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A Zero Sum User Charge System for Rationing the Use of Inland Waterway Locks

by

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THE QUESTION of levying charges for the use of shallow draft inland waterway facilities in the United States has been a long-lived political and economic issue. Each of the last three Presidents has proposed to Congress that some form of user charge be levied, but to date no such legislation has been enacted. Hence all of the federally provided facilities have remained absolutely free of charge to users. The fixed facilities in question include an extensive system of locks, dams and dredged channels, which are built, maintained and operated by the U.S. Army Corps of Engineers.

A variety of arguments may be offered in favor of charging for the use of any facility (for further discussions, see [3] and [4]). Two reasons for imposing such charges are (1) to recover costs of providing the facility and (2) to ration its use. The level of the fee to be charged for the second objective—rationing the use of a congested facility—is independent of facility cost. The ideal charge is that which makes an individual user's cost equal to the increase in total delay costs incurred by all users of the facility as a result of adding a user.

Every proposal for waterway user charges designed to recover costs of providing fixed facilities has failed in the political arena. Moreover, it is likely that any user charge proposal—even if it were intended only for rationing purposes—would be opposed just as vigorously and just as successfully as have those of the past. In recognition of the prevailing situation, this paper will propose a rationing system which falls short of the ideal user charge scheme in its rationing affects, yet which has the potential practical advantage of exacting no net toll from the users. Attention will be focused on rationing the use of a single lock.

A Zero Sum Toll for a Lock

Lave and DeSalvo [6] have developed a formula for computing the optimal user charge for rationing the use of a lock, based upon the economic argument mentioned above and a simple queuing model to predict delays.[1] Their system of charges is theoretically ideal, however it fails to meet the criterion proposed here in that it results in a net positive charge to waterway users. Such a positive charge is inescapable if the optimal usage level is to be attained.

The approach taken in this paper will be to pursue the narrower goal of influencing the efficiency with which barge tows use the lock. There is considerable variation in the times required for tows to enter and depart a lock chamber. Some of the influencing factors are tow size and configuration, towboat horsepower, pilot skill, water current and weather conditions. Obviously, some of these variables are subject to control by the tow operator while others are not. The objective will be to give tow operators an incentive to adjust the controllable parameters in such a fashion as to maximize the efficiency with which the tow passes through the lock. The exact meaning of efficiency will be discussed later.

If the incentive for efficient operation is to take the form of a user charge, and yet exact no net toll, this implies the collection of both positive and negative charges. That is, the inefficient user would pay a positive amount, while the more efficient user would "pay" a negative amount, or actually receive money as a reward for his efficiency. The charges would have to be adjusted so that they sum to zero over all users.

Define the following:

V cost per unit of time of keeping a tow waiting

T_i total locking time for tow i

D delay time for all tows, excluding the one currently using the lock

C_i charge to tow i

W_i value of tow i

T_i is the length of time during which tow i ties up the facility

$\frac{\partial D}{\partial T_i}$, then, is the rate of increase of total delay time for all other tows (except tow i) as the locking time for tow i

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increases. Note that D does not include locking time.

Lave and DeSalvo assert that "... the optimal toll should depend on actual service time." [6, p. 390] Since the locking time, T_i, for a tow varies with its size and other characteristics, a gross average locking time would not be satisfactory, hence the emphasis on actual service time which reflects the trade-offs between, say, tonnage and time required to enter the lock chamber. The reasoning is that if a carrier operates tows in configurations which require longer locking times, then he should be required to pay for the additional delays caused thereby.

In actual practice, charging based upon actual service time might create some serious problems. The difficulties would arise as a result of delays which are beyond the control of the tow operator. Examples are lock gates jammed by debris, inoperative locking mechanisms and delays caused by tows entering or departing a parallel chamber. It would seem desirable, then, to have a formula to predict "normal" or "expected" locking time for any tow based upon its relevant physical characteristics. This would assure that carriers would not be charged for delays which should not, in fairness, be attributed to them. Further, it would provide a basis for carriers' decisions regarding tow configurations. There would be no uncertainty about the amount of tolls to be paid, so that financial trade-offs between, say, number of barges and user tolls could be made rationally. A later section of this paper deals directly with the problem of developing such an expected locking time formula. At this point, the discussion will continue under the assumption that such a formula exists.

