Application of the Microeconomic Concepts of Production and Cost Functions to the Analysis of Highway Maintenance Efficiency

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Annual national highway maintenance expenditures increased from $6 billion in 1975 to $15 billion in 1983 and are still increasing each year. Maintenance needs for the highway system are increasing as well, but the funds available for highway maintenance have been decreasing in real terms. The result is a growing gap between highway maintenance needs and available resources and an urgent need to improve the productivity and cost efficiency of highway maintenance operations. In this paper, a microeconomic-based approach for analyzing the allocation of aggregate resources (labor and equipment) and the characteristics of production in highway maintenance operations is presented. The proposed methodologies allow determination of the maximum quantity of any given maintenance activity that can be accomplished with given quantities of labor and equipment, identification of basic characteristics of the production process of a given maintenance activity, determination of the optimal (cost minimizing) combination of labor and equipment needed to perform a given level of maintenance activity, and estimation of the minimum cost of accomplishing any given amount of a specified maintenance activity. The validity of the results and the practical usefulness of the proposed methodology are limited, due primarily to data limitations. Recommendations regarding the needed highway maintenance data base are discussed. The microeconomic concepts of production and cost functions seem to provide a promising theoretical basis for analyzing the productivity and cost efficiency of highway maintenance operations.

National annual highway maintenance expenditures increased from $6 billion in 1975 to $15 billion in 1983 (*1*), and are still increasing each year. Along with the increase in unit maintenance cost, the maintenance needs for the highway system are increasing as well. Growing lane-miles, more complex highway appurtenance, and aging contribute to greater maintenance needs. At the same time, the funds available for highway maintenance have been decreasing in real terms. Highway user revenues from gasoline tax decreased by 7 percent between 1975 and 1979 (*2*). These changes have resulted in a growing gap between highway maintenance needs and available resources, and have led to an urgent need to improve the productivity and cost-efficiency of highway maintenance operations.

No previous study has attempted to analyze the allocation of resources and productivity in highway maintenance operations based on microeconomic theory. Several studies have previously been undertaken to identify highway maintenance research needs and/or to empirically address maintenance productivity. The FHWA has sponsored comprehensive research projects in all aspects of highway maintenance (*2,3*). Recently, the Strategic Highway Research Program (SHRP) identified highway maintenance as one of the six main research areas (*4*). Two early studies conducted for the Louisiana Department of Highways (*5,6*) and the City of Los Angeles (*7*) investigated the relationship between productivity and crew size. A value engineering study on bituminous patching was conducted by a group of four state DOTs to determine the unit cost associated with various combinations of labor, equipment, and materials (*8*). More recently, Sanderson and Sinha (*9*) proposed a monitoring procedure for identifying the high unit cost of some maintenance activities. Several studies attempted to develop regression models for estimating maintenance cost. The early models included explanatory variables such as traffic volume, surface width, and surface condition (*10*). McNeil and Hendrickson (*11*) proposed linear and nonlinear models that represented pavement age and equivalent axle load applications. Sharaf et al. (*12*) proposed a model in which the explanatory variables were equivalent axle load applications and climate zone.

The main objective of this study is to present a microeconomic-based approach for analyzing the allocation of aggregate resources (labor and equipment) and the characteristics of production in highway maintenance operations. The focus is on proposing a methodology based on the microeconomic concepts of production and cost functions that makes it possible to

1. Determine the maximum quantity of any given maintenance activity that can be accomplished with given quantities of labor and equipment;
2. Identify basic characteristic of the production process of a given maintenance activity;
3. Determine the optimal (cost-minimizing) combination of labor and equipment needed to perform a given level of maintenance activity; and
4. Estimate the minimum cost of accomplishing any given amount of a specified maintenance activity.

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It should be emphasized that the focus of this study is on proposing a methodology, not on providing accurate empirical results.

At this time, the validity of the results and the practical usefulness of the proposed methodology are limited primarily because of data limitations. These limitations are identified and stated in the paper. Specific suggestions regarding the needed database for highway maintenance are discussed in the last section. However, an effort is made to show that the microeconomic theory of production and cost functions provides a promising theoretical basis for analyzing the productivity and cost efficiency of highway maintenance operations.

