Probability Model of Lockage Stalls and Interferences

HARRY H. KELEJIAN

A model of lock failures as manifested by stalls or interferences and specified in terms of a logit formulation is presented in this paper. Stalls or interferences that correspond to commercial tow and recreational vessel lockages and that result from lock hardware problems or to testing or maintaining the lock or its equipment are first considered. The expected frequency of such lock failures relative to the number of commercial tow and recreational vessel lockages is then explained. These expected frequencies can be viewed as measures of reliability or interpreted as the probability that such failures will occur on any given commercial tow or recreational vessel lockage. The qualitative results corresponding to the underlying variables are consistent with expectations. The usefulness and flexibility of the model in evaluating changes in the values of these variables is demonstrated. Among other things, this demonstration suggests that many major maintenance projects relating to lock chambers can be evaluated by their consequent effect on lock failure probabilities. It is demonstrated that the extent of the renewal of a chamber in response to major maintenance can be calculated.

The following scenario was suggested in a recent study (Charles Yoe, unpublished data). The Army Corps of Engineers operates and maintains 260 lock chambers and 536 dams at 596 sites. These structures are in various states of repair, performance, and obsolescence. Many of them are older than their original 50-year design life. Maintenance, repair, major maintenance, and replacement of these facilities are becoming increasingly necessary and increasingly costly. Furthermore, the recent inland navigation investment program, as reflected by total appropriations for general construction and operations and maintenance has declined from $689 million in fiscal year 1980 to $655 million in fiscal year 1987. After adjusting for price level differences, this 5 percent nominal decline becomes a 35 percent real decline. Continued and even increasing strain on fiscal resources is expected for the foreseeable future. Further details are given elsewhere (*1*).

As a result of increasing needs and decreasing fiscal resources to meet those needs the Corps' decision problem is how best to allocate scarce resources to operation, maintenance, repair, major maintenance, and replacement of structures on the inland waterway. In evaluating the economic impacts of many of these investment decisions, it is necessary to quantify the costs of increasingly unreliable or insufficient service at locks and/or the benefits of improving reliability or increasing capacity. This analysis of reliability generally requires an effort to quantify the probabilities of impaired lock services with and without proposed projects.

This study presents a model of lock failures as manifested by stalls or interferences. A stall is an occurrence which stops lock operation. An interference is an occurrence which slows lock operation during a lockage. For more detail see the Corps' *User's Manual for Data Analysis* (*2*).

The model considers stalls or interferences (henceforth, stalls) that correspond to commercial tow and recreational vessel lockages and that result from lock hardware problems or to testing or maintaining the lock or its equipment. It then explains the expected frequency of such lock failures relative to the number of commercial tow and recreational vessel lockages. This can be viewed as a measure of reliability. It can also be interpreted as the probability that such a failure will occur on any given commercial tow or recreational vessel lockage.

The model is specified in terms of a logit formulation. The explanatory variables relate to characteristics of the lock chambers, to the extent of major maintenance (if any), and to variables which identify the Corps of Engineer district the lock chamber is associated with. Among other things, the usefulness of the model as a tool of prediction and as an instrument for allocating major maintenance funds is demonstrated.

DATA ISSUES

The data underlying this study were taken from the U.S. Army Corps of Engineers' Lock Performance Monitoring System (PMS) data tapes, details of which are reported elsewhere (*2*). The data taken from these tapes relate to lockages at 125 lock chambers for 1981 through 1986. These lock chambers correspond to 14 Corps of Engineer districts. The 125 lock chambers were chosen from the entire list of lock chambers described in the PMS tapes because the corresponding data were of a higher quality in the sense that fewer errors were present and more complete in terms of having fewer missing observations. Data relating to an individual lockage at these 125 chambers were not used unless observations on all of the relevant variables were available.

A description of the 125 lock chambers is contained in Kelejian (*3*). The 14 districts corresponding to these 125 lock chambers are listed in Table 1. It became convenient to describe each district by a number (i.e., District 1, District 2, etc.). These district numbers are also listed in Table 1.

The data file used to estimate the model contained two types of PMS data. The first relates to individual lockages. The second relates to calendar year sums (e.g., total stall time). The individual lockage data represents a one-out-of-twelve sample from the original PMS data tape. The annual sums are based on a 100 percent sample.

Department of Economics, University of Maryland College Park, Md. 20742.