Define $\hat{T}_i$ to be the expected or standard locking time for tow i as predicted by the formula. Also, define

$$U_i = \hat{T}_i / W_i \cdot$$

U_i is the (standard) locking time per unit of value for tow i. If an objective in operating a congested lock is to move the greatest value of cargo through the lock in a given time, then U_i is a measure of the inefficiency with which tow i is using the lock. The user charge system should give tow operators an incentive to reduce U_i for their own tows. Notice that W_i has only been defined as the "value" of tow i. The interpretation of value can be adjusted to fit one's concept of efficient lock operation. It could, for example, be defined as the number of loaded barges, the total number of barges, gross tonnage, payload tonnage or the actual dollar value of the commodities carried. The choice would be affected by what kinds of tows one wished to discourage from using the facility.

For a particular lock, suppose $\hat{T}_i$ and W_i have been observed for a large number of tows. Then $\bar{U}$, the mean of the U_i, is defined as

$$\bar{U} = \sum_i \hat{T}_i / \sum_i W_i \cdot$$

Note that this average is weighted by value; it is not the simple average age of U_i over all tows. That is,

$$\bar{U} \neq \frac{1}{N} \sum_i (\hat{T}_i / W_i)$$

where N is the number of tows.

Now consider a user charge computed as follows:

$$C_i = (U_i - \bar{U}) W_i V \frac{\partial D}{\partial T} \cdot \qquad \text{(I)}$$

C_i satisfies the zero sum requirement, since

$$\sum_i C_i = V \frac{\partial D}{\partial T} [\sum_i U_i W_i - \bar{U} \sum_i W_i]$$

$$= V \frac{\partial D}{\partial T} [\sum_i \frac{\hat{T}_i}{W_i} W_i - \frac{\sum_i \hat{T}_i}{\sum_i W_i} \sum_i W_i]$$

$$= 0.$$

$\bar{U}$ serves as a standard for the amount of locking time which should be required per unit of value moved through the lock. Tows that require more time than the standard pay according to just how "inefficient" they are. Tows that beat the average are rewarded for their efficiency. Assuming a fixed value, W_i, the user charge equation (I) takes the form

$$C_i = \text{constant} + \hat{T}_i [V \frac{\partial D}{\partial T}].$$

The Quantity $V \frac{\partial D}{\partial T}$ is the delay cost to all other users of having the facility tied up for an additional unit of time. Hence, the charge, C_i, makes the cost of using the lock for an additional unit of time exactly equal to the cost of delays caused to others as a result of that additional use. This is true for any user, regardless of whether his particular charge happens to be positive or negative.

It should be re-emphasized that the charge, C_l, calculated according to equation (I), does not ration the use of the lock in the economically ideal manner. It rations only insofar as it provides a cost penalty for inefficient use of the facility In this way, when congestion levels (and hence delay costs) are sufficiently high, it may price inefficient users out of using the lock. If value, W, were defined as the actual monetary value of a tow's cargo, then carriers might not be able to afford to move low-valued cargo through the lock. In any event, it gives tow operators an incentive to operate tows which are more efficient from the standpoint of entering and departing the lock chamber.

Equation (I) provides the conceptual basis for a zero sum user charge system. Implementation of such a system, however, depends upon the existence of an algorithm for calculating the standard locking time, $\hat{T}_l$, and upon the estimation of numerical values for V and $\frac{\partial D}{\partial T}$. The remainder of the paper is addressed to these issues by way of an empirical study of traffic through an Ohio River lock.

