Economic Efficiency Implications of Optimal Highway Maintenance Policies for Private Versus Public Highway Owners

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The idea of transport infrastructure privatization has been receiving increased attention recently from researchers and policy makers. In both Britain and the United States, as well as in some developing countries such as India, the idea of highway ownership privatization is being seriously considered and in some cases is being implemented. Most research to date has focused on the technical or financial feasibility of highway privatization or of using tolls to finance roads. This paper is motivated, rather, by the question of the economic efficiency of highway ownership privatization. The paper focuses on in-depth analysis in an effort to quantify what may be the main issue in the question of the economic efficiency of privately owned highways—the problem of suboptimal highway physical quality, which could result over the long run from highway maintenance policies that seek to maximize immediate private profit rather than overall economic welfare. The paper shows that for a typical representative highway the profit-maximizing maintenance policy would produce poor highway quality that over the long run would be considerably poorer than the welfare-maximizing quality. However, the paper concludes with a benefit-cost discussion, which indicates that it still could be economically beneficial to privatize the ownership of some highways.

The idea of transport infrastructure privatization has been receiving increased attention among researchers and policy makers. The English Channel Tunnel and the British Airports Authority are examples of privatization in practice in Britain. In the United States, where more nonhighway transport infrastructure is already in private or semiprivate ownership, interest is growing in the idea of expanding the role of the private sector in public infrastructure provision and finance, in particular, in the fields of highway and mass transit facilities. In a particularly striking example, a group of private investors in Denver has announced a project to develop a 180-mi, $800-billion, 80-mph turnpike in Colorado. A private development consortium has also proposed to build, own, and operate a 30-mi extension of the Dulles Airport Tollway in the Washington, D.C., area of Northern Virginia.

Much of the attention in the discussion of infrastructure privatization has to date been focused on the question of its financial feasibility and its capability for obtaining additional revenues to pay for infrastructure without recourse to taxation and the government budget. Relatively little attention has been focused on the question of the economic efficiency of transport infrastructure privatization. Key questions in this regard are (a) Would private infrastructure owners charge an economically efficient price to the users of the infrastructure? and (b) Would private infrastructure suppliers provide efficient levels of quantity and quality of product or service over the long run?

This paper focuses on a specific aspect of the second question. In particular, a hypothetical privately owned toll highway is considered. The profit-maximizing highway pavement quality maintenance policy for this highway is compared with the socially optimal or economically efficient policy. Methodologically, this paper contains an extension and application of other work previously presented to the TRB *(1, 2)*.

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DEVELOPMENT AND IMPLEMENTATION OF THE ANALYTICAL MODEL

In this section the assumptions and mathematical model used in the analysis are presented.

Economic Background and Definitions

A highway market is defined as the supply of and demand for highway facilities between two geographic points. The highway supply in such a market is characterized by its quantity or capacity (e.g., number of lanes); its quality, such as pavement surface quality; and its use price, or toll. The highway market is said to be inefficient in the allocational sense if the supply characteristics (quantity, quality, and price) could be altered so that potentially everybody affected by the market could be made better off. For example, if the toll is set too high, some people who otherwise value the use of the highway at more than what it costs society for them to use it will be priced off the road, resulting in a net loss of welfare for society. In such a case, society would be allocating too few resources to the use of the highway with the too-high toll, and perhaps allocating too many resources to the use of other alternatives.

Most highway markets exhibit imperfections or market failure that cause the profit-maximizing supply characteristics of the highway to differ from the efficient (or socially optimal or welfare-maximizing) levels. If toll roads only are addressed, there are two major imperfections or sources of market failure in such markets: (a) economies of scale or indivisibilities in production, as well as sunk costs involved in market entry, all of which lead to some degree of natural monopoly or incontestability (market power); and (b) external benefits and costs,

TABLE 7 VALUES OF TIME, WEIGHTED AND UNWEIGHTED, BY TIME OF DAY AND SEAT BELT USAGE

Time of Day	1984 $/hr		
	Belted	Unbelted	Average
Unweighted by Hours of Travel			
Day	10.76	13.00	11.84
Night	9.61	14.27	11.71
All	10.47	13.32	11.81
Weighted by Hours of Travel			
Day	6.67	8.72	7.65
Night	5.71	10.91	8.05
All	6.43	9.67	7.75

TABLE 8 VALUE OF TIME

Condition	1984 $/hr			
	Four-Lane		Two-Lane	
	Belted	Unbelted	Belted	Unbelted
Day	6.67	8.72	4.71	8.56
Night	5.71	10.91	7.18	18.73
Overall weighted value of time	7.75		8.01	

$7.75/hr. For comparative purposes, Table 8 gives the values of time derived for using desired speeds (and costs) on four-lane and two-lane highways. Although there is considerable variation between subgroup values, the overall average is similar for the two road types. It is recommended that the value of $7.75/hr be used for benefit-cost analysis.