The next section provides a brief overview of the microeconomic concepts of production and cost functions in the context of highway maintenance operations. Next is an analysis that applies these concepts to real-life highway maintenance data. The final section summarizes the conclusion of the study and discusses its major recommendations.

MICROECONOMIC CONCEPTS

A production function represents the relationship between quantities of input factors (production factors) and the maximum level of output that can be produced, given those quantities. Common output measures of highway maintenance activities are tons of materials applied or lane-miles of highway maintenance. A maintenance activity can be viewed as a production process in which raw material is being "transformed" into material in place. Consequently, in applying the concept of production function to highway maintenance activities, material is not viewed as a production factor. The input factor in highway maintenance operations can be classified into two aggregate categories: labor and equipment. Quantities of labor and equipment inputs are commonly measured in man-hours and equipment-hours, respectively.

The production function of any given highway maintenance activity may be written as follows:

$$Z = f(L,E) = a_0 L^{a_1} E^{a_2} \tag{1}$$

where

Z = quantity of output,
L = quantity of labor,
E = quantity of equipment, and
a_0, a_1, a_2 = parameters.

Equation 1 provides a common form of a production function known as a Cobb-Douglas function. Other common forms are presented and analyzed in the next section.

Based on a production function, several characteristics of the production process can be derived. The *marginal product* (MP) of any given input factor is the change in output from a unit change in the quantity of that input factor, keeping the quantities of all other input factors unchanged. The *rate of technical substitution* (RTS) between two input factors is the amount by which one input factor can be reduced when there is a unit increase in the amount of the other factor such that the output quantity is kept unchanged. The return to scale represents the behavior of output quantity relative to a proportional change in the quantities of all input factors. Consider a proportional change by a factor K_1 in the quantities of all input factors, resulting in a change of output quantity by a factor K_2. Depending on the relationship between K_1 and K_2, the return to scale may be decreasing ($K_2 < K_1$), constant ($K_2 = K_1$), or increasing ($K_2 > K_1$). As is shown in the next section, these characteristics of the production process may provide important guidelines for the management of highway maintenance operations. Assuming that the prices of labor and equipment inputs remain constant during the analysis period, and are independent of the quantities used, the total expenditures on labor and equipment can be expressed as

$$C = h_L \cdot L + h_E \cdot E \tag{2}$$

where

C = total expenditures on labor and equipment and
h_L, h_E = unit prices of labor and equipment.

A *cost function* provides the minimum cost of producing any given level of output. The *average cost* is the ratio of total cost and output quantity. A cost function can be derived by minimizing Equation 2 subject to the constraint on production, as specified by the production function of Equation 1. This constitutes a constraint minimization problem that can be solved using the method of Lagrange multipliers, as illustrated below:

$$A = h_L \cdot L + h_E \cdot E - \lambda(a_0 \cdot L^{a_1} \cdot E^{a_2} - Z) \tag{3}$$

where A is the "Lagrangian" and is known as the Lagrange multiplier. The first-order conditions for the Lagrangian of Equation 3 result in the following set of simultaneous equations:

$$\frac{\partial A}{\partial L} = h_L + \frac{\lambda^{a_1}}{L} \cdot Z = 0 \tag{4a}$$

$$\frac{\partial A}{\partial E} = h_E + \frac{\lambda^{a_2}}{E} \cdot Z = 0 \tag{4b}$$

$$\frac{\partial A}{\partial \lambda} = a_0 L^{a_1} E^{a_2} - Z = 0 \tag{4c}$$

Solving the simultaneous Equations 4a through 4c provides the optimal (minimum cost) quantities of labor and equipment inputs (L^*, E^*) needed to produce a given quantity of output Z.

$$L^* = a_0^{-1/p} a_1^{a2/p} a_2^{-a2/p} h_L^{-a2/p} h_E^{a2/p} \cdot Z^{1/p} = \alpha \cdot Z^{1/p} \tag{5a}$$

$$E^* = a_0^{-1/p} a_1^{-a1/p} a_2^{a1/p} h_L^{a1/p} h_E^{-a1/p} \cdot Z^{1/p} = \beta \cdot Z^{1/p} \tag{5b}$$

where $p = a_1 + a_2$, and α, β are constants, as implied by Equations 5a and 5b, respectively. Substituting the optimal quantities of labor (L^*) and equipment (E^*) in the expenditures, Equation 2 yields the cost function shown below:

$$TC(Z) = p \cdot a_0^{-1/p} (h_L/a_1)^{a1/p} (h_E/a_2)^{a2/p} \cdot Z^{1/p} = \gamma \cdot Z^{1/p} \tag{6}$$

where

$TC(Z)$ = total cost of producing output quantity Z and
γ = constant.

