

TRANSPORTATION RESEARCH FORUM

PROCEEDINGS–

Twenty-fifth Annual Meeting

Theme:

"Beyond Deregulation: Let Freedom Ring!"

October 22-24, 1984
Parker House
Boston, MA

Volume XXV • Number 1 1984

T
R
F

TRANSPORTATION RESEARCH FORUM
in conjunction with

CANADIAN TRANSPORTATION RESEARCH FORUM

Simulation-Based Estimates of Delays at Navigation Locks

*by Michael S. Bronzini**

ABSTRACT

Tow delay is an important component of cost at navigation locks, and delay reduction is a major benefit of lock improvement. Computer simulation is a valuable method of estimating lock delay under a variety of existing and future or proposed conditions. However, a single simulation run, which can be quite costly in terms of both computer and analyst time, produces a delay estimate for only one traffic level under one set of conditions. This paper describes methods which can be used to estimate an entire delay vs. traffic curve from a limited amount of simulation data. Estimation techniques appropriate for various amounts of data are derived and factors affecting the accuracy of the delay estimates are discussed. Applications of these methods to inland waterway planning projects are given.

INTRODUCTION

Analysis of proposed improvements to navigation locks requires consideration of the delays to lock traffic with and without each improvement. Computer simulation is widely used to produce these delay estimates. This paper presents techniques which can be used to estimate the entire delay curve for a lock from limited amounts of simulation data. The next section summarizes the current approach to economic analysis of navigation projects and shows how the delay curve concept fits into this approach. Various computer models which have been developed to simulate lock operations are then described. A mathematical delay function is then introduced and methods for estimating the parameters cf the function are given. The use of these methods is illustrated with simulation data for a lock on the Illinois Waterway.

ECONOMIC ANALYSIS OF NAVIGATION PROJECTS

Recent studies of the inland waterway system in the United States, including the National Waterways Study (1) and the Upper Mississippi River Master Plan (2), conclude that many navigation structures are near the end of their physical or economic lives and will require either replacement or major rehabilitation. Decisions are also imminent on several major projects such as replacement of Gallipolis Lock on the Ohio River and the Inner Harbor Lock in New Orleans, and provision of a second chamber at the new Lock 26 on the Mississippi River. Since these programs involve the investment of user fee revenues and other public funds, there is a continuing need to develop sound methods for economic analysis of navigation projects.

The basics of economic analysis as applied to inland waterways have been stated by numerous authors; a concise treatment is given in (3). Figure 1 is a simple diagram of some of the important relationships involved at locks or other system constraint points. Curve D is the typical downward-sloping demand curve, which shows the amount of use the facility will receive at different levels of user cost. Curve AC is the average cost curve, which shows how the cost incurred by each user varies with the traffic level. This primarily shows the effect of traffic congestion and waiting time, since most other user costs do not vary significantly with the number of vessels transiting the lock[1] The marginal cost imposed on all users by each additional traffic unit is shown by curve MC. Under normal conditions the traffic at the lock will be q_e, where the user cost, c_e, is exactly equal to the willingness to pay of the marginal user. In congestion pricing theory, the socially optimal traffic level is defined to be q_m, where marginal cost and marginal willingness to pay are both c_m.

Figure 1 illustrates the importance of having accurate estimates of lock delays. The relationship between average tow delay and lock traffic level, commonly referred to as the lock delay curve, is the primary determinant of the AC curve.

Under current planning regulations, project benefits are measured by the change in average cost which the project produces. Consequently, changes in the lock delay curve which occur in response to system improvements show up directly in the benefit/cost analysis.[2] In addition, current regulations call for consideration of a congestion toll as one means of avoiding or delaying investment in new facilities. The vertical distance between the MC and AC curves defines the theoretically optimum schedule of congestion tolls. However, there is no convenient way to directly observe the marginal cost curve, so it must be derived from the average cost curve. As already noted, this curve depends heavily on the lock delay curve.

COMPUTER SIMULATION OF WATERWAY LOCKS

It is virtually impossible to observe lock operations over a sufficiently large range of traffic levels to develop a totally empirical delay curve. Consequently, computer simulation is routinely used to generate estimates of lock delays. This has the added advantages of putting the analyst firmly in con-

Director, Transportation Center, The University of Tennessee

trol of the conditions under which each delay estimate is made and allowing relatively quick and convenient investigation of a variety of alternative lock improvements. The simulation approach also insures that the alternatives will be compared under a common set of assumptions about commodity flows, barge loadings, empty barge traffic, tow sizes, lock operating rules, etc.