CONCLUSIONS AND RECOMMENDATIONS

The speed choice model was chosen for estimating values of time because it can be applied across a representative statewide sample of Texas motorists. Two other methods judged to be good theoretical approaches—the choice of mode (especially bus versus automobile) and the choice of route (especially toll road versus alternate free route) methods—cannot be used as effectively because many Texans seldom, if ever, ride buses (especially not for rural trips) and few situations are available in Texas where choices involving toll roads are made. The speed choice model has been criticized by some researchers as having the weakness of assuming that motorists know the expected costs of different road types as related to travel speed. This criticism, however, can also be applied to the other techniques. For example, in the bus-automobile modal choice situation, it is assumed that the driver knows his out-of-pocket vehicle operating costs, even though the trip usually involves several different highway types, intersections, and so forth, not to mention widely varying traffic volumes and other operating conditions. In addition, expected accident costs as perceived by the motorist must be estimated to use this approach in a valid way. Similar calculations must be made of operating costs and accident costs on toll roads versus alternate free routes to use the route-choice models. Therefore, in this study, it is concluded that the speed choice model is at least as valid theoretically as the other techniques and has the definite advantage of being applicable to a statewide cross section of Texas motorists.

Previous researchers in Great Britain and the United States have used the speed choice model to calculate the trade-off between time and accident costs at different average speeds and for different average costs. This study represents an improvement over previous studies in that specific speed decisions and cost curves are used for each individual in the study, instead of using average speeds and average cost functions.

The principal data problem in using the speed choice model involves the estimation procedure for the cost of fatalities. To estimate this cost, the study adopted the foregone earnings approach. Depending on hourly wage, age, race, sex, and education level, each individual's value of life was estimated. The value of time for a driver of a passenger car after being weighted by annual travel time spent by individuals, by seat belt use, and by the time of day, is found to be $7.75 in 1984 dollars, or $8.03/hr after being updated to 1985 using the consumer price index. Assuming an occupancy rate of 1.3 persons per car, the recommended 1985 value of time for passenger vehicles is $10.44/veh-hr. This is the value recommended to be used in benefit-cost analysis in Texas.

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which cause either the highway provider or the user to be unable to experience all of the benefits and costs of the highway and its use. As a result of imperfections or market failure, the highway user cannot usually have available a perfect substitute for any given highway. This situation causes the highway provider to face a downward sloping demand curve for the road, enabling the provider to increase profits only by increasing the toll or by providing less quantity or quality of product, or both, up to a point. Partly as a result, the extra cost to the users caused by deterioration of road quality (vehicle wear and tear, extra travel time, and discomfort) will to some extent remain an external cost to the highway provider (i.e., a cost the provider does not fully experience).

Thus, assuming an objective of profit maximization, one would expect a privately owned toll highway to provide less than the socially optimal level of quality maintenance over time, at least in the absence of any intervention or control by a government body *(2)*.

In the remainder of this paper, attempts are made to explore quantitatively the question of how bad or serious this problem of suboptimal private highway quality might be. This analysis is pursued by taking the case of a hypothetical highway representative of the type that might be a likely candidate for privatization as a toll road—a high-traffic-density, large-scale urban or suburban expressway or beltway. Privatization would be most likely to be financially feasible for such a road.

It is assumed that the highway is privatized as a new or newly reconstructed (hence, high-quality) facility. Next, the profit-maximizing versus welfare-maximizing pavement maintenance policies are modeled over time, observing the resultant difference in the highway pavement quality profile over time, and the difference in net welfare that results from profit maximization as opposed to welfare maximization. It is assumed that the same toll would be charged in both cases, for example, a level of toll fixed by the government.

The General Analytical Model and Assumptions

A general mathematical model of the optimal highway quality maintenance policy over time is presented. The model is described under two possible alternative objectives—net welfare maximization and highway owner's profit maximization. No matter what the objective, the problem is formulated mathematically as a dynamic optimization problem. In other words, the unique highway quality maintenance policy over time represented by the annual maintenance expenditure profile over time that maximizes the present value of the objective (either net social welfare or owner's profit, whichever the case) is determined.

Consider an infinitely long-lived highway with a pavement life cycle that repeats itself every T years. Let $v(t)$ be the highway maintenance expenditure per unit of time, at time t, where t is less than T. Let $Q(t)$ be the traffic volume demand on the highway in equivalent standard axle loads (ESALs) per unit of time, at time t. Let $S(t)$, represented by some index, such as the average pavement serviceability index (PSI) of AASHTO, be the physical quality of the highway at time t. The state differential equation that describes the change in the condition of the pavement with time can be written

$$\dot{S}(t) = g\,[v(t), Q(t), S(t)] \tag{1}$$

where $\dot{S}(t)$ equals dS/dt at time t.