Dividing the total cost by the quantity of output provides the average cost (unit cost):

$$AC(Z) = \frac{TC(Z)}{Z} = \gamma \cdot Z^{(1/p - 1)}$$

where $AC(Z)$ = average cost (unit cost) at output level Z.

ANALYSIS

The practical application of the microeconomic theory of production and cost functions involves two types of difficulties: (1) difficulties associated with the availability of adequate data and (2) difficulties related to the assumptions of the theory. The difficulties associated with the availability of adequate data are acute in pavement maintenance operations where little previous work has been done in applying microeconomic analysis methods. The estimation of a production function such as that discussed in the previous section requires homogeneous cross-sectional data on total output level (ton, lane-miles, etc.) and the associated aggregate quantities of labor and equipment, for individual maintenance activities. At this time, there is a little uniformity among state highway agencies in the collection of pavement maintenance data. There are significant differences in the maintenance activities for which data are collected, the types of data collected for each activity, and the units in which the data are represented (*13*).

Even when adequate data are available, there are some practical difficulties associated with the assumptions of the microeconomic theory of production and cost functions. First, the theory assumes homogeneous input factors. Clearly, in the context of pavement maintenance operations, each of the aggregate factors represents a large variety of specific input factors. For an individual maintenance activity, there are multiple types of equipment and employees of different categories. The homogeneity assumption may be satisfied more closely when the production function is estimated at the district level within a given state than when it is estimated at the statewide level. Second, in estimating a production function on cross-sectional data, it is assumed that the data represent the maximum level of output that can be accomplished with the employed combination of input factors. Since some inefficiencies in current pavement maintenance practices can be expected, it is likely that the data represent some points that are not on the "true" production functions. It should be stated that the difficulties associated with the theoretical assumptions are not specific to highway maintenance and are encountered in any application of these concepts. Nevertheless, when appropriate data are available, some useful important approximate results can still be obtained.

The data for this study come from a recent compilation of highway maintenance data produced for the Maryland State Highway Administration (*13*). As part of this data compilation effort, one state provided a uniform cross-sectional data set at the district level. The study uses these data for estimating the production functions. The purpose of the following analysis is twofold: (1) to illustrate the process of developing production functions for pavement maintenance activities and the use of these functions for obtaining information on the characteristics of various maintenance activities and (2) to illustrate the use of production functions for analyzing the productivity of resources and the cost efficiency of highway pavement maintenance operations.

The overall analysis consists of two phases. In the first phase, production functions (models) are estimated for five selected maintenance activities: hand patching, machine patching, concrete patching, joint/crack sealing, and seal coating. For each activity, eight different common forms of production models are estimated and evaluated. Based on this evaluation, "valid" production models are identified for use in the second phase. The second phase demonstrates how estimated production functions can be used for analyzing the productivity of resources and the cost efficiencies of highway pavement maintenance operations. This analysis is conducted at the state level. For each maintenance activity, five states are selected and the productivity of labor and equipment resources in each state is evaluated as discussed below.

Given a production function for a specific maintenance activity estimated in phase 1, the unit prices for labor and equipment, and the actual quantity of output for that activity at the selected state, the "optimal" quantities of labor and equipment are computed mathematically, as illustrated in the previous section. These "optimal" quantities provide target values of the most productive utilization of the two resources. The productivity of the two resources in performing the activity under consideration at the selected state are assessed by comparing the "optimal" and actual quantities of the resources used. Following the discussion of the previous section, the optimal quantities of labor and equipment are substituted in the expenditure function to determine the cost function for the state. Based on the cost function, the minimum unit cost (average cost) of producing the given level of output in the state is computed. The state's cost efficiency is assessed by comparing the "optimal" and actual unit costs.