Empirical Study of a Lock

Captain Anthony Meldahl Lock and Dam near Cincinnati on the Ohio River was chosen for the experimental study. Meldahl has two parallel lock chambers with dimensions of 110 by 1200 and 110 by 600 feet, respectively. The vertical displacement varies from less than one foot to about thirty feet, depending on the levels of the water in the upper and lower pools. These levels are influenced by opening and closing twelve dam (tainter) gates. Data were recorded by an observer present at the lock for four- to ten-hour periods between April 3 and June 3, 1972. The schedule of observations covered all hours of day and night.[2]

In all, 210 lockages were observed, of which 38 were pleasure craft. Most of the pleasure craft used the smaller chamber. The great majority of barge tows (84%) were too long to use the small chamber without a setover.[3] Only 15 of the observed tows actually used the smaller chamber, although a few more would have had it not been inoperative for a time.

For each tow that passed through the lock, the following kinds of data were recorded: identification and horsepower of the towboat, commodities carried, number and dimensions of barges, tow configuration (sketch), direction of movement (upstream or downstream), chamber used, weather conditions, water levels, dam gate openings and whether a setover was required. Also recorded were clock times at fourteen points in the locking operation, beginning with arrival at the arrival point and ending with the passing of the departure point. Arrival and departure points are markers on the shore about 3100 feet upstream and downstream from the respective lock gates.

The normal locking operation proceeds roughly as follows. A tow arrives at the arrival point and waits for an entry signal from the lockmaster. The tow pilot has been in radio communication with the lockmaster, so that if the chamber is not in use, the entry signal may be given before the tow arrives at the arrival point, eliminating any delay. A tow following another which is locking through in the same direction may be given permission for a short entry. This means it is allowed to position itself just outside the lock gate so that when the chamber is ready for its entry, it is much closer than if it had waited at the arrival point. The tow enters the chamber and ties up to floating mooring bits while the gates are being closed behind it. The chamber is then emptied or filled, the opposite gates are opened and the tow departs. The times required for tows to lock through Meldahl vary from less than twenty minutes to well over an hour (not including delays at the arrival point).

For this study, attention is limited to tows using the larger chamber. At sites where only a 600 foot chamber is available, a procedure called double lockage is quite common. This is required when a tow is too large to fit in the chamber, so that it must be broken into two parts which are then locked through individually. The availability of the larger chamber at Meldahl makes the occurrence of double lockages relatively rare, so that they were ignored in this study. (Only two double lockages occurred during the observation period.) Eliminating inapplicable, incomplete and inconsistent data left 143 lockage data sets, some of which still suffered from some missing entries.

A Locking Time Equation for Meldahl

Locking time, T, is the period beginning when the tow passes the arrival point[4] and ending when it passes the departure point. For purposes of modeling, the operation will be broken into three parts, as follows:

Segment of Locking Time	Begins	Ends
S_1, Entry time	Tow passes arrival point	Tow secured in lock
S_2, Time in chamber	Tow secured in lock	Exit signal given
S_3, Exit time	Exit signal given	Tow passes departure point

Of the three segments, the greatest variation occurs in entry time. Variations arise as a result of tow size and configuration, power of the towboat, commodities carried, weather, time of day (or night) and pilot skill. The same factors tend to affect exit time, although generally to a somewhat lesser degree. The approach here will be to develop separate predictor equations for entry and exit time based upon the variables described above via linear regression analysis. Since the middle segment of locking time, "time in chamber," is generally unaffected by any carrier actions, the variations therein are of little interest for purposes of this study. A simple arithmetic mean will be sufficient to represent its expected time.

In developing the regression equations, of initial concern is the form the equations should take. Two basic forms were originally considered: linear and log-linear. The log-linear form had some intuitive appeal for this problem in view of the interactive nature of several of the independent (explanatory) variables. For example, an underpowered tow requires longer to enter the lock than does one with sufficient power for its load. A heavy wind or strong current might be expected to compound the problem of the underpowered tow, adding more to its entry time than to that of the one with sufficient power. Despite this reasoning, however, the simple linear form proved to be clearly more effective as a predictor, so the log-linear model was dropped from consideration.