The maintenance expenditure $v(t)$ is a proxy for the physical level of maintenance effort performed on the pavement during the time increment from t to $t + dt$. Within the highway pavement cycle, it is assumed that only routine maintenance is performed on the pavement. The role of routine maintenance applied at any time t is to slow the instantaneous rate of deterioration $\dot{S}(t)$ but not to cause any positive improvement in the condition of the pavement. In Equation 1, therefore,

$$\dot{S} \le 0,\ \dot{S}'(v) = \partial\dot{S}/\partial v \ge 0,\ \partial\dot{S}/\partial Q \le 0$$

At the end of the T-year pavement life cycle, reconstruction or rehabilitation is performed on the highway at a cost of R. This reconstruction cost is assumed to be a decreasing function of the terminal pavement quality $S(T)$.

$$R(T) = R[S(T)] \tag{2}$$

Thus, there are two reasons for the highway owner to spend money on maintenance. One is to keep the highway use cost down during the life cycle. The other is to reduce the required reconstruction cost at the end of the life cycle or to prolong the life cycle, pushing back the date when the road must be reconstructed, thereby reducing the present value of the reconstruction cost.

The traffic volume demand on the highway per unit of time at time t, $Q(t)$, is given by the demand function

$$Q(t) = D[P(t)] \tag{3}$$

where P is the average variable composite price users of the highway pay per unit of use (i.e., per ESAL-mi). Thus, P includes time and inconvenience or discomfort value as well as direct and indirect monetary outlays sensitive to travel on this highway.

The inverse of the demand function is the marginal social value MSV function that represents society's willingness to pay for each increment of aggregate use of this highway. The function is expressed as

$$MSV = P(Q) = D^{-1}(Q)$$

This definition amounts to assuming that there are no major external benefits associated with marginal use of this highway. Thus, the total instantaneous net user benefit NUB of quality level S at time t on the highway is given by the integral of the demand function as

$$NUB[S(t)] = \int_{P[S(t)]}^{\infty} D[P(S)]\,dP(S) \tag{4}$$

The average variable composite user price P includes some monetary payments (e.g., tolls and gasoline taxes) that represent intrasocietal transfers to the government or to the highway owner rather than deadweight losses to society. These transfer payments are therefore not social costs or economic costs in the sense that they involve no loss of aggregate net social welfare (one person's loss is another's gain within the society). Therefore, the average variable social cost of highway use (net welfare loss, as distinct from user price) per unit of use (apart from the highway maintenance expense, which is considered separately) is given by

$$C = P - (\tau + f) \tag{5}$$

where τ is the toll and f is the use-sensitive nontoll user fees, such as gasoline taxes, both measured per ESAL-mi.

The average highway user social cost C is in general a function of many things, including Q itself if the highway is congested. But in order to focus on the main issue and to keep our problem tractable, it is assumed that C is independent of Q. For clarity of presentation, it is also assumed that all exogenous influences on C are constant over time so that the instantaneous user cost at time t, $C(t)$, can be expressed as a function only of $S(t)$, the pavement condition at time t, as follows:

$$C = C(S) \tag{6}$$

However, the assumption that exogenous influences on C are constant is not necessary for the analytical tractability of the model.

Based on the foregoing definitions, the aggregate net welfare W obtained by society from the highway per unit of time at time t is given as

$$W(t) = NUB[S(t)] + (\tau + f)Q\{P[S(t)]\} - v(t) \tag{7}$$

where $P(S)$ equals $C(S) + (\tau + f)$.

On the other hand, the profit per unit of time, π, obtained by the private highway owner at time t is given by

$$\pi(t) = \tau Q\{P[S(t)]\} - v(t) \tag{8}$$

Here corporate income taxes are ignored to simplify the analysis and because the government could make highway companies tax exempt (just as the current toll highway owners, state and local government agencies, are tax exempt). Also, it is assumed that the toll τ is constant, although this assumption is not necessary and is made only for simplicity.

Figure 1 shows graphically the difference between Equations 7 and 8. The shaded area in the left-hand graph represents $W + v$, which is seen to consist of the large net user benefit triangle plus the small rectangular area of the intrasocietal transfers. The shaded area in the right-hand graph represents $\pi + v$, which consists only of a part of the intrasocietal transfer rectangle. Clearly, the private owner's profit represents only a small subset of the total social welfare from highway use prior to consideration of the level of maintenance outlays v. Of course, v, which is not explicitly shown, may not be the same in the two graphs (it would be smaller in the right-hand graph, to maximize profits). This difference is the focus of the analysis.