TABLE 1 DISTRICTS AND THEIR ASSOCIATED NUMBERS

District	Associated Number	District	Associated Number
Pittsburgh	1	Huntington	8
Mobile	2	St. Louis	9
Nashville	3	St. Paul	10
Walla Walla	4	Little Rock	11
Wilmington	5	Tulsa	12
Louisville	6	Vicksburg	13
Rock Island	7	Seattle	14

The data file also contained information pertinent to lock chambers described in (*1*). Among other things, this information relates to the age of lock chambers and the cost of completed major maintenance projects. The cost of the maintenance projects were given in current dollars. These data were converted into constant 1982 dollars by deflating by the Construction Cost Index. Data on this index were supplied by Corps personnel. A more complete discussion of the data and their original source is given in Kelejian (*3*).

LOGIT MODEL OF STALL PROBABILITY

Basic Formulation: An Overview

There are typically many lockages that take place during a year at a given lock chamber. Corresponding to each of these lockages there is a probability that a stall will occur.

Let P_{it} be the probability that a commercial tow or recreational vessel lockage taking place during the tth year at lock chamber i results in a stall. Note that P_{it} is indexed to vary from lock chamber to lock chamber (over i) and from year to year, but not from one lockage to another within a year at a given chamber.

The assumption that the probability of a stall is the same for all lockages taking place within a year at a given chamber is clearly an approximation. For example, a lock chamber ages continuously and, therefore, from lockage to lockage. However, one might view the effective aging of a chamber as being very gradual and therefore reasonably well approximated by the age of the chamber as measured in years. If so, and if the other relevant factors change gradually from lockage to lockage, the assumption of a constant stall probability within a year at a given chamber is reasonable.

Let X_{it} be a vector of variables corresponding to the ith lock at time t, which might be taken to explain P_{it}. Let B be a corresponding vector of parameters such that

$$I_{it} = X_{it}B \tag{1}$$

can be taken to be an index determining P_{it}. Then, in the logit formulation P_{it} is related to I_{it} as

$$P_{it} = EXP(I_{it})/[1+EXP(I_{it})] \tag{2}$$

It is not difficult to show that P_{it} lies between zero and unity for all possible values of the index I_{it}. In addition $(dP_{it}/dI_{it}) > 0$ for all I_{it} so that the larger is the index I_{it} the higher is P_{it}. Therefore, variables that are components of I_{it} that increase P_{it} should have positive weights; negative weights correspond to variables which decrease P_{it}.

Details of the Index

In this study, the index relating to the ith chamber at time t, namely I_{it}, is

$$\begin{aligned} I_{it} = {} & b_0 + b_1\,\mathrm{Age}_{it} + b_2\,\mathrm{MPT}_{it-1} + b_3\,\mathrm{ICE}_{it-1} \\ & + b_4\,\mathrm{AIT}_{it} + b_5\,\mathrm{Maint}_{it} + b_6\,\mathrm{ST}_{it-1} \\ & + b_7\,\mathrm{SF}_{it-1} + a_1\,\mathrm{DD1}_i + a_2\,\mathrm{DD3}_i \\ & + a_3\,\mathrm{DD7}_i + a_4\,\mathrm{DD8}_i + a_5\,\mathrm{DD10}_i \end{aligned} \tag{3}$$

where $b_0, \ldots, b_7, a_1, \ldots a_5$ are parameters to be estimated and all of the remaining terms on the right hand side of expression 3 are explanatory variables whose definitions are given in Table 2.

In expression 3 Maint_{it} represents the extent of a major maintenance, if any. It was formulated as

$$\mathrm{Maint}_{it} = 1 - \mathrm{EXP}(-\mathrm{cost}_{it}) \tag{4}$$

where $\mathrm{cost}_{it} = 0$ if, up through time t, lock chamber i did not have major maintenance; if such maintenance did take place, cost_{it} is its 1982 dollar cost. The specification in expression 4 implies that $\mathrm{Maint}_{it} = 0$ if $\mathrm{cost}_{it} = 0$. This is the case in which a major maintenance did not take place. If it did take place, $\mathrm{cost}_{it} > 0$ and so $\mathrm{Maint}_{it} > 0$, and the more extensive it was (the higher is cost_{it}), the higher is Maint_{it}. In this sense, the variable Maint_{it} is a positive measure of the extent of a major maintenance.

A number of other variables were also considered but found not to be statistically significant. Results relating to these other variables can be found elsewhere (*3*).