The criteria for selecting the final model included not only the coefficient of determination (R squared), but also simplicity and intuitive reasonableness. Following are descriptions of the basic variables which are found in the final equations, some in cross-product form:

1. **Gross tonnage.** Tonnage was not recorded in the data so that it had to be estimated from barge dimensions, the density of water and an assumed draft of nine feet for loaded barges and one and one-half feet for empty barges. Variations in actual drafts and the fact that some barges have raked ends reduce the reliability of this estimate somewhat. Gross tonnage for a tow, then, includes the total gross weight of loaded and empty barges calculated in this manner. The units are kilotons (1000 tons).

2. **Flammable tonnage.** Five commodities—petroleum, gasoline, wood alcohol, benzene and glycol—were considered flammable. Flammable tonnage is the total estimated gross tonnage of these commodities.

3. **Horsepower** is simply the published horsepower of the towboat.

4 **Short entry** is an indicator variable equal to one if the tow made a short entry and zero otherwise.

5. **Clearance** is the difference between the maximum width of the tow configuration and the width of the lock chamber (110) in feet.

6. **Wind** is another indicator variable, equal to one if "windy" and zero otherwise.

7. **Frontal area** is the sub-surface lateral cross sectional area of the tow in square feet. It represents the surface which must meet the resistance of the water.

8. **Dark** is another indicator variable, equal to one if dark and zero otherwise.

As mentioned above, some of these basic variables entered the equations in cross-product combinations. Table 1 represents the final form of the independent variables, the regression coefficients in each equation and some statistics of interest. In both equations (entry and exit times) the dependent variable is time in minutes.

The independent variables in the entry time equation reflect the importance of maneuverability. The flammable tonnage variable indicates the extra care taken by pilots with flammable cargoes. The clearance factor may be important for two reasons. First, clearly it is more difficult to maneuver a tow with little lateral clearance into the chamber. Second, there is a pronounced piston effect, causing the water level in the chamber to rise as the tow enters and then recede as water rushes out of the chamber. This creates some difficulty in bringing the tow to a halt at the desired point. The wind-tonnage variable reflects the difficulty of handling a large tow in the wind. Gross tonnage per horsepower might be expected to have a significant effect upon tow speed as well as upon maneuverability. The R squared of .63 for this equation is not outstanding, but on the other hand, it tends to support the earlier statements concerning random, uncontrollable elements which affect locking time. The presence of such random perturbations was the rationale for developing a model in the first place. Perhaps the most important variable not taken into account by the model is that of pilot skill, measurement of which

	ENTRY TIME EQUATION				EXIT TIME EQUATION			
Variable definition	**B**	**Standard error B**	**F**	**Beta**	**B**	**Standard Error B**	**F**	**Beta**
100x(Gross tonnage)/ (Horsepower)	10.33	2.01	26.19	0.310	1.867	1.21	2.39	0.182
Flammable tonnage	0.4388	0.08	33.73	0.347				
(Wind)x(Gross tonnage)	0.3068	0.09	10.71	0.198				
$(10/\text{Clearance})^2$	0.2771	0.11	6.27	0.143				
Short entry	−11.68	1.51	59.84	−0.439				
Dark	2.710	1.26	4.61	0.126				
Frontal area					0.2432	0.11	4.89	0.261
Intercept (A)		15.28				8.89		
R^2		0.63				0.17		
Mean S (dependent variable)		21.69				11.04		
Standard deviation S		10.14				3.12		
Observations		126				120		

TABLE 1
Regression Results

would involve a major undertaking in itself.

Both of the independent variables in the exit time equation are determinants of tow speed. Maneuverability clearly is of relatively less importance here than for entry time. The R squared of .17 is not so dismal as it might seem. The standard deviation of exit time is only a little over three minutes, a good share of which could be due to rounding to the nearest minute and to slight observation errors resulting from the distant locations of the departure points. The value of R squared for the two equations when summed to estimate entry time plus exit time is .58.

Mean time in the lock chamber was found to be 10.5 minutes, completing the algorithm for estimating total locking time, T. The estimate, $\hat{T}$, is calculated as

$$\hat{T} = \hat{S}_1 + \hat{S}_2 + \hat{S}_3 \qquad \text{(II)}$$

where $\hat{S}_1$ is estimated entry time, $\hat{S}_3$ is estimated exit time and $\hat{S}_2$ is estimated time in the chamber (=10.5 minutes).