Let r_w and r_p be the social and the private owner's discount rates, respectively, applicable to money-valued future returns on cash investments. Then the welfare maximization objective is given by the present discounted value of the future net welfare flows, including consideration of the reconstruction cost at the end of the cycle,

$$\max_{v(t)} \int_0^T \exp(-r_w t)\, W(t)dt - R[S(T)] \exp(-r_w T) \tag{9}$$

where $W(t)$ is given by Equation 7.

The private owner's objective function is given by

$$\max_{v(t)} \int_0^T \exp(-r_p t)\, \pi(t)dt - R[S(T)] \exp(-r_p T) \tag{10}$$

where $\pi(t)$ is given by Equation 8.

Equations 9 and 10 represent the objectives of finding among all the possible profiles of maintenance outlays over time $v(t)$ that one, call it $v^*(t)$, which is optimal in the sense that it maximizes either the present discounted value of net welfare (Equation 9) or of the private highway owner's profits (Equation 10).

The state equation governing the rate of deterioration of the highway quality over time represents the physical and tech-

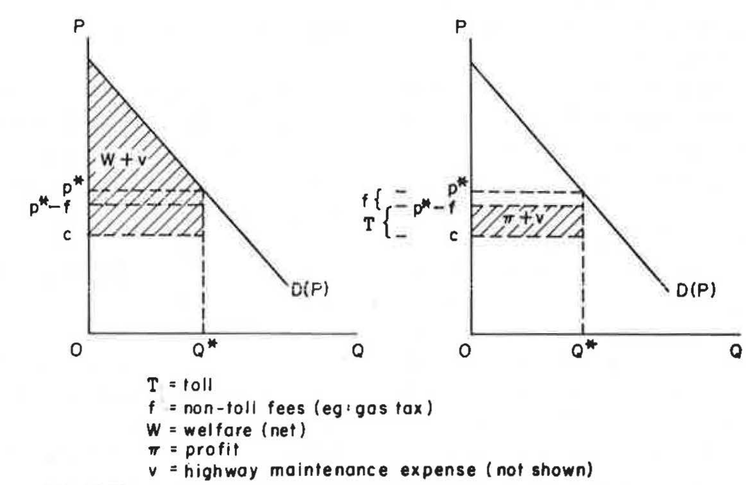

FIGURE 1 Comparison of social welfare versus profit from the highway.

nological constraints within which the maximization problem must be solved. This state equation is the same (Equation 1) no matter which objective motivates the highway maintenance policy decision.

In addition to the objective function and to the state equation, to fully characterize the optimal highway maintenance and reconstruction policy for the T-year life cycle, the boundary condition must be specified as

$$S(nT) = S_0 = 4.5 \text{ (PSI) for } n = 0, 1, 2, \ldots \quad (11)$$

and the nonnegativity constraint as

$$v(t) \geq 0, \text{ for each } t \quad (12)$$

The boundary condition (Equation 11) is derived by hypothesis because the highway is assumed to be like new at the initial time of privatization. (New highways have the maximum possible PSI of 4.5.) Note also that in the standard optimal control formulation of this problem there is a second boundary condition at the terminal time T of the cycle, specified by the reconstruction cost function. Thus, the dynamic optimization problem that must be solved is a two-point boundary value problem, with an inequality constraint on the control variable. Such problems can be solved by a variety of techniques to find the optimal $v^*(t)$ path and the resultant optimal highway quality profile over time $S^*(t)$. This solution can then be evaluated according to the objective function (Equation 9 or 10) for a range of different cycle terminal times T. The optimal cycle duration T^* can then be selected as that which maximizes the objective function.

Specific Quantitative Assumptions

Specific assumptions about functional forms and parameter values are required for application of the general model. To begin, the example highway is characterized as a six-lane urban tollway experiencing approximately 40,000 veh/day or 3 million ESALs/year at the assumed toll. The toll is assumed in the base case to be 20 cents/ESAL-mi, a level similar to that charged on several existing urban tollways (e.g., the Massachusetts Turnpike Extension in Boston). The nontoll use fees (parameter f in the previous subsection) are assumed to be 8 cents/ESAL-mi, or about 2.5 cents/veh-mi for the average vehicle. (Three to four veh-mi to the ESAL-mi is assumed.)

For simplicity, it is assumed that demand is linear. Thus, Equation 3 obtains the form

$$Q = Q_0 - bP \quad (13)$$

It is also assumed for simplicity and clarity of presentation that the intercept and slope, Q_0 and b, respectively, are constant, which amounts to assuming that the socioeconomic or other exogenous determinants of highway demand are stationary over time. The parameters Q_0 and b are specified so as to give a point elasticity, at the initial user price, of approximately unity (in the base case). While this elasticity value assumption may at first seem high—for example, an often-employed rule of thumb for transit demand is that the fare elasticity is about one third, and empirical studies of highway demand for urban travel show highway demand to be insensitive to money cost—it must be remembered that the concern here is with a total composite price elasticity, where the price P includes both travel time value and money costs. Thus, because value of time makes up a substantial portion of the total composite price, a total elasticity of unity (the base-case assumption) would not be inconsistent with an out-of-pocket direct money price elasticity of considerably less than one-half. This value would appear to be consistent with typical empirical findings *(3–6)*.

