The Structure of Congestion Costs and Optimum Pricing in Inland Waterway Transportation

CHARLES W. HOWE, Resources for the Future, Inc.; and
ROBERT M. STEINBERG, Federal Reserve System

•THIS PAPER describes the nature of a computer simulation model that analyzes the congestion costs of and the benefits accruing from improvements to an inland (shallow water) transportation system such as that found on the major navigable rivers of the United States. Some specific application of the model will be illustrated. The reasons for constructing the model were (a) that congestion, which frequently occurs on the major rivers of the United States, not only increases the physical capacity of the waterways beyond their current status but also has become extremely expensive; (b) that analysis of the impact of structural improvements on congestion costs is quite difficult in a complex system; and (c) that efficient use of the waterways in the face of congestion requires the pricing of the services of the waterway in such a way that the prices charged reflect congestion costs.

The model is a computer simulation model capable of representing the flows of commercial barge tows over a waterway system consisting of (a) channel segments of assignable lengths, widths, depths, and currents, (b) ports with specified types of delays, (c) locks of specific characteristics, which may include different numbers of chambers and any distributions of locking time components, and (d) restricted stretches, if applicable, such as those in which speeds must be restricted or in which passing may be prohibited. The traffic itself consists of any specified mix of characteristics of modern tows that arrive at the ends of the system at specified average rates per day but whose actual arrival times are randomly distributed. The components of locking times are also randomly generated.

Various statistics compiled on the operations of the system include the number of tows and barges processed at each lock, average queue lengths at each lock, total delay times in queues, total gross tonnage, total delay costs, and total system operating costs. Optional outputs permit tracing of individual tow movements, costs, and delay times. [For a more complete description of the model, see Howe (1).]

The costs incurred on the waterway system consist of the public costs of constructing and operating the waterway and the private costs of operating tows on it. The variable public costs are extremely low in almost all areas. The variable private costs can be divided into those that are incurred by operating on the system when no congestion is present and those that are incurred because of congestion. The first category of private operating costs are, by definition, not variable with the volume of traffic and are reflected in the height of the demand curve for the service of the waterway (Fig. 1). The congestion costs will be zero up to some traffic level and then begin to increase as queues grow at locks, ports, and other restricted points of the system. This growth of delay costs may be represented by the average delay cost (ADC) and marginal delay cost (MDC) functions of Figure 1.

The economically efficient volume of traffic on the waterway, Q^*, is the volume at which marginal delay cost just equals the willingness of the marginal waterway user to pay (demand value). For reasons that have been amply explained elsewhere (2), the likely equilibrium level of traffic will be at Q^e in the absence of appropriate tolls. At

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TABLE 1

INPUTS, OUTPUTS, AND DELAY COSTS OF A THREE-DAM RIVER SYSTEM

Expected Arrival Rates per Day		Total Tows Into System in 30.6 Days (actual)	Total System Delay Cost Over 30.6 Days ($)	Average Delay Cost per Tow Into System ($)	Marginal Delay Cost per Tow ($)
Up	Down				
10	10	598	22, 900	38	–
12	12	736	36, 800	50	101
14	14	854	68, 000	80	265
16	16	987	118, 900	120	382
18	18	1, 092	217, 400	199	938
20	20	1, 214	587, 600	484	3, 035

this level, marginal delay costs are far in excess of the marginal value of traffic on the river by the amount a. A toll in the amount of c dollars per tow passage would efficiently bring about the optimum level of traffic.

How can these schedules of congestion costs be derived? It is almost impossible to derive them from historical statistics because the cost figures have never been kept, and the historical range of values does not cover what is generally needed—forecasts of future conditions. The simulation model makes it possible to generate the needed congestion cost data.

Table 1 gives partial program output when the model was run for a small system that has three dams located approximately 100 miles apart. (This model closely resembles the reaches of the Ohio River, starting with Meldahl Lock and Dam and extending downstream just past McAlpine Lock and Dam.) The average (expected) arrival rates of traffic were simultaneously augmented in both directions. The points to note are the rapid increase in total, average, and marginal delay costs.

A second point investigated by the model was the extent of divergence between locally observable benefits stemming from a system improvement (such as increasing the capacity of a lock) and the benefits accruing to the entire system. The motive for investigating this was an often-voiced suspicion that local and system benefits may diverge widely. Running the model to a month's activity at two different traffic-arrival rates before and after improvements at Lock 2 measured the benefits in terms of minutes of delay time saved both at Lock 2 and for the entire system. (The actual operating costs of the tows used in this run of the model averaged very close to $1 per min.)

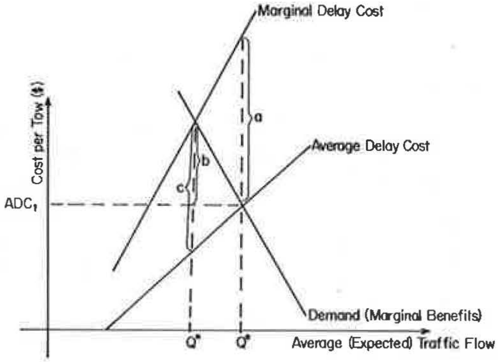

Figure 1. Growth of delay costs represented by functions of average delay and marginal delay costs.