Since age, other things being equal, is associated with lock deterioration, one would expect $b_1 > 0$. Similarly, higher values of mean processing time may be indicative of equipment which is not in top operating condition and so one ex-

TABLE 2 DEFINITIONS OF EXPLANATORY VARIABLES

Variable	Definition
Age_{it}	The age of lock chamber i at time t
MPT_{it-1}	Mean processing time of lock chamber i at time t-1.
ICE_{it-1}	The number of ice days at lock chamber i during year t -1.
AIT_{it}	Average idle time at lock chamber i during year t.
Maint_{it}	A variable describing the real dollar value of a major maintenance (if any) of lock chamber i.
ST_{it-1}	Total stall time due to testing or maintenance of lock chamber i, or its equipment during year t-1.
SF_{it-1}	The stall frequency at lock chamber i at year t-1. The stall frequency is the ratio of stalls to lockages.
DDJ_i	A dummy variable which is unity if the ith lock chamber is in District J, and zero otherwise.

pects $b_2 > 0$. One would also expect $b_3 > 0$ and $b_7 > 0$ because ice formation accelerates decay and a previous stall frequency is indicated of general conditions, which are not radically different from one year to the next.

One would expect $b_4 < 0$. The reason for this is that idle time could be used to perform minor maintenance and repair, and so on. Thus, higher values of AIT_{it} should lower the index, I_{it}, and hence lower the probability of a stall. Similarly, for very evident reasons one expects $b_5 < 0$. On a somewhat more moderated scale, one would also expect $b_6 < 0$. That is, the more testing and maintenance, and corresponding minor repairs, of the lock chamber and its equipment in one year, the better the condition (other things equal) of that chamber in the following year. For the readers' convenience, the sign expectations relating to the coefficients of expression 3 are summarized in expression 5 as follows:

$$b_1 > 0,\ b_2 > 0,\ b_3 > 0,\ b_7 > 0;$$
$$b_4 < 0,\ b_5 < 0,\ b_6 < 0 \tag{5}$$

The coefficient of a dummy variable in expression 3 indicates whether or not the stall probability corresponding to that district is higher (if positive) or lower (if negative) than in the districts not represented in expression 3 after the effects of the other variables in the index have been accounted for. Conceptual arguments do not suggest the signs of these coefficients.

The Issue of Estimation

Assume that P_{it} is neither zero nor unity. Then from expression 2 it can be shown that $P_{it}/(1 - P_{it}) = \mathrm{EXP}(I_{it})$ so that

$$\log_e (P_{it}/(1 - P_{it})) = I_{it} \tag{6}$$

The result in expression 6 is useful in that it leads to a relatively simple procedure for estimating the parameters determining the index I_{it} as given in expression 3. For example, let SF_{it} be the number of stalls at lock chamber i during year t. Then SF_{it} may be expressed as $SF_{it} = S_{it}/L_{it}$ where S_{it} is the number of stalls of the type being considered at lock chamber i during year t, and L_{it} is the corresponding number of lockages. Because the probability of a stall on any given lockage is assumed to be the same for all lockages during the year at a given chamber, SF_{it} can be taken as an estimate of P_{it}. The reason for this is that SF_{it} can be viewed as the ratio of the number of successes (stalls) to the number of trials (lockages).

For ease of presentation, suppose that SF_{it} is neither zero nor unity. Then let

$$u_{it} = \log_e[SF_{it}/(1 - SF_{it})] - \log_e(P_{it}/(1 - P_{it})) \tag{7}$$

so that

$$\log_e(SF_{it}/(1 - SF_{it})) = \log_e[P_{it}/(1 - P_{it})] + u_{it} \tag{8}$$

The first term on the right hand side of expression 8 is equal to the index I_{it} via expression 6. Replacing this index by its expression in expression 3 yields

$$\begin{aligned}\log_e(SF_{it}/(1 - SF_{it})) = {} & b_0 + b_1\,Age_{it} + b_2\,MPT_{it-1} \\ & + b_3\,ICE_{it-1} + b_4\,AIT_{it} \\ & + b_5\,Maint_{it} + b_6\,ST_{it-1} \\ & + b_7\,SF_{it-1} + a_1\,DD1_i \\ & + a_2\,DD3_i + a_3\,DD7_i \\ & + a_4\,DD8_i + a_5\,DD10_i \\ & + uit\end{aligned} \tag{9}$$

It can be shown that if the number of lockages during year t at chamber i is "large", the term u_{it} has a mean and variance which are approximated by the following expression

$$Eu_{it} = 0,\ \mathrm{Var}(u_{it}) = [L_{it}\,P_{it}\,(1 - P_{it})]^{-1} \tag{10}$$

The implication of expression 10 is that expression 9 can be viewed as a regression model having a heteroskedastic error term. Because the variance of u_{it} involves P_{it}, which is not known, the appropriate estimation procedure is a feasible form of generalized least squares that is based on an estimated value of the variance of u_{it}; this estimated value would be based on an estimate of P_{it}.