Also, bear in mind that the relevant elasticity here is the elasticity of demand for the highway or route alternative owned by the private highway owner, not the elasticity of demand for all automobile travel in the given market (provided there are other alternative routes between the origins and destinations served by the highway).

As noted, the user average variable social cost function $C(S)$ as given by Equation 6 consists of value of travel time, cost of fuel, cost of vehicle wear-and-tear, cost of accidents, and so on. This cost is a function of the highway quality. Experiments and empirical studies have shown that user costs as a function of pavement quality can be represented by an exponential function similar to that presented as follows and shown in Figure 2 *(7–10)*.

$$C(S) = C_0 + C_1 \exp(-C_2 S) \quad (14)$$

where C_0 represents the cost component that is independent of pavement quality (e.g., price of fuel), and $C_0 + C_1$ represents the maximum possible cost when the pavement is in a completely deteriorated condition (PSI = 0). The parameters C_0, C_1, and C_2 need not be constant over time although in the analysis, they have been so assumed for simplicity. The parameter values that have been assumed and that are shown in Figure 2 are

C_0 = \$1.00/ESAL-mi,
C_1 = \$15.00/ESAL-mi, and
C_2 = 1.8.

These values assume a user cost of about 30 cents/veh-mi up to a PSI of approximately 2.0, after which user costs begin to rise rapidly.

The state equation has been expressed as a negative exponential function, reflecting decreasing returns to scale in the application of maintenance effort on the highway at any time.

$$\dot{S}(t) = \alpha(t) \exp[-v(t)\mu(t)] \quad (15)$$

where α is a positive constant and μ is a parameter of maintenance effectiveness.

Note that by Equation 15, as increasing amount is spent on maintenance at any time [$v(t) \rightarrow \infty$], the highway deterioration rate approaches zero. On the other hand, in the absence of any maintenance, the highway would deteriorate linearly at the rate of $\alpha Q(t)$ (PSI) per unit of time. In the analysis, α is selected so that if the initial traffic $Q(0)$ were maintained on the highway in the absence of any maintenance, the highway would deteriorate completely from PSI of 4.5 to 0 in 30 years. This period is assumed to equal the pavement design lifetime.

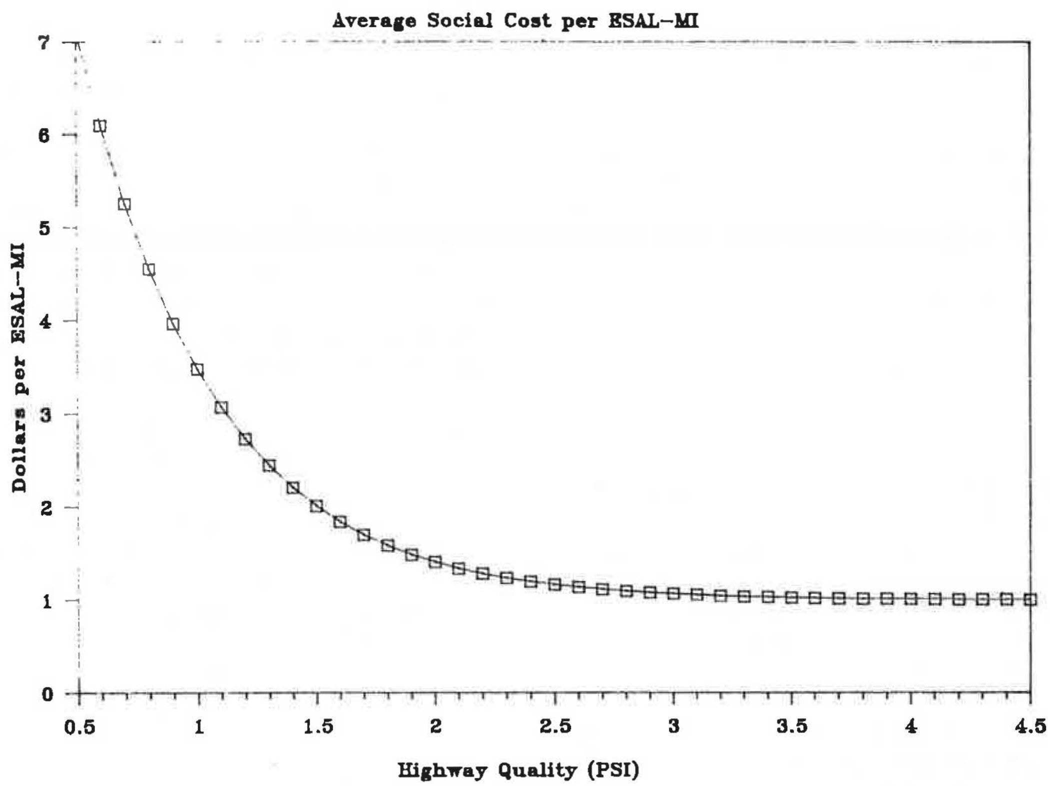

FIGURE 2 Plot of highway user cost function.