The estimation district-level data are presented in the appendix (*13*). The data include 12 observations for hand patching, 24 for machine patching, 10 for concrete patching, 11 for joint/crack sealing, and 14 for seal coating. For each activity, the data include annual production, annual manhours used, annual workdays, and standard equipment fleet size. Total equipment-hours are obtained by multiplying the annual work hours (based on eight work hours per day) by the standard equipment fleet size. Eight different production functions are estimated for each activity: linear, Cobb-Douglas, exponential, semilog linear, quadratic, translog, constant elasticity of substitution (C.E.S.), and modified C.E.S. (M.C.E.S.). The mathematical forms of these production models and their characteristics are shown in Table 1. The estimation is performed by multiple linear regression, where the nonlinear functions are linearized using the appropriate transformations.

The evaluation of the estimated production functions is conducted in two stages. The first stage validates the calibrated functions relative to the characteristics of the production functions specified in Table 1. The validation criteria are as follows:

1. The marginal products of labor and equipment should be non-negative.
2. The second partial derivative of output with respect to the quantities of labor and equipment should be negative, as implied by the law of diminishing returns.
3. The second partial derivative of labor quantity relative to equipment quantity should be non-negative. The second stage of the evaluation constitutes a statistical evaluation with regard to the overall statistical significance of the model (*F*-test), the statistical significance of individual coefficients (*T*-test), the expected signs of individual coefficients, and the proportion of variations explained by the model (R^2).

The "valid" calibrated production models are shown in Table 2. Only ten of the forty models have been accepted

TABLE 1 MATHEMATICAL FORMS OF PRODUCTION MODELS AND THEIR CHARACTERISTICS

Model	Function	$MP = \frac{\partial Z}{\partial L}$	$MP = \frac{\partial Z}{\partial E}$	$\frac{\partial^2 Z}{\partial L^2}$
Linear	$Z = a_0 + a_1 \cdot L + a_2 \cdot E$	a_L	a_2	0
Cobb-Douglas	$Z = a_0 \cdot L^{a_1} \cdot E^{a_2}$	$a_0 a_1 L^{a_1 - 1} \cdot E^{a_2}$	$a_0 a_2 L^{a_1} \cdot E^{a_2 - 1}$	$a_0 a_1 (a_1 - 1) L^{a_1 - 2} \cdot E^{a_2}$
Exponential	$Z = a_0 \cdot a_1^L \cdot a_2^E$	$a_0 \log a_1 \cdot a_1^L \cdot a_2^E$	$a_0 \log a_2 \cdot a_1^L \cdot a_2^E$	$a_0 \cdot (\log a_1)^2 \cdot a_1^L \cdot a_2^E$
Semilog Linear	$Z = a_0 + a_1 \log L + a_2 \log E$	$\frac{a_1}{L}$	$\frac{a_2}{E}$	$-\frac{a_1}{L^2}$
Quadratic	$Z = a_0 + a_1 L + a_2 E + b_1 L^2$ $+ b_2 LE + b_3 E^2$	$a_1 + 2b_1 L + b_2 E$	$a_2 + b_2 L + 2b_3 E$	$2b_1$
Translog	$\log Z = a_0 + a_1 \log L + a_2 \log E$ $+ b_1 (\log L)^2 + b_3 (\log E)^2$ $+ b_2 (\log L)(\log E)$	$\frac{Z}{L} \cdot (a_1 + 2b_1 \log L + b_2 \log E)$	$\frac{Z}{E} \cdot (a_2 + b_2 \log L + 2b_3 \log E)$	$\frac{Z}{L^2}(d^2 - d + 2b_1)$ $d = a_1 + 2b_1 \log L + b_2 \log E$
C.E.S.	$Z^{-\rho} = a_1 \cdot L^{-\rho} + a_2 \cdot E^{-\rho}$	$a_1 \cdot \left(\frac{Z}{L}\right)^{\rho+1}$	$a_2 \cdot \left(\frac{Z}{E}\right)^{\rho+1}$	$\frac{a_1 (\rho+1) Z^{\rho+1} \cdot (a_1 Z^{\rho} - L^{\rho})}{L^{2\rho+2}}$
Modified C.E.S.	$Z^{-\rho} = a_0 + a_1 L^{-\rho} + a_2 E^{-\rho}$	$a_1 \cdot \left(\frac{Z}{L}\right)^{\rho+1}$	$a_2 \cdot \left(\frac{Z}{E}\right)^{\rho+1}$	$\frac{a_1 (\rho+1) Z^{\rho+1} \cdot (a_1 Z^{\rho} - L^{\rho})}{L^{2\rho+2}}$