Navigation lock simulation models are currently at a rather advanced stage of development. Much of the work in this field is reviewed in (4) and (5). Some of the earliest work was by Carroll, who developed models of both single locks (6) and systems of locks (3, 7). Carroll's work was seminal, in that many of his concepts have been carried through to succeeding models. These include: the locking routines in the waterway system simulator developed for the Corps of Engineers Inland Navigation Systems Analysis project (5); Hayward's (8) multiple chamber single lock simulation model, LOKSIM; and a more detailed single lock model, (LOKSIM2) (9), developed for the Upper Mississippi study referenced previously (2). A deterministic model called LOKCAP (10, 11), which is based on a combination of simulation concepts and data and queueing theory, is also in widespread use (1, 2).

A simulation model replicates the operation of a lock for a short period of time, typically 30 days, with a constant average vessel arrival rate. The model output indicates the average delay per tow during the simulated time interval. Thus each simulation run provides a single estimate of average delay at a single traffic level. Producing an entire delay curve requires additional model runs at different traffic levels, so that the relationship between delay and traffic can be captured.[3] Unfortunately, simulation runs often require considerable time and effort, so generating each lock delay curve can be rather costly. The next section introduces a mathematical lock delay function which can be estimated with only a limited amount of simulation data and gives methods for estimating the function's parameters.

LOCK DELAY FUNCTION

Description and Properties

The delay curve for any lock may be represented as the following hyperbolic function:

$$d = \frac{Dq}{Q - q}, \quad 0 \leq q < Q \tag{1}$$

where:

q = lock traffic level
d = average delay per tow at traffic level q
Q = lock capacity
D = lock delay parameter.

The lock flow and capacity, q and Q, are expressed in units of traffic flow per time period, such as tows per month or tons per year. This congestion function was first proposed, in a slightly different form, by Mosher (12); it can also be derived from queuing theory (13).

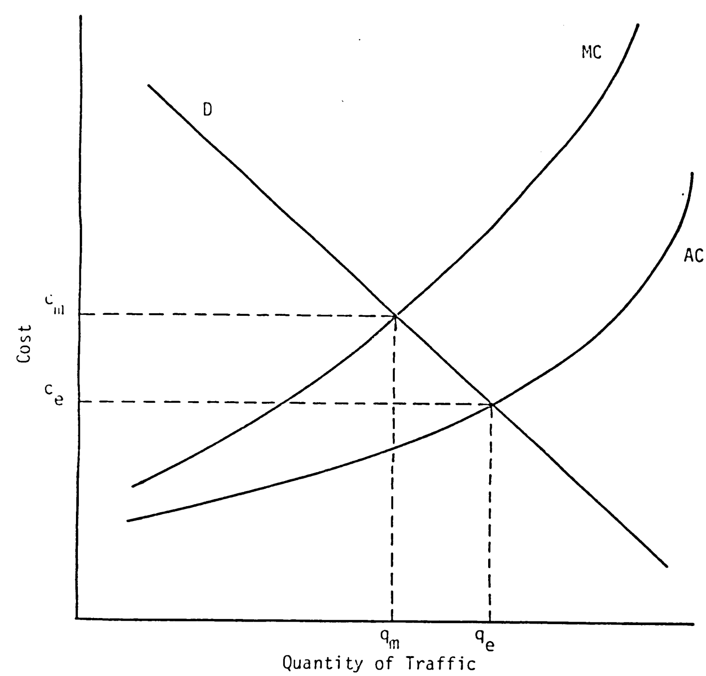

FIGURE 1. Cost-Flow Relationships at Navigation Locks.

The delay curve parameters, Q and D, both have useful physical interpretations. Equation 1 shows that as q approaches Q, delay becomes infinite. Thus *Q is the theoretical capacity of the lock* and has the same meaning as the maximum service capacity defined in queueing theory. Looking again at equation 1, it is seen that D is a scaling factor with units of delay. Setting $d = D$ and solving for q yields $q = Q/2$. In other words, *D is the average delay when the flow is 50% of capacity.* The function also has the desirable feature that $d = O$ at $q = O$. Taken together, these properties allow the function to be easily visualized and, in fact, sketched rather accurately.