In the analysis, T is assumed to be 30 years. In fact, the optimal cycle duration T^* was determined, but in the simple model neither highway profits nor social welfare was sensitive to the cycle duration and the optimal duration tended to be about the same under either of the two objective functions.

In the state equation, highway maintenance, as represented by the expenditures $v(t)$, is viewed to have an instantaneous effect in slowing down the rate of highway quality deterioration. Thus, the larger μ is, the more effective is 1 unit of maintenance effort. Specifically, μ represents the percentage reduction in the highway quality deterioration rate caused by a 1-unit increase in maintenance expenditure, as follows:

$$\mu = [\partial \dot{S}(v)/\partial v]/\dot{S}$$

Intuition and engineering judgment suggest that μ is a function of the existing pavement quality S and that this function should be shaped roughly like that shown in Figure 3. Maintenance is most effective over a broad region of moderate quality pavement. When the pavement is badly deteriorated, routine maintenance (as opposed to rehabilitation or reconstruction) is not effective because the existing pavement and possibly support structures are too weak to allow maintenance to have much effect. When the existing pavement quality is good, it is impossible for maintenance to cause much additional improvement.

In fact, the argument that μ as a function of S is shaped generally as shown in Figure 3 has been supported by a recent empirical study *(11)*. The specific functional form that has been assumed for $\mu(S)$ is

$$\mu = A\ [1 - \exp(-\theta_2 S)]/\{1 + \exp[\theta_1(S - a)]\} \qquad (16)$$

Because data are not available to statistically estimate the parameters of Equation 16, the following values in the base case have been assumed, based on engineering judgment and consistent with the evidence found in *(11)*.

$\theta_1 = \theta_2 = 2.5$
$a = 4.0$
$A = 1/775{,}000$

The curve drawn in Figure 3 is a plot of μ/A as a function of S with these parameter assumptions.

Note that the state equation (Equation 15) can also be interpreted as a kind of maintenance production function, with the output of maintenance being viewed as reductions in the rate of deterioration of the highway. As noted, Equation 15 is such that this production function will exhibit declining returns to scale. However, the degree of scale diseconomies can be manipulated by altering the parameter A in Equation 16, without changing the basic shape of the maintenance effectiveness as a function of pavement quality as depicted in Figure 3. This procedure allows sensitivity analysis to be applied with respect to the nature of the maintenance technology in terms of its effectiveness and degree of scale diseconomies.

Finally, the assumption regarding pavement rehabilitation costs at the end of the life cycle (Equation 2) was that these costs would be a linear function of the terminal pavement quality. Specifically, the following function for R was assumed:

$$R = \$225{,}000 - \$50{,}000\ [S(T)] \qquad (17)$$

RESULTS OF THE ANALYSIS

Using the foregoing specific quantitative assumptions, the optimal maintenance and reconstruction problem described was