Distribution of User Charges

Now that a formula (equation II) is available for estimating total locking time, the variables which must still be quantified in order to calculate user charges are $\overline{U}$, V and $\frac{\partial D}{\partial T}$ (see equation I). Also, a decision must be reached concerning the interpretation of tow value, W. For purposes of illustration, in the following, W will be taken as total gross tonnage. (Recall that this does not include the towboat.) The implicit objective, then, is to move "tonnage" through the lock, where a ton of empty barge, a ton of sludge, a ton of coal or a ton of chemicals are all of equal value. $\frac{\partial D}{\partial T}$ depends upon the level of use of the lock. It can vary from near zero for a lightly used lock to very high values for a heavily congested one. To give some feel for its magnitude, $\frac{\partial D}{\partial T}$ is always at least as large as the average queue size. That is, spending an extra minute in the lock causes, at the least, an extra minute of delay for each tow in the queue. Average queue size might serve as an acceptable substitute for $\frac{\partial D}{\partial T}$ for practical purposes. This quantity could be estimated with a lock simulation model or from actual on-site observations. The cost, V, of keeping a typical modern tow waiting has been estimated in excess of \$200 per hour, or over \$3 per minute [3, p. 4-11]. In the interest of simplicity, the following calculations will be carried out under the assumption that the product, $V \frac{\partial D}{\partial T}$ is equal to unity. This would imply an average queue size between one-fourth and one-third—a relatively uncongested lock. The reader should keep in mind that the magnitude of the charges would vary substantially with the level of use of the lock. The distribution of charges over all users, however, would remain the same but for a scale factor.

In this study, the mean of W, gross tonnage, was 12.7 kilotons and the mean of $\hat{T}$, expected locking time, was 43.2 minutes. This yields

$$\overline{U} = 43.2/12.7 = 3.4 \text{ minutes/kiloton.}$$

Based upon this value for $\overline{U}$, a hypothetical user charge was calculated for each of the tows in the study. Table 2 summarizes the net hypothetical user charges by company. Recall that a negative charge represents payment of a positive reward to the user. The companies are sequenced by total gross tonnage moved through the lock during the observation period. Notice that the smaller users—in terms of total tonnage moved—tend to be charged considerably more per ton. A better indicator than total gross tonnage, however, is gross tonnage per lockage. Every company that averaged more than 13.9 kilotons per lockage would have incurred net negative charges, while every company that averaged less than 11.8 kilotons per lockage would have incurred net positive charges. Only four of the forty carriers fell between these two limits. Clearly there would be an incentive to move larger tows. Again, the reader should keep in mind that Table 2 represents charges for a relatively uncongested lock. At a lock with an average queue size of 2, for example, each user charge in Table 2 would be multiplied roughly by a factor of 7. Also, the charges are based on the interpretation of value, W, as total gross tonnage. If that concept is altered, the distribution and magnitude of the charges will change significantly. For example, if W were defined as the market value of the cargo, those tows carrying low-valued cargoes would be charged higher tolls.

Administration of User Charges

The regression equations developed here are a first pass at calculating expected locking times as a basis for user charges. Hopefully they demonstrate the feasibility of such an undertaking. There