In implementing this procedure for the PMS data, two complications arose. The first is that for certain years at certain lock chambers SF_{it} is zero. In these cases, the dependent variable in expression 9 is not defined. The second complication is that in certain years the number of lockages at certain lock chambers, L_{it}, is small. In these cases the large sample approximations in expression 10 are not appropriate and so, therefore, neither is the model in expression 9.

The discussion in Kelejian (*3*) suggests that if the number of lockages for each chamber in each time period is large, the first of these problems can be overcome by replacing the dependent variable in expression 9 by

$$Y_{it} = \log_e\{(SF_{it} + (2L_{it})^{-1})/[1 - SF_{it} + (2L_{it})^{-1}]\} \tag{11}$$

The reason for this is that Y_{it} is defined for all values of SF_{it} in the interval $0 \le SF_{it} \le 1$; furthermore, under reasonable conditions, Y_{it} and $\log_e[SF_{it}/(1 - SF_{it})]$ converge in probability as L_{it} increases beyond limit.

The procedure that was followed in this study is on the basis of a variant of expression 11 and is described in steps detailed in the following. Note that the estimators so obtained are asymptotically efficient because they are equivalent to the corresponding maximum likelihood estimators.

Details of the Procedure

Step 1

Some restriction on the original PMS sample was necessary because the number of lockages in certain years at certain chambers (henceforth, cells) was very small (e.g., as low as

4). The restriction that was imposed was that only data relating to cells for which $L_{it} > Q$ were considered in the estimation procedure. Q was taken as the largest multiple of 50 such that at least ⅔ of the original cells remain in the revised sample. It turned out that $Q = 150$, and the smallest value of L_{it}, say MIN, satisfying $L_{it} > 150$ was MIN = 151. The cut off value of 150 is reasonably large, but not overly restrictive in terms of the scope of the revised sample. For example, the condition $L_{it} > 150$ only eliminates reference to 32 lock chambers, thus leaving 93 such chambers in the sample. The number of cells in the revised sample is 499 which is roughly 67 percent of the original number of cells.

Step 2

Because the number of lockages in each cell of the sample constructed in Step 1 varied from 151 to 1,355, a modified form of Y_{it} in expression 11 was considered; namely

$$^{*}Y_{it} = \log_e\{SF_{it} + (2 \times \text{MIN})^{-1}/[1 - SF_{it} + (2 \times \text{MIN})^{-1}]\} \quad (12)$$

$^{*}Y_{it}$ was considered for two reasons. First, unlike Y_{it}, $^{*}Y_{it}$ does not induce an artificial variation in the dependent variable, which is due solely to the wide range of values of the number of lockages. Second, there is no penalty in terms of asymptotic efficiency in the use of $^{*}Y_{it}$ as compared with Y_{it} because $^{*}Y_{it}$ and Y_{it} converge as L_{it} increases beyond limit.

Step 3

Taking $^{*}Y_{it}$ as the dependent variable, expression 9 was first estimated by least squares. This provided a consistent estimate of the index I_{it}, say IE_{it}, for each of the 499 cells of the sample.

Step 4

The estimated index, IE_{it}, was then used to obtain an initial but consistent estimate, PE_{it}, of the stall probability P_{it} for each of the 499 cells

$$PE_{it} = \text{EXP}(IE_{it})/[1 + \text{EXP}(IE_{it})] \quad (13)$$

Correspondingly, the variance of u_{it} as given in expression 10 was then estimated as

$$\hat{\text{var}}(u_{it}) = [L_{it}\, PE_{it}(1 - PE_{it})]^{-1} \quad (14)$$

Step 5

Finally, with $^{*}Y_{it}$ in expression 12 taken as the dependent variable, expression 9 was reestimated by least squares after deflating each variable by the square root of $\hat{\text{var}}(u_{it})$ in expression 14. This is the feasible generalized least squares procedure.