Figure 2 shows the hyperbolic delay curve, plotted for various values of D, and Table 1 gives some of the points on these curves.[4] The scaling effect of D is clearly shown in the figure and table. Low values of D produce a curve which hugs the horizontal axis, then rises sharply to become asymptotic to the capacity lines; at the lower limit $D = O$, the curve lies on the horizontal axis. The curve rises more quickly for larger values of D; if D becomes infinite, the delay curve lies on the vertical axis. This great flexibility of shape allows a variety of actual delay relationships to be represented with this single mathematical form. Because of this and its desirable properties, the hyperbolic delay function is widely used in waterway models and studies (2, 5, 10, 14) and has been used to represent the delay characteristics of other modes (12, 13, 15, 16).

Estimating the Delay Curve

If either parameter Q or D is known with certainty and one data point (q, d) is available, then equation 1 can be used to solve for the missing parameter. In the usual situation neither parameter is fixed, so at least two data points are needed. Given two points, (q_1, d_1) and (q_2, d_2), equation 1 can be solved for Q and D to yield:

$$Q = \frac{1 - (d_1/d_2)}{1 - (d_1q_2)/(d_2q_1)}\, q_2 \qquad (2)$$

and

$$D = \frac{d_2(Q - q_2)}{q_2} = \frac{d_1(Q - q_1)}{q_1}\,. \qquad (3)$$

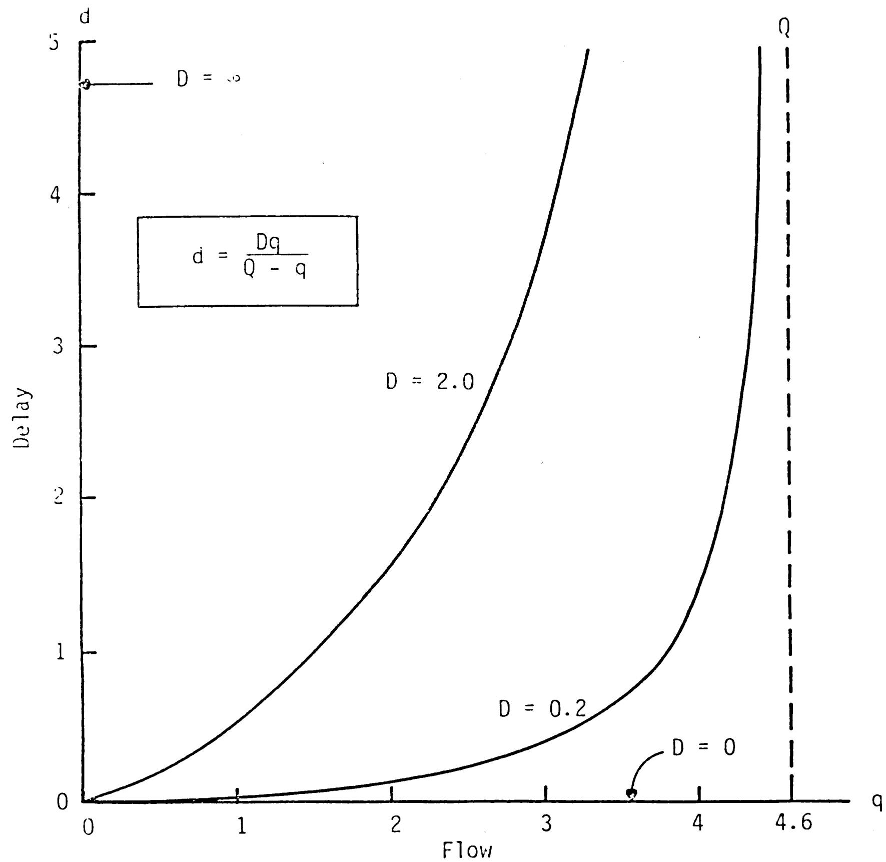

FIGURE 2. Hyperbolic Delay Function.

TABLE 1

EXAMPLE DELAY FUNCTIONS

q		d: D = 0.2	d: D = 2.0
1		.056	.555
2		.154	1.54
3		.375	3.75
3.4		.567	5.67
4		1.33	13.33
4.2	Note: Q = 4.6	2.1	21.0
4.4	for both functions.	4.4	44.0

This method is referred to later on as the two-point method.