Company	Number of Lockages	Gross Tonnage (kilotons)	Gross Tonnage per Lockage	Net User Charges (dollars)	User Charges per kiloton
1	24	392.3	16.3	—353.03	— 0.90
2	16	249.2	15.6	— 90.95	— 0.37
3	8	191.5	23.9	—246.51	— 1.29
4	8	104.1	13.0	— 1.78	— 0.02
5	3	87.6	29.2	—155.20	— 1.77
6	4	59.3	14.8	— 12.37	— 0.21
7	6	59.0	9.8	63.80	1.08
8	5	57.1	11.4	19.83	0.35
9	7	56.2	8.0	120.68	2.15
10	2	55.6	27.8	—107.00	— 1.92
11	6	54.4	9.1	63.86	1.17
12	8	49.4	6.2	128.05	2.59
13	2	39.0	19.5	— 40.32	— 1.03
14	3	33.4	11.1	26.21	0.79
15	4	32.5	8.1	56.04	1.72
16	3	28.4	9.5	36.31	1.28
17	3	27.7	9.2	29.15	1.05
18	2	23.6	11.8	— 4.99	— 0.21
19	2	22.6	11.3	19.89	0.88
20	2	20.1	10.0	0.49	0.02
21	1	16.5	16.5	— 9.93	— 0.60
22	1	15.7	15.7	— 7.41	— 0.47
23	2	15.5	7.7	33.37	2.16
24	1	14.2	14.2	— 0.73	— 0.05
25	1	13.9	13.9	4.72	0.34
26	2	13.8	6.9	35.61	2.58
27	1	13.3	13.3	3.33	0.25
28	2	13.2	6.6	27.61	2.10
29	1	10.2	10.2	7.82	0.77
30	1	7.5	7.5	19.93	2.65
31	1	7.0	7.0	16.83	2.41
32	1	5.7	5.7	34.24	6.00
33	1	5.6	5.6	24.45	4.39
34	1	5.0	5.0	23.85	4.73
35	2	5.0	2.5	60.98	12.26
36	1	4.9	4.9	29.74	6.04
37	1	4.8	4.8	22.97	4.79
38	2	2.8	1.4	50.17	18.17
39	1	2.2	2.2	35.16	15.98
40	1	1.3	1.3	34.85	27.26

TABLE 2
Summary of hypothetical user charges by company.

are some additional considerations requiring attention before the proposed system could be implemented. These include separate analyses of multiple lockages for locks at which they are more common, and decisions regarding the charges to be assessed on pleasure craft.

Straightforward calculation of user charges based on the regression equations developed in this study would result in higher tolls being collected at night and during windy conditions. The objectives of the user charges proposed here do not include influencing tow operators to modify their operations in such a way as to avoid using the lock at night or during windy conditions. Rather, it is hoped that they should adjust their tow configurations so that tows are not unmanageable at night and in the wind. An approach to this problem is not to let the wind and darkness variables vary with prevailing conditions (for calculating user charges), but to keep them constant at values which are the fractions of the time that it is windy and dark, respectively, from past experience. This will have the effect of adding an average amount to the charge for each lockage representing the expected added delay costs due wind and darkness over the long run. Since the incidence of short entries is beyond the control of the tow operators, a similar adjustment ought to be made to the short entry variable. This would eliminate the payment of what amounts to special rewards to tows that happen to make short entries.

Ideally, a separate locking time function would be developed for each lock in a system, and corresponding charges would be levied for the use of each. As an experimental first approach, however, one or a few of the most congested facilities could be selected for imposition of charges. Levying user charges at the bottlenecks should have the effect of rationing the use of the whole system. Also, this partial implementation would provide some experience with the use of the user charge system without requiring a full commitment to it.

Actual computation and collection of the charges would not be done at the lock. The only necessary duties to be carried out there would be recording the tow characteristics that are used in the locking time equations (horsepower, tonnage, etc.) and the identity of the towboat. Then the net user charges could be billed on a periodic basis, by company, from a central point.

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FOOTNOTES

1 Unpublished research at the Pennsylvania Transportation and Traffic Safety Center has cast serious doubt on the appropriateness of the simple queuing model with exponential service times for predicting delays at a lock.

2 The data for this study were collected in connection with the research on computer simulation of inland waterway systems which has been carried out over the past several years by the Pennsylvania Transportation and Traffic Safety Center. A general description of some of the recent work is in [2].

3 If a tow configuration is too long for the lock chamber, the towboat or one or more barges can be disconnnected from the end of the configuration and brought along side so that the lock gates can be closed. This procedure is called a setover.

4 For a short entry, the period begins when the tow begins its entry from just outside the lock gates.