Let the estimates of the parameters of expression 9 obtained in Step 5 be $b_0, \ldots, b_7, a_1, \ldots, a_5$. Then, because these estimates are based on a consistent and efficient procedure, the final estimate of the stall probability for the ith lock chamber at time t was taken as

$$\hat{P}_{it} = \text{EXP}(\hat{I}_{it})/[1 + \text{EXP}(\hat{I}_{it})] \quad (15)$$

where

$$\begin{aligned}\hat{I}_{it} = {} & \hat{b}_0 + \hat{b}_1\, \text{Age}_{it} + \hat{b}_2\, MPT_{it-1} \\ & + \hat{b}_3\, ICE_{it-1} + \hat{b}_4\, AIT_{it} + \hat{b}_5\, \text{Maint}_{it} \\ & + \hat{b}_6\, ST_{it-1} + \hat{b}_7\, SF_{it-1} + \hat{a}_1\, DD1_i \\ & + \hat{a}_2\, DD3_i + \hat{a}_3\, DD7_i \\ & + \hat{a}_4\, DD8_i + \hat{a}_5\, DD10_i \end{aligned} \quad (16)$$

EMPIRICAL RESULTS

Results Relating to the Probability Model

The empirical results obtained by the procedure described in Steps 1 through 5 are given in expression 17. The figures in parentheses beneath the parameter estimates are the absolute values of the corresponding t-ratios. $\hat{r}^2$ is the square of the correlation coefficient between the observed stall frequency, SF_{it}, and its model predicted value $\hat{P}_{it}$ (see expression 15).

$$\begin{aligned}\hat{I}_{it} = {} & -5.956 + .0102\, \text{Age}_{it} + .0071\, MPT_{it-1} \\ & \quad (41.31)\ (5.130) \qquad (2.997) \\ & + .0066\, ICE_{it-1} - .0899\, AIT_{it} \\ & \quad (4.458) \qquad (1.599) \\ & - 1.197\, \text{Maint}_{it} - .0048\, ST_{it-1} + 23.09\, SF_{it-1} \\ & \quad (1.818) \qquad (3.997) \qquad (8.881) \\ & - .2422\, DD1_i + .8219\, DD3_i - .2121\, DD7_i \\ & \quad (2.651) \qquad (7.292) \qquad (2.716) \\ & + .3416\, DD8_i - .3167\, DD10_i\ ;\ \hat{r}^2 = .366 \\ & \quad (3.888) \qquad (3.093) \end{aligned} \quad (17)$$

The units of measurement underlying expression 17 are: Age is in years; MPT is in minutes per lockage; ICE is in days per year; AIT is in hundreds of minutes; Maint = 1 − EXP(−C) where C is in hundreds of millions of 1982 dollars; SF is the observed stall frequency; ST is in thousands of minutes.

The value of $\hat{r}^2 = .366$ suggests that, overall, the model offers a reasonable explanation of stall probabilities associated with individual lockages. In interpreting this figure one should note that stall probabilities, as measured by stall frequencies, vary widely across lock chambers and time, and therefore are not easily explained. For example, the R^2 statistic (over the sample underlying expression 17) between the annual stall frequency at a lock chamber, and its age is only .015. More extensive results along these lines are given in Kelejian (*3*). Nevertheless, $\hat{r}^2 = .366$ does imply that 63.4

percent of the variation in stall probabilities is unexplained, and so further studies along these lines could be of value.

On a qualitative level, note that the sign of each estimate given in expression 17 is consistent with prior expectations as described in expression 5. Also note that each of these estimates, if considered alone, is statistically significant at the one-tail .05 level with the sole exception of the coefficient of the average idle time variable. The sign of this coefficient is negative, as anticipated, but its one-tail significance level is .0548. Because strong prior Bayesian beliefs suggest that average idle time is important, and because the one-tail significance level is quite close to .05, the idle time variable was not dropped from the model.

There are no prior sign expectations for the coefficients of the district dummy variables and therefore a test of significance would be determined by a two-tail procedure; clearly the results in expression 17 imply that if these variables are considered individually, each and every one of them would be statistically significant at the two-tail .05 level. The joint significance of the district dummy variables is confirmed by the corresponding F test, namely $\hat{F} = 15.18 > F(.95/5,486) = 2.23$.

Districts that are represented in the sample but for which there are no dummy variables in expression 17 are Mobile, Walla Walla, Louisville, St. Louis, Little Rock, and Seattle. Therefore, if a coefficient corresponding to a dummy variable in expression 17 is positive, the stall probability in the corresponding district is higher than in the excluded 5 districts for given and equal values of the other variables in expression 17. Districts 3 and 8 (Nashville and Huntington) fall into this category. Similarly, if such a coefficient in expression 17 is negative, the stall probability in the corresponding district is lower than in the excluded five districts for given and equal values of the other variables in expression 17. Districts 1, 7, and 10 (Pittsburgh, Rock Island, and St. Paul) fall into this category.