If the two data points are selected judiciously, the delay curve estimated in this fashion is quite accurate. This estimation method offers the obvious advantage that only two simulation runs are required.[3]

In the most general case, a number of data points (q_i, d_i), are obtained. The problem is to find values for Q and D which best fit the data. Although a general nonlinear estimation procedure could be used, a simple search technique is also available. Given an independent estimate of Q, the least squares estimate of D is:[5]

$$D = \frac{\sum_i (d_i q_i)/(Q - q_i)}{\sum_i q_i^2/(Q - q_i)^2}, \quad q_i < Q. \qquad (4)$$

Thus, the estimation problem can be reduced to a one-dimensional search over various values of Q.

The following procedure can be used to estimate the delay function parameters.

1. Arrange the n data points in the order $q_1 < q_2 < ... < q_n$. Select the first and last data points, (q_1, d_1) and $(q_n 9, d_n)$, and compute a trial value Q^* using equation 2.
2. Select the following values of Q_k as the search set: ($0.90Q^*$, $0.95Q^*$, Q^*, $1.05Q^*$, $1.10Q^*$), subject to $Q_1 > q_n$. In cases where this condition does not hold, use $Q_1 = 1.02\ q_n$.
3. For each Q_k in the search set:
   (a) Compute D_k with equation 4
   (b) Compute estimated delays, $\hat{d}_i$, for each data point, using Q_k, D_k, and equation 1
   (c) Given values $(d_i, \hat{d}_i)$, compute their squared linear correlation coefficient, $R_k^2(d_i, \hat{d}_i)$.
4. Plot the R_k^2 values from step 3 against the corresponding values of Q_k. Draw a smooth curve through these points and select as the best estimate of Q that value at which the R^2 *curve* reaches its maximum. Compute D from equation (4) and compute R^2 for these final estimates of Q and D.

This procedure was developed in (17) to estimate delay curves based on simulation data for railroad lines, where it was observed to produce highly satisfactory results. For small amounts of data, it is readily implemented on a small manual or programmable calculator and it is easily programmed on a microcomputer.

Estimation Error

The data points used to estimate the parameters of the hyperbolic delay function, whether obtained from direct observation or computer simulation, are subject to random error. The question then arises as to what effect this error has on the parameter values and subsequent delay estimates. Normally, the traffic levels, q_1, are known without error.[6] Thus, attention can be focused on the delay observations, d_i.

Equation 4 shows that parameter D is linearly dependent on the delay values. In fact, the last one or two data points, at the higher values of q and d, contribute the most to the estimate of D. This is the very region of the flow regime where average delay can fluctuate widely, due to the instability of the queuing system. Consequently, it is a good idea to have replications of the high delay data points, to avoid propagating random error to the D estimate. Obviously (equation 1), the delay estimates calculated with the function are linearly dependent on D, so errors in D are propagated to the final function values and to any further economic analyses based on the delay curve.

The situation is a little less clear for the capacity

TABLE 2

SIMULATION DATA FOR PEORIA LOCK ON THE ILLINOIS WATERWAY

i Run No.	q_i Annual Traffic (net kilotons)	d_i Average Delay per Tow (min.)
1	15,980	28
2	32,065	123
3	36,864	253
4	42,457	701

Does not include effect of navigable pass conditions.

TABLE 3

ESTIMATION OF DELAY CURVE PARAMETERS FOR PEORIA LOCK

Trial k	Parameters: Capacity (kilotons) Q_k	Parameters: Delay (min.) D_k	Estimated Delays, $\hat{d}_i$ (min.): $\hat{d}_1$	$\hat{d}_2$	$\hat{d}_3$	$\hat{d}_4$	R_k^2
1	43,300	14.40	8.4	41.1	82.5	725	.9498
2	43,320	14.75	8.6	42.0	84.2	726	.9504
3	45,600	52.6	28.4	125	222	711	.997
4	47,880	85.8	43	174	287	672	.994
5	50,160	116	54	206	322	639	.976
Opt.#	46,200	61.8	33	140	244	701	.9988
2-point*	45,610	52.0	28	123	219	700	.9968

#Optimum estimate of Q; see Figure 3.

*Parameters estimated by passing delay curve through second and fourth data points (i = 2 and 4 in Table 2).

parameter. Using the search technique suggested above, the estimate of Q which provides the best fit of the delay curve to the data points is selected so there will normally be little estimation error. This can also be argued by considering equation 2 for the two-point method. Using the first and last data points (q_1, d_1) and (q_n, d_n), the expression for Q is dominated by the ratio d_1/d_n, which appears in both the numerator and the denominator. Thus, capacity estimates are very robust with respect to random error in the delay data.