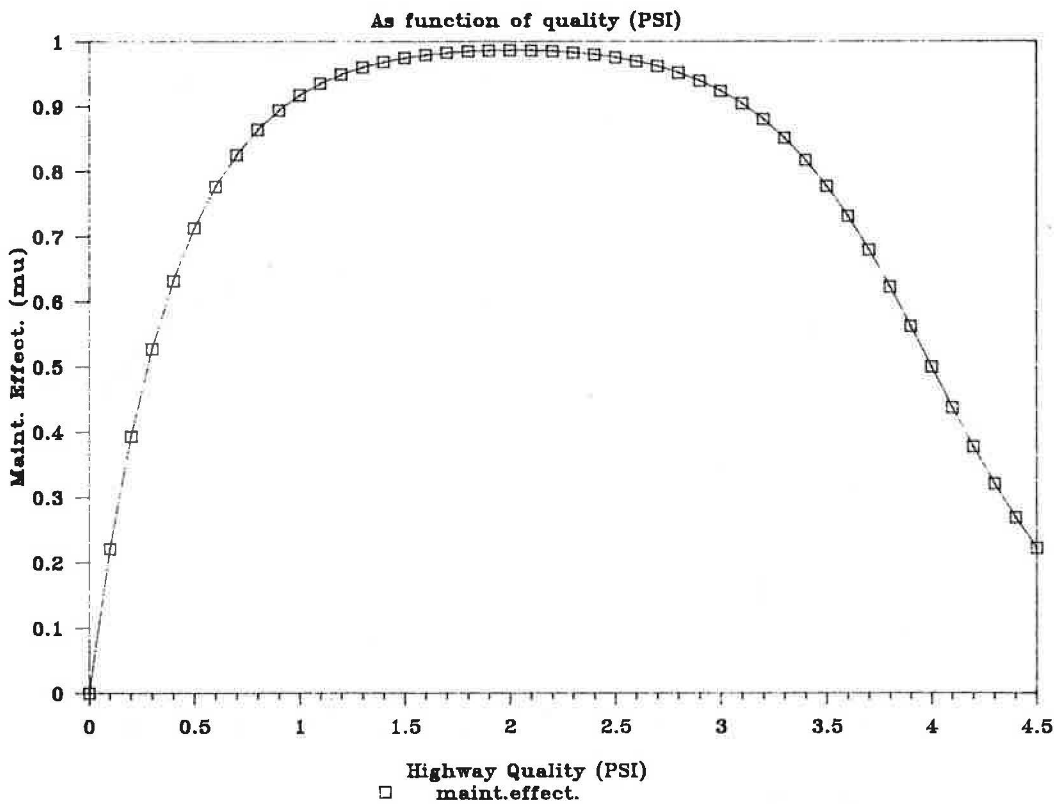

FIGURE 3 Plot of maintenance effectiveness.

solved using a first-order gradient method *(12)*. The results of this solution are shown in Figures 4 and 5, assuming $r_w = 8$ percent and $r_p = 10$ percent.

Figure 4 shows the optimal maintenance expenditure profile over the 30-year life cycle under the base case assumptions. The higher curve is optimal for maximizing net aggregate social welfare from the highway according to the objective function of Equation 9, whereas the lower curve is optimal for maximizing the profits according to the objective function of Equation 10. As one would expect, the profit-maximizing maintenance expenditures are considerably less than the welfare-maximizing expenditures, and they start later in the cycle.

Figure 5 shows the resulting optimal highway quality profile over time. The highest quality profile is, of course, the welfare-maximizing or efficient quality. The middle line is the profit-maximizing quality. The lowest line indicates the do-nothing profile of highway quality that would result if nothing at all were ever spent on maintenance and the traffic using the highway decreased accordingly. Note that the profit-maximizing quality level is closer to the efficient level than to the do-nothing level throughout most of the life cycle.

More important, note that the average level of pavement quality over time under the profit-maximizing objective (about PSI 3.6) compares favorably with what is achieved in practice by many government agencies managing the Interstate highway system. Indeed, the profit-maximizing terminal quality at the end of the 30-year cycle is about PSI 2.7 in the base case, which compares favorably with the life cycle terminal quality of 2.5 PSI that is often taken to represent the standard practice on the Interstate highway system (when funding allows). The implication is that a private profit-maximizing highway owner would maintain the example highway no worse than, and perhaps better than, the current typical standard government practice. This result may not be generalizable across all government agencies because of the wide variety of methods of analysis and the different indexes for the measurement of pavement condition used by different authorities.

Sensitivity analysis has been conducted on the previously described results with respect to four key parameters—the demand elasticity, the discount rates, the toll, and the maintenance effectiveness—or scale diseconomy parameter A in Equation 16. Summaries of these sensitivity analysis results are given in Table 1. The description of the various scenarios is given in Table 2. Each scenario was run under both the welfare-maximizing and profit-maximizing policies, with the results as indicated. The overall result of the sensitivity analysis appears to confirm the foregoing general conclusions.

The last column in Table 1 presents the terminal quality of the highway, that is, the PSI after 30 years. Because the optimal quality profile over time is roughly linear (as shown in Figure 5), and the quality starts out at PSI 4.5, this terminal quality is a good relative index of the average highway quality over time. Note that one would expect the optimal terminal quality to be less for a highway with less traffic density than for the example, so the optimal terminal qualities found in the analysis are not necessarily general indictments of the current standard of 2.5 PSI.

The first column in Table 1 gives the value of the social objective function for the scenario and policy in question (from Equation 9, the present discounted value of the net welfare provided by the highway, per mile of highway). The second column presents the per-mile present discounted value of the