One measure of the magnitude of these district effects is the consequent change in the stall probability. For example, in District 1, (Pittsburgh), the sample mean of the index in expression 17 is $I_1 = -5.447$; the corresponding stall probability is $\hat{P}_1 = .00429$. If District 1 were typical, as say described by the five excluded districts, the coefficient of its dummy variable would be zero. In this case, the sample mean of its index would be $IE_1 = -5.2048$, and the corresponding stall probability would be $PE_1 = .00546$. Therefore, whatever the special effects associated with District 1, they lead to a reduction of .00117 in the stall probability. Since these probabilities are small, this small change represents a large percentage change. Specifically, taking $(\hat{P}_1 + PE_1)/2$ as the base, the district effect (at the sample mean) associated with District 1 leads to a 24 percent reduction in the stall probability. Corresponding figures for Districts 3, 7, 8, and 10 are given in Table 3. Consistent with the results for District 1, a glance at the table suggests that these districts also have effects that are important in percentage terms concerning stall probabilities.

Further results relating to the empirical model are given in Table 4. Specifically, the table gives the stall probability corresponding to sample mean values of the variables determining the index in expression 17. This figure, namely .0056, can be interpreted as the probability that the average or typical chamber will have a stall on a given lockage. Conversely, the probability that a stall will not take place at such a typical chamber is .9944. This probability is so high that even if a reasonably large number of lockages take place over a given period of time, the probability that a stall will not occur during that time could remain non-negligible.

TABLE 3 DISTRICT EFFECTS AT SAMPLE MEAN VALUES

District	Probability Changes	Probability Change (%)
Nashville	.0084	77
Huntington	.0041	50
Rock Island	-.0013	-21
Pittsburgh	-.0012	-24
St. Paul	-.0043	-31

TABLE 4 STALL PROBABILITIES AND ELASTICITIES

Stall Probability			Elasticities					
Lowest	Highest	Mean	AGE	MPT	ICE	AIT	MAINT	ST
.0023	.0374	.0056	.386	.287	.106	-.079	-.009	-.027

The table also gives the lowest and highest values of the stall probability based on the values of the index over the chambers and years in the sample. These figures, namely .0023 and .0374, correspond, respectively, to Chamber 1 of the Old River Lock on the Mississippi River (ORLMR) for 1982, and Chamber 1 at the Gallipolis Locks and Dam on the Ohio River (GLDOR) in 1986. These figures differ by more than a factor of ten. As an indication of time variation, the stall probability at the ORLMR for 1986 is .0025; the stall probability is .0096 for 1982 at the GLDOR. Among other things, these results suggest that stall potentials, as measured by stall probabilities, vary considerably from chamber to chamber, as well as over time. Given the results in expression 17, and the model in expression 15, the stall probability can be calculated for any chamber, for any year, as long as the values of the independent variables are known. Clearly, the calculation of such stall probabilities should be helpful in allocating scarce major maintenance funds.

Table 4 also gives estimates of the elasticities of the stall probability with respect to six of the index variables, again at sample mean values. These elasticities were calculated as

$$\mathrm{dlog_e}(P_{it})/\mathrm{dlog_e}(Z^j_{it}) = {}^*Z^j\,\hat{b}_j/(1 + \mathrm{EXP}({}^*I)),\ j = 1, \ldots, 6 \qquad (18)$$

where Z^j_{it} is the jth explanatory variable (excluding the intercept) in expression 16; $\hat{b}_j$ is its corresponding estimated coefficient given in expression 17, and ${}^*Z^j$ and ${}^*I$ are the sample averages of Z^j_{it} and $\hat{I}_{it}$.

The elasticities in Table 4 indicate the relative sensitivity of the stall probability with respect to a given percentage change in the value of the corresponding explanatory variable at sample mean values. For example, the elasticity with respect to the age variable is .386. This figure suggests that, at sample mean values, a 1 percent (a 10 percent) increase in

the age of a chamber would (other things equal) lead to a .386 percent (a 3.86 percent) increase in the stall probability. Among other things, the figures in Table 4 suggest that stall probabilities for a typical lock chamber are more sensitive to small percentage changes in the age of the chamber, than to small percentage changes in the other variables of the index.