APPLICATIONS

The examples presented below all use data and simulation results from the Upper Mississippi River Master Plan study (2). The LOKSIM2 model (9) was used to perform all lock simulations.

Estimation of a Lock Delay Curve

Table 2 gives the results of simulating four traffic levels at Peoria Lock on the Illinois Waterway. The lock chamber is 600 feet long and 110 feet wide, so it will accommodate a maximum of nine jumbo barges. The simulations were conducted in 1981 using commodity mix and tow size data for the year 1976, when the lock was passing approximately 32 million tons per year. At each traffic level a separate simulation was conducted for each season, and the data were annualized.[7] Thus, each data point is a composite of four simulation runs, which provides the replications needed to accommodate random error.

Table 3 gives the result of applying the search technique to estimate the delay curve parameters. In step 1, the trial value Q* was computed to be 45,600 kilotons, and the other trial values (step 2) are shown in column 2 of the table. For each trial value, Q_k, the remaining columns give the items computed at step 3. The delay estimates in each row can be compared with the data in Table 2 to assess the representativeness of each of these potential delay curves. Panel (a) in Figure 3 shows the R^2 plot obtained at step 4. Based on this plot, the best estimate of Q is 46,200 kilotons. The sixth row of Table 3 gives the corresponding D estimate (from equation 4) and the resulting delay estimates at each of the flow levels, q_i. For this function a nearly perfect linear correlation between the data points and the fitted curve is obtained ($R^2 = 0.9988$). Panel (b) of Figure 3 shows the data points and the delay curve.

Although only four data points are used, the curves in Figure 3 are representative of the results which are obtained when using this method to fit a hyperbolic function to simulation data, even when more data is available. The R^2 values are typically very high, and the R^2 plot normally has a rather flat portion near its peak. This means that small variations in the capacity estimate will not have much effect on the goodness of fit.

The last row of Table 3 gives the parameter estimates obtained using the two-point method. The two points used are at flows which are 69 percent and 92 percent of capacity. The parameter estimates are very close to those determined with the search procedure using all of the data, and the statistical fit of this curve to the data is excellent ($R^2 = 0.9968$). This result is typical. For judicious selection of the data points, the two-point method will normally produce a highly satisfactory delay curve. For this result to hold, the two data points should be at flow values which produce lock utilizations in the neighborhood of 50 percent and 75 percent of capacity.

Analysis of Lock Improvements

LOKSIM2 was used to simulate the effects of lock capacity and delay of various potential nonstructural improvements. Some of these measures were designed to expedite the handling of large tows and reduce the marginal delays caused by double lockages (where the tow is too large to be locked through the chamber in one pass). Three of these measures are:

1. *Bowboats*—extra power units placed at the head of a tow to assist in maneuvering and in entering and exiting locks;
2. *Helper Boats*—low horsepower towboats stationed at locks and used to remove unpowered cuts from the lock chamber; and
3. *Switchboats*—towboats somewhat larger than helper boats which remove unpowered cuts from the chamber and move them to remote mooring facilities, which allows the remake of the double lockage tow to occur without tying up the lock approach/exit area.

Detailed descriptions of these measures and how they were simulated are given in (2).

Delay curves for the base condition and each improvement were estimated from the simulation data, using the two-point method.[8] The results are given in Table 4. It appears that bowboats and switchboats provide benefits of the same order of magnitude. Both alternatives would increase capacity by 9-10 percent and reduce average delays by 20-25 percent. The helper boat alternative, in contrast, has negligible benefits.

Analyses such as the above were performed for numerous alternatives at all locks in the Upper Mississippi River Master Plan study. The delay curves, estimated as described above (with the two-point method), were used to formulate average cost curves which played a prominent role in the economic analysis of alternative system improvement plans.

CONCLUSIONS

The hyperbolic delay curve is a flexible and accurate means of representing the flow and delay characteristics of inland waterway locks. The simple methods described in this paper can be used to estimate the parameters of the delay curve which best fits the delay data generated by computer simulation. It is possible to determine acceptable delay curves from as few as two simulation runs at different traffic levels, though accuracy will be increased if more points and replications of individual runs (especially at high flow and delay levels) are utilized. The delay curves obtained by this method have been successfully used as the basis for average cost curves in a number of navigation studies. This basic methodology is applicable to virtually any transportation system element where capacity and delay are important considerations.