based on the preceding evaluation process. The relatively low quality of the calibration results can be attributed to three basic factors. First is the inadequacy of the estimation data in terms of both the size and quality of the data set. The estimation data were not readily available in the required form and had to be manipulated based on certain assumptions. Second, owing to data limitations, the input factors are defined at the highest level of aggregation, which most likely results in a significant violation of the homogeneity assumption. Third, given the level of aggregation used, there is a significant degree of multicollinearity between the two independent variables, which leads to inaccurate partial coefficients. In highway maintenance operations, one may expect a relatively high correlation between total labor and total equipment because a substantial portion of labor crews are equipment operators. The remedies for the multicollinearity problem are discussed in the next section.

Table 2 shows better calibration results for machine and concrete patching than for hand patching. In all the models for machine patching and concrete patching, the partial coefficient of equipment quantity has the correct sign. This may result from better equipment data. The equipment fleet sizes for machine patching and concrete patching are larger and less variable than those for hand patching. Consequently, the errors associated with the manipulation of equipment data as well as the errors in recording equipment data may be less significant. The superiority of the calibration results of concrete patching over other activities may be attributed to the routine and less variable nature of that activity. No "valid" model for joint/crack sealing was obtained. One possible explanation for the difficulty of calibrating a production model for joint/crack sealing with the available data is that the available unit of output (100 feet of joint or crack) does not reflect actual surface conditions. Joints or cracks that need sealing may have different widths, depths, and severities of damage. A more appropriate unit of output may be the quantity of sealant applied.

Table 3 shows the following three characteristics of each activity, based on the calibrated production models: (1) marginal products of labor (MP_L) and equipment (MP_E), (2) rate of technical substitution between the quantities of labor and equipment (RTS_{EL}), and (3) return to scale. These characteristics are computed at the average level of output from the estimation data. It can be noticed that the values are highly sensitive to the type of production model used. Not all the values presented in Table 3 are "valid." This can be attributed to the three basic reasons for estimation difficulties discussed earlier. The results of Table 3 show that for hand patching, the marginal products of labor at the average level of output, obtained from the translog and quadratic models, are 0.48 and 0.55, respectively. From the translog model, an additional man-hour in hand patching would result in an additional 0.48 ton of hand patching output. The results also indicate that hand patching has a large range of increasing return to scale. This implies that hand patching is often more efficient when done in large-scale operations. Again, it should be recognized that this conclusion is based on the estimated production functions and may not be highly accurate, given the low accuracy of the estimation results.

The results of Table 3 show that the marginal product of labor in machine patching is larger than that in hand patching. Machine patching is the leveling and patching of a roadway