TABLE 2

LOCAL AND SYSTEM SAVINGS IN DELAY TIME OVER 30.6 DAYS AFTER IMPROVEMENTS TO LOCK 2

Arrival Rates	Apparent Savings at Lock 2 (min)	Actual System Savings (min)
Up = 16 Down = 16	48, 767	52, 347
Up = 22	1, 515, 775	989, 972

TABLE 3

AVERAGE QUEUE LENGTHS AFTER IMPROVEMENTS TO LOCK 2

(Arrival Rates = 22 per Day)

Lock		Average Queue Length Before Change	Average Queue Length After Change
1:	Up	5.37	10.13
	Down	5.75	11.34
2:	Up	16.30	0.12
	Down	18.43	0.16
3:	Up	0.88	1.62
	Down	1.20	2.07

TABLE 4

CHARACTERISTICS OF SYSTEM PERFORMANCE FOR INCREMENTS OF UPBOUND SMALL TOWS[a]

(8 Barges, 2,000 Horsepower)

Upbound Arrival Rate, Small Tows	Total System Cost ($000)	Total Delay Cost ($)	Total Ton-Miles Produced (millions)	Total No. Tows Into System	Average Total Cost per Million Ton-Miles ($)	Average Delay Cost per Million Ton-Miles ($)	Average Delay Cost per Tow Into System ($)	Marginal Delay Cost per Tow Into System ($)	Average Delay Cost per Tow Locked ($)		
									Lock 1	Lock 2	Lock 3
5	2,110	52,980	3,055	870	690	17	61	–	24	21	11
7	2,311	62,618	3,207	950	720	20	66	120	27	20	16
9	2,564	90,432	3,457	1,048	740	26	86	284	33	32	19
11	2,741	119,920	3,641	1,123	750	33	107	393	40	44	24
13	2,981	144,027	3,848	1,215	770	37	119	262	44	49	29
15	3,416	191,095	3,820	1,254	890	50	152	1,207	38	80	38

[a] Downbound arrival rate = 16 per day and upbound arrival rate = 5 per day, over a period of 34.7 days.

TABLE 5

CHARACTERISTICS OF SYSTEM PERFORMANCE FOR INCREMENTS OF UPBOUND LARGE TOWS[a]

(17 Barges, 3,200 Horsepower)

Upbound Arrival Rate, Large Tows	Total System Cost ($000)	Total Delay Cost ($)	Total Ton-Miles Produced (millions)	Total No. Tows Into System	Average Total Cost per Million Ton-Miles ($)	Average Delay Cost per Million Ton-Miles ($)	Average Delay Cost per Tow Into System ($)	Marginal Delay Cost per Tow Into System ($)	Average Delay Cost per Tow Locked ($)		
									Lock 1	Lock 2	Lock 3
5	2,119	52,980	3,055	870	690	17	61	–	24	21	11
7	2,439	82,458	3,377	972	720	24	85	289	34	30	15
9	2,650	102,326	3,720	1,044	710	28	98	276	35	35	25
11	2,908	151,342	3,916	1,119	740	39	135	654	34	55	45
13	3,223	201,568	4,314	1,191	750	47	169	698	46	64	53
15	3,531	365,012	4,520	1,262	780	81	289	2,302	46	126	109

[a] Downbound arrival rate = 16 per day and upbound arrival rate = 5 per day, over a period of 34.7 days.

It appears that at the lower traffic rate, system-wide benefits somewhat exceed those measured only at Lock 2; but at the higher traffic rate, local benefits clearly overstate system benefits (Table 2). The importance of this observation to system planning and benefit-cost analysis is obvious. The actual transfers of delay time from one lock in the system to the others, which underlie the savings figures of Table 2, are given in Table 3. Again, at the higher traffic rate, the improvement of Lock 2 causes a significant part of the delay time to be shifted to Locks 1 and 3.

It would be expected that different types of traffic would impose different degrees of congestion cost on the system. The characteristics of the tows that might affect their contribution to system delay costs would include size (number of barges), draft, and direction of travel. Various runs of the model make it quite clear that these differential effects hold. Tables 4 and 5 give the results of the analysis of the differential impacts of large and small tows on system delay costs. The marginal delay cost per tow increases much more rapidly when the arrival rate of large tows is increased than when that of small tows is increased. The average total cost per million ton-miles (delay plus noncongested operating costs) increases less rapidly for the large tows, however, because the running economies of the large tows tend somewhat to offset their greater contribution to delay costs.

The usefulness of this model extends to the analysis of other problems, and it can be used for any waterway system. The program is currently being used by and is available from Professor Joseph L. Carroll, Transportation and Traffic Safety Center, Pennsylvania State University, University Park.

REFERENCES

1. Howe, Charles W., et al. Inland Waterway Transportation: Studies in Public and Private Management and Investment Decisions. The Johns Hopkins Univ. Press, Baltimore, 1969, Ch. 5.
2. Mohring, Herbert D., and Harwitz, Mitchell. Highway Benefits: An Analytical Framework. Northwestern Univ. Press, Evanston, Ill., 1962, Ch. 2.