Figures 1 through 4 give further insights concerning the probability model. Figure 1 describes the relationship between the stall probability and the age of the chamber at sample mean values of the other variables involved in the index. Again, since these sample mean values could be viewed as typical, Figure 1 essentially describes a time profile of a stall probability for a typical chamber. As the chamber ages, the probability increases. Calculations based on the diagram suggest that this probability is roughly 20 percent higher when the chamber is 60 as compared with 40 years old.

Figure 2 describes the relationship between the stall probability and the extent of major maintenance, as measured by its 1982 dollar cost, again at sample mean values. As expected, the more extensive the maintenance, the lower the probability. Calculations performed on the basis of the diagram suggest that, for a typical chamber, a 30 million 1982 dollar major maintenance reduces the stall probability by, roughly, 35 percent. Similarly, a 20 million 1982 dollar major maintenance reduces this probability by, roughly, 20 percent. Figure 3 describes the relationship between the stall probability and mean processing time, at sample mean values. The figure suggests that, for the typical chamber, stall probabilities are roughly 45 percent more likely when the mean processing time is 100 minutes per lockage than when it is 40 minutes per lockage.

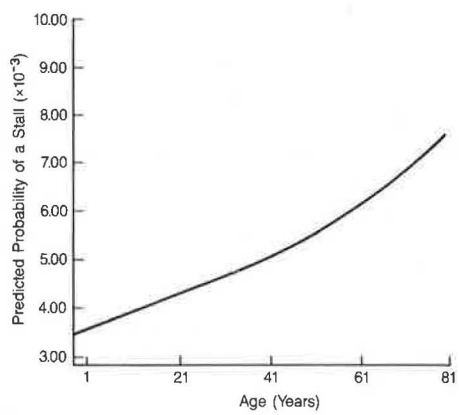

FIGURE 1 Effect of age on the predicted probability of a stall.

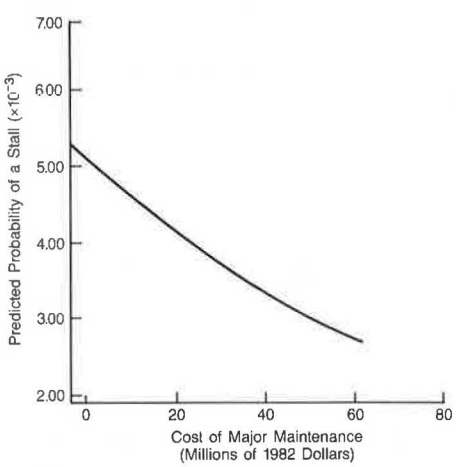

FIGURE 2 Effect of major maintenance on the predicted probability of a stall.

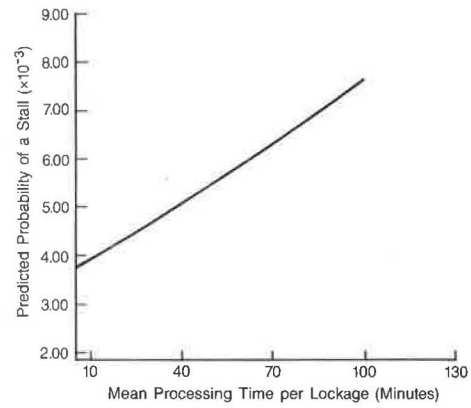

FIGURE 3 Effect of mean processing time on the predicted probability of a stall.

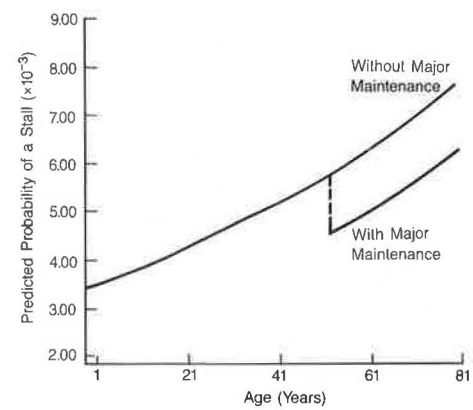

FIGURE 4 Effect of major maintenance on the effective age of a lock.

Finally, Figure 4 describes how major maintenance reduces the effective age of a chamber. The upper curve in that figure outlines the relationship between the stall probability and the age of the chamber if there is no major maintenance and the other relevant variables are equal to their sample means. The lower curve describes the change in the probabilities outlined by the upper curve if a 20 million 1982 dollar major maintenance were undertaken when the chamber is 50 years old. A 20 million 1982 dollar major maintenance was considered in this illustration because it is, roughly, the average cost of such maintenance completed during or before 1987.