REFERENCES

1. National Waterways Study—Final Report. U. S. Army Engineer Water Resources Support Center, Institute for Water Resources, Ft. Belvoir, VA, 1982.

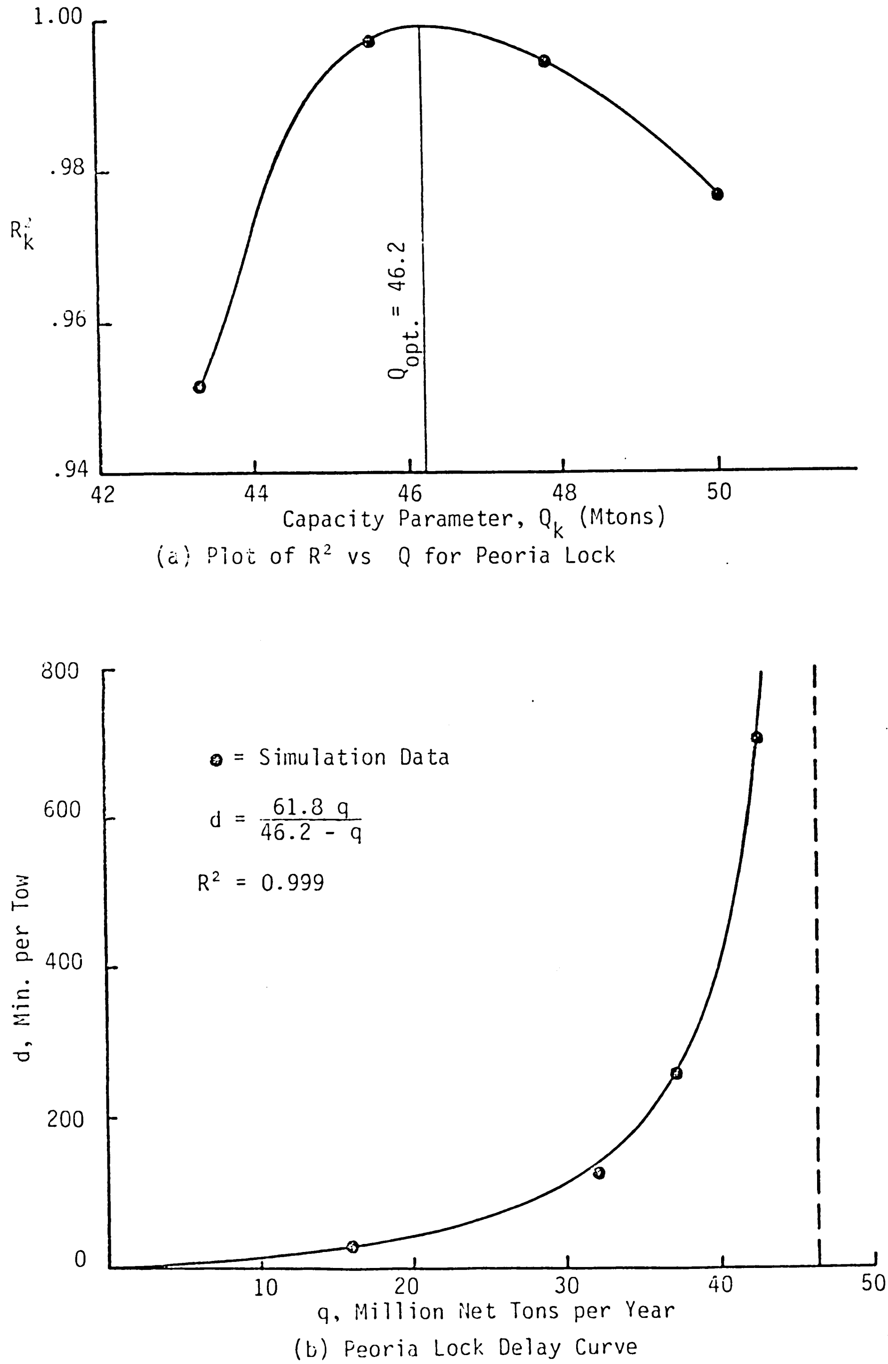

FIGURE 3. Estimation of Delay Curve for Peoria Lock.