TABLE 2 CALIBRATED PRODUCTION MODEL

Activity	Model	Calibrated Production Model
Hand Patching	Quadratic	$Z = -1395 + 0.34L + 0.009E - 0.000082L^2 + 0.00022L \cdot E$ (0.91) (0.02) (-1.7) (1.66) $-0.00015E^2$ $R^2=0.71$ (-1.7)
	Translog	$\log Z = -19.2 + 1.84\log L + 2.69\log E - 6.24(\log L)^2$ (0.23) (0.31) (-2.05) $+12.8(\log L)(\log E) - 6.77(\log E)^2$ $R^2=0.86$ (2.13) (-2.20)
Machine Patching	Translog	$\log Z = -71.3 - 37.7\log L + 52.8\log E - 2.56(\log L)^2$ (-1.38) (1.64) (-0.45) $+8.85(\log L)(\log E) - 6.98(\log E)^2$ $R^2=0.52$ (0.69) (-0.94)
Concrete Patching	Linear	$Z = -22 + 0.14L + 0.02E$ $R^2=0.59$ (1.00) (0.22)
	Cobb-Douglas	$Z = 0.00065 \cdot L^{0.87} \cdot E^{0.91}$ $R^2=0.92$ (1.78) (1.28)
	Exponential	$\log Z = -0.23 + 0.0015L + 0.0022E$ $R^2=0.76$ (0.55) (1.29)
	Quadratic	$Z = -11.8 + 0.13L + 0.02E - 0.001L^2 + 0.002L \cdot E$ (0.20) (0.05) (-1.58) (2.30) $-0.00046E^2$ $R^2=0.88$ (-2.51)
	Translog	$\log Z = -12 - 22.6\log L + 23.3\log E - 4.34(\log L)^2$ (-1.33) (1.31) (-1.47) $+11.2(\log L)(\log E) - 6.69(\log E)^2$ $R^2=0.95$ (1.43) (-1.38)
	C.E.S.	$Z^{0.9} = 0.15L^{0.9} + 0.008E^{0.9}$ $R^2=0.74$ (0.99) (0.08)
	M.C.E.S.	$Z^{-0.25} = -0.36 + 2.96L^{-0.25} + 0.9E^{-0.25}$ $R^2=0.97$ (6.11) (1.01)

surface with bituminous mix, using paving machines. The large marginal product of labor in machine patching may result from the fact that additional labor increases the utilization of machines. The calibration results indicate that there are no scale economies in machine patching, which implies that machine patching may be done more efficiently with a relatively large number of small-scale operations than with a small number of large-scale operations. Concrete patching is more "labor-intensive" than either hand patching or machine patching. Maintenance work on concrete pavement usually requires more labor input than do similar activities in asphalt pavements. This may explain the relatively low marginal product of labor obtained for concrete patching. The results show significant variability in the rate of technical substitution in concrete patching, depending on the production model used. The average rate of technical substitution is 6.4, which means that every additional man-hour may allow the reduction of six equipment-hours without affecting the level of output.

Because of the three basic reasons for the expected low accuracy of the calibration results stated earlier, the values of Table 3 are most likely not highly accurate. The preceding discussion, however, illustrates the potential usefulness of accurate production models in enabling the derivation of important characteristics of the production processes of various highway maintenance activities, thereby providing important managerial guidelines.

The second phase of the analysis uses the calibrated production functions of Table 2 to determine the "optimal" quantities of labor and equipment for producing the reported level of output and the "optimal" unit cost (average cost), in each

TABLE 3 CHARACTERISTICS OF PRODUCTION PROCESSES, BASED ON CALIBRATED MODELS

Activity	Acceptable Model	MP_L	MP_E	RTS_{EL}	Return to Scale
Hand Patching	Quadratic	0.55	-0.30	-	$1<K_1<6.67$, increasing $K_1=6.67$, constant $K_1>6.67$, decreasing
	Translog	0.43	-0.31	-	$1<K_1<2.57$, increasing $K_1=2.57$, constant $K_1>2.57$, decreasing
Machine Patching	Translog	2.00	-1.30	-	$1<K_1<\infty$, decreasing
Concrete Patching	Linear	0.14	0.02	-7	$1<K_1<\infty$, increasing
	Cobb-Douglas	0.061	0.034	-1.79	$1<K_1<\infty$, increasing
	Exponential	0.018	0.028	-0.67	$1<K_1<\infty$, decreasing
	Quadratic	0.85	0.26	-3.27	$1<K_1<1.5$, increasing $K_1=1.5$, constant $K_1>1.5$, decreasing
	Translog	-0.12	0.20	-	$1<K_1<\infty$, decreasing
	C.E.S.	0.12	0.006	-19.7	$1<K_1<\infty$, constant
	M.C.E.S.	0.22	0.035	-6.28	$1<K_1<\infty$, increasing

one of the selected five states. The "optimal" values are compared with the actual values reported by the states to assess the productivity of the two aggregate resources and the cost efficiency for each state. For illustration purposes, the results of this phase of the analysis are presented only for concrete patching. Tables 4 and 5 present comparisons of the "optimal" and actual quantities of labor and equipment and the values of unit cost, for the five selected states, based on the M.C.E.S. and Cobb-Douglas production functions, respectively.