If the lower curve, at any age exceeding 50 years, is horizontally extended to the left, it will intersect the upper curve corresponding to an age which is, roughly, between 20 and 25 years earlier. The suggestion is that, for the typical chamber, a 20 million 1982 dollar major maintenance, undertaken

when the chamber is 50 years old, reduces the effective age of that chamber by, roughly, 20 to 25 years.

The reduction in the effective age of a particular chamber corresponding to a proposed major maintenance of a certain dollar magnitude can be done in a similar, but more exact way. Specifically, let $\hat{I}_{it}^{B}$ be the value of the index in expression 17 for lock Chamber i at time t before the major maintenance. Let $\hat{I}_{it}^{A}$ be the value of that index after the major maintenance. Because the index is reduced if major maintenance is undertaken, $\hat{I}_{it}^{A} < \hat{I}_{it}^{B}$ and so the "after" stall probability would be less than the "before" stall probability. The effective age of the chamber after the maintenance is the value of the age variable that equates the before index, $\hat{I}_{it}^{B}$, to the after index, $\hat{I}_{it}^{A}$. That is, let $^{-}I_{it}^{B}$ be the net sum of the right hand side of expression 17, before the major maintenance, with the exception of the age variable: $\hat{I}_{it}^{B} = {}^{-}I_{it}^{B} + .0102 * \mathrm{Age}_{it}$. Then the effective age of chamber i at time t is Age_{it}^{E} where

$$\mathrm{Age}_{it}^{E} = (\hat{I}_{it}^{A} - {}^{-}I_{it}^{B})/.0102 \tag{19}$$

The reduction in the effective age is therefore $\mathrm{Age}_{it} - \mathrm{Age}_{it}^{E}$.

Suggestions Concerning Further Calculations

Calculations concerning chambers in districts which are not in the sample require an assumption concerning the district effect as described in the index (see expression 17). One possibility is that Corps personnel could use expert opinion to determine the district effect; given this, stall probabilities could be evaluated for any chamber of interest, for any year, as long as the values of the variables determining the index in expression 17 are known. The magnitude of the district effects of Districts 1, 3, 7, 8, and 10 should offer guidance if this route is taken.

Another possibility is to assume that the district effect corresponding to a chamber of interest, which is not in the sample, is equal to the average of the effects of those for Districts 1, 3, 7, 8, and 10. Still another possibility is to consider worst and best case scenarios. For example, the district effect could be taken to be equal to that of District 3, which would be a worst case scenario. Given this, a policy could be evaluated in terms of its effect on the stall probability. The district effect could then be taken to be equal to that of District 10, which would be a best case scenario. Given this, the policy could again be evaluated. Comparisons between the two cases should be of interest.

SUMMARY AND CONCLUSIONS

A probability model of lock failures has been presented. The qualitative results corresponding to the underlying variables are consistent with expectations. The usefulness and flexibility of the model in evaluating changes in the values of these variables has been demonstrated. Among other things, this demonstration suggests that many major maintenance projects relating to lock chambers can be evaluated in terms of their consequent effect on lock failure probabilities. It was also demonstrated that the extent of the renewal of a chamber in response to major maintenance can be calculated.

ACKNOWLEDGMENTS

I would like to thank Craig Hiemstra, Michael Wagner, and Charles Yoe for useful discussions and comments on an earlier version of this paper. I would also like to thank Craig Hiemstra and Michael Wagner for help at various computer-related stages of this study. This study would not have been possible without the support of George Antle of the Army Corps and I am grateful for that support. I would also like to thank Yvonne Sisler who cheerfully typed, and retyped, the various drafts of this paper. Finally, I would like to thank the Computer Science Center at the University of Maryland for its generous support of computer time.

REFERENCES

1. Institute for Water Resources. *The 1988 Inland Waterway Review*. Report 88-R-7. U.S. Army Corps of Engineers, 1988.
2. Institute for Water Resources. *Lock Performance Monitoring System: User's Manual for Data Analysis*. User Manual 85-UM-2. U.S. Army Corps of Engineers, 1985.
3. H. H. Kelejian. *A Study of Lockage Stall Probabilities*. Report to Institute for Water Resources, Fort Belvoir. U.S. Army Corps of Engineers, 1989.
4. G. S. Maddala. *Limited Dependent and Qualitative Variables in Econometrics*. Cambridge University Press, New York, 1983.

The views expressed in this study are solely those of the author, and are not necessarily those of the Army Corps.

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