TABLE 4

DELAY CURVES FOR NONSTRUCTURAL IMPROVEMENTS AT PEORIA LOCK

Lock Improvement Alternative	Parameters	
	Capacity Q ktons/yr.	Delay D min./tow
Base Condition	44,090	40.1
Bowboats	47,910	30.9
Helper Boats	45,120	41.1
Switchboats	48,400	32.6

2. Upper Mississippi River Basin Commission. Comprehensive Master Plan for the Management of the Upper Mississippi River System. October 1981.
3. Howe, C. W., et al., *Inland Waterway Transportation; Studies in Public and Private Management and Investment Decisions.* Resources for the Future, Inc., The Johns Hopkins Press, Baltimore, MD, 1969.
4. Carroll, J. L. and Bronzini, M. S., Simulation of Waterway Transport Systems. *Transportation Engineering Journal of ASCE,* Vol. 97, No. TE3, Proc. Paper 8311, pp. 527-539, August 1971.
5. CACI, Inc., Inland Navigation Systems Analysis; Vol. V—Waterway Analysis. Office of the Chief of Engineers, Corps of Engineers, Washington, D. C., July 1976.
6. Carroll, J. L., Waterway Lock Simulation Model. *Papers—Sixth Annual Meeting,* Transportation Research Forum, pp. 217-238, 1965.
7. Carroll, J. L., and Bronzini, M. S., Waterway Systems Simulation; Vol. I—Summary Report. TTSC 7108, Pennsylvania Transportation Institute, Pennsylvania State University, University Park, August 1971.
8. Hayward, J. C., Simulation Analysis of a Multiple Chamber Lock on the Inland Waterways. TTSC 7211, Pennsylvania Transportation Institute, Pennsylvania State University, University Park, August 1972.
9. Bronzini, M. S., and Margiotta, R. A., Analysis of Lock Capacity by Simulation. *Transportation Research Record,* No. 880, pp. 7-13, 1982.
10. CACI, Inc., Waterway and Rail Capacity Analysis. Transportation Systems Center, U. S. Department of Transportation, Cambridge, Ma, September 1976.
11. CACI, Inc., Improvement of the LOKCAP Model to Handle Double Chamber Queuing. Office of the Chief of Engineers, Corps of Engineers, Washington, D. C., September 1979.
12. Mosher, W. E., Jr., A Capacity Restraint Algorithm for Assigning Flow to a Transportation Network. *Highway Research Record,* No. 6, pp. 258-289.
13. Davidson, K. B., A Flow Travel Time Relationship for Use in Transportation Planning. *Proceedings, Australian Road Research Board,* Vol. 3, No. 1, pp. 183-194, 1966.
14. CACI, Inc., Inland Waterway Transportation Cost Model. Transportation Systems Center, U. S. Department of Transportation, Cambridge, MA, June 1977.
15. Baxter, W., Bronzini, M., Limaye, D., and Sherman, D., Transportation Network Models for Energy Supply Analysis. EA-2324, Electric Power Research Institute, Palo Alto, CA, March 1982.
16. Boyce, D. E., Janson, B. N., and Eash, R. W., The Effect of Equilibrium Trip Assignment of Different Link Congestion Functions. *Transportation Research,* Vol. 15A, pp. 223-232, 1981.
17. Bronzini, M. S., and Sherman, D., Railroad Routing and Costing. Electric Power Research Institute, Palo Alto, CA (forthcoming).

NOTES

1. The cost curves may be downward sloping at low flow quantities, due to user-borne fixed costs. The behavior of the curves in the low flow regime is not of interest here.
2. A system improvement normally lowers the lock delay curve and its related AC curve. This produces delay savings for existing traffic and causes some additional users to begin using the facility, presumably at a lower cost than they were experiencing using some alternative service.

3. Run replications at each traffic level may also be needed, to account for random effects.

4. These data are purely illustrative and are not representative of any lock. Thus, the measurement units along the axes are arbitrary and, therefore, not stated.

5. This method ws introduced in the LOKCAP model (11), which estimates the entire lock delay curve. In this case, Q is computed directly from input data on the lock service times and the tow size distribution.

6. If traffic is specified in units of annual tonnage, there my be some error in converting from tows to tons, and in accounting for seasonal effects and traffic peaking phenomena. However, this error is not random and it is directly controllable (in a statistical sense) by the analyst.

7. Navigable pass conditions, which occur at Peoria for some portion of nearly every year, were not considered in this part of the analysis, but were handled separately later (2).

8. The base condition used different data than the simulations tabulated previously, so the delay curves differ. The two-point method was selected because of the large number of simulations needed and the short time available.