The low accuracy of the calibration results not withstanding, the results of Table 4 and 5 show some significant differences between the "optimal" quantities of labor and equipment and the actual reported quantities. In general, the "optimal" quantities of labor and equipment are lower than the actual reported quantities, indicating a potential for gains in both labor and equipment productivities. The results also show that in some states, the unit cost of concrete patching may be reduced. As before, because of the relatively low accuracy of the calibrated production models, some of the results of Tables 4 and 5 that show "optimal" unit cost values that are higher than the corresponding actual values are invalid. With more accurate and disaggregate data and more reliable production functions, however, this type of analysis can provide important information regarding the productivity and cost efficiency of various highway maintenance activities, as well as guidelines for improving both the productivity of resources and the cost efficiency of these activities at the state and/or district levels.

CONCLUSIONS AND RECOMMENDATIONS

The microeconomic theory of production and cost functions provides a promising theoretical basis for analyzing the productivity and cost efficiency of highway maintenance operations. This theory may provide (1) guidelines on the approximate quantities of input resources needed to produce any given quantity of highway maintenance, (2) estimates of minimum unit costs for performing various quantities of maintenance operations, and (3) characteristics of the production process of various maintenance activities (e.g., marginal prod-

TABLE 4 A COMPARISON OF OPTIMAL AND ACTUAL VALUES OF LABOR QUANTITY, EQUIPMENT QUANTITY, AND UNIT COST FOR CONCRETE PATCHING, BASED ON M.C.E.S. PRODUCTION MODEL

State		Labor	Equipment	Unit Cost[b]
1	Optimal	3,179	1,554	41.2
	Actual	8,610	8,610	118
	% Difference[a]	171%	454%	186%
2	Optimal	360.4	362.0	679
	Actual	295.8	443.7	621
	% Difference[a]	22%	22%	9%
3	Optimal	1,540	1,392	124
	Actual	5,840	3,504	432
	% Difference[a]	279%	152%	248%
4	Optimal	205	50.7	611
	Actual	37.5	19.0	147
	% Difference[a]	447%	167%	316%
5	Optimal	1,514	2,662	78.8
	Actual	3,336	5,156	169
	% Difference[a]	120%	94%	115%

[a] % Difference is the greater value minus the smaller value and then divided by the smaller value of the "optimal" and "actual".

[b] Includes the costs of labor and equipment only.

TABLE 5 A COMPARISON OF OPTIMAL AND ACTUAL VALUES OF LABOR QUANTITY, EQUIPMENT QUANTITY, AND UNIT COST FOR CONCRETE PATCHING, BASED ON COBB-DOUGLAS PRODUCTION MODEL

State		Labor	Equipment	Unit Cost[b]
1	Optimal	4,299	5,425	79.1
	Actual	8,610	8,610	118
	% Difference[a]	100%	59%	99%
2	Optimal	211.2	651.8	590
	Actual	295.8	443.7	621
	% Difference[a]	40%	47%	5%
3	Optimal	1,202	3,254	142
	Actual	5,840	3,504	432
	% Difference[a]	386%	8%	204%
4	Optimal	204	109	823
	Actual	37.5	19.0	147
	% Difference[a]	444%	167%	460%
5	Optimal	1,010	6,266	80.4
	Actual	3,336	5,156	169
	% Difference[a]	230%	22%	110%

[a] % Difference is the greater value minus the smaller value and then divided by the smaller value of the "optimal" and "actual".

[b] Includes the costs of labor and equipment only.

ucts, scale economies). As illustrated by the discussion of the previous section, these guidelines and characteristics can provide highly useful information for the management of highway maintenance operations.

The validity and quality of the results that can be obtained based on the proposed microeconomic approach depend on the availability of adequate data. The development of a uniform structure of a database for highway maintenance is needed. This will enable the collection of data at the state or district level, which will be consistent with the requirements of a microeconomic analysis. Research on the appropriate measures of inputs and outputs in various highway maintenance activities is also needed. Input factors should be defined at more disaggregate levels than that used in this study. The definition of labor input may be disaggregated by classifying maintenance labor into its major categories (i.e., foreman, equipment operator, truck driver, manual laborer, and flagman). Equipment classification may be more difficult. A possible classification may consist of material hauling equipment, crew cab, traffic handling devices, other major equipment, and small tools.

The definition of appropriate output measures in highway maintenance operations is a difficult issue that requires a great deal of study. In general, the volume (or weight) of the materials being processed is a better measure than the surface area being treated. Ideally, not only the quantity but also the quality of maintenance should be represented. This may require the estimation of different production functions for different quality standards. Highway maintenance activities may also be performed using alternative materials. Since different kinds of materials may imply different relationships between the quantities of input factors and the level of output, different production functions may have to be estimated for different materials. The need to determine the maximum quantity of output of any given maintenance activity that can be accomplished from any given combination of disaggregate resources with a given material (such as to achieve a prespecified quality standard) may imply that the data for the development of production functions should be collected from designated highway segments, under controlled conditions, as proposed recently in the SHRP program (*4*).

APPENDIX Estimation District-Level Data

Activity	Fiscal Year	District	Z	L (Man-Hr.)	E (Equi-Hr)
Hand Patching Z (ton) Equip. Size = 4	1984-1985	1	5638	29676	26580
		2	7194	35993	22212
		3	2003	10538	9474
		4	837	8789	8989
		5	3354	24618	22984
		6	4199	20601	19197
		7	2824	19077	16201
		8	2087	11616	7305
		9	2937	14440	11918
		10	2844	12288	10610
		11	2536	14972	9105
		12	6406	24737	17672
	1985-1986	1	3137	18963	17387
		2	5179	28670	19274
		3	1026	5465	4516
		4	886	8094	7081
		5	2430	19331	18127
		6	4218	18133	16978
		7	2821	17358	14870
		8	1409	9056	5986
		9	2220	11813	10025
		10	2435	10700	9760
		11	3294	15894	9594
		12	12050	26329	17800
Machine Patching Z (ton) Equip. Size =13	1984-1985	1	15995	13707	13893
		2	39820	23984	28488
		3	31893	19097	24580
		4	32257	53610	58912
		5	23472	21395	26135
		6	19933	20895	24554
		7	16432	15066	21389
		8	42732	34130	36114
		9	44591	39036	45144
		10	45068	29800	33539
		11	32095	12063	17682
		12	22300	10552	13151

APPENDIX Estimation District-Level Data

Activity	Fiscal Year	District	Z	L (Man-Hr.)	E (Equi-Hr)
Machine Patching Z (ton) Equip. Size =13	1985-1986	1	27165	20488	19846
		2	58547	32570	37040
		3	30090	22261	21694
		4	46112	58195	59751
		5	41048	30487	35284
		6	26016	26337	29534
		7	23480	18826	23003
		8	52688	40161	40093
		9	42760	34600	38094
		10	71371	47880	48948
		11	53711	19893	25794
		12	60933	22434	25547
Concrete Patching Z(Cu.Yd.) Equip. Size =11	1984-1985	1	1	57	99.4
		2	7	365	627
		4	187	1246	1837
		5	46	343	616
		7	53	372	913
		8	26	952	1062
	1985-1986	4	295	1097	1705
		5	50	765	1848
		10	1	56	88
		12	0.1	7	77
Joint/ Crack Sealing Z (Ft.) Equip. Size =10	1984-1985	1	20800	440	810
		2	17200	631	705
		4	7500	40	40
		11	700	100	160
		12	10000	8	40
	1985-1986	1	6300	136	240
		4	22000	120	160
		5	171700	332	440
		6	100	8	80
		8	4500	192	240
		11	12000	352	480
Seal Coating Z (ton) Equip. Size =13	1984-1985	1	7963	5135	5110
		2	144	151	196
		4	2422	1730	1430
		5	4105	2609	2522
		6	7001	3997	2900
		8	607	695	1145
		10	123	151	208
		12	10	75	104
	1985-1986	1	15362	8859	9142
		2	11801	6719	7768
		4	6505	3836	2532
		5	1074	1061	956
		6	7565	4521	3932
		9	5125	3420	3924

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