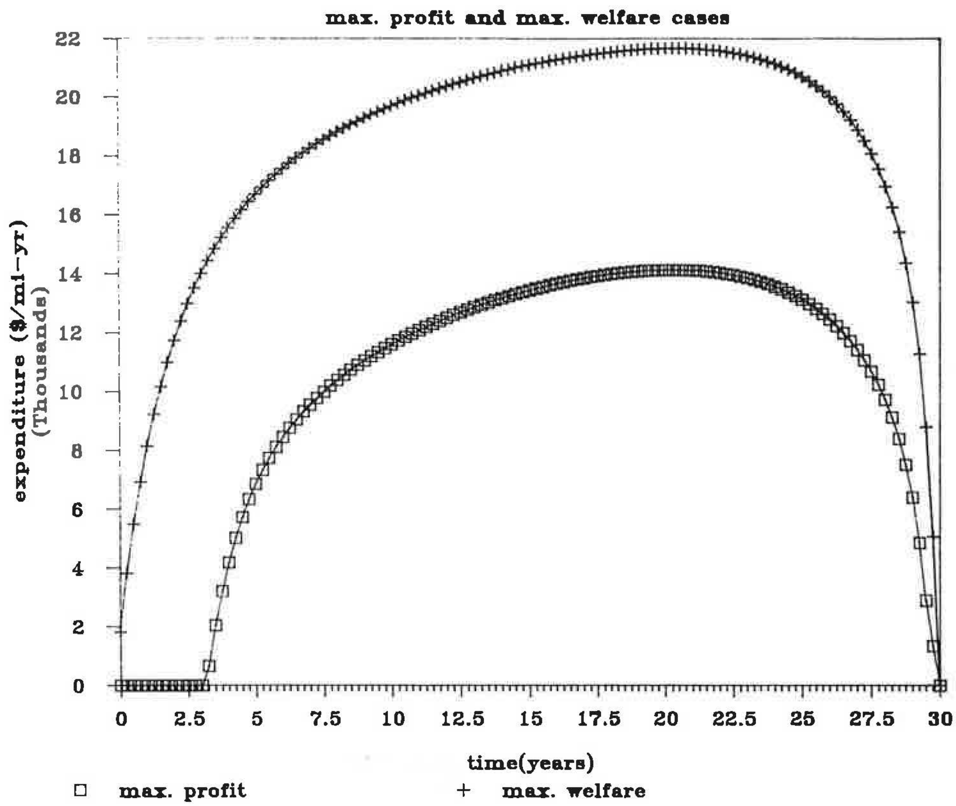

FIGURE 4 Maintenance expenditure versus time.

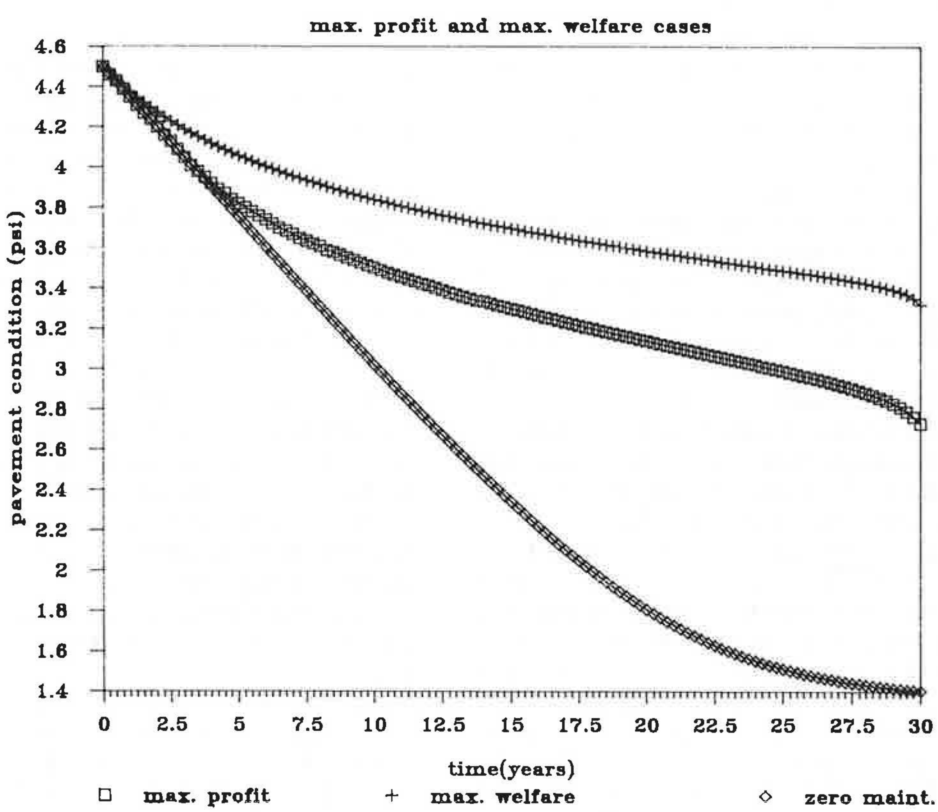

FIGURE 5 Pavement condition versus time.

TABLE 1 SENSITIVITY ANALYSIS OF RESULTS

Scenario Number (Policy)	Economic Benefits[a]	Profits[a]	Potential Cost[a]	Terminal Quality (PSI)
1. (W-max)[b]	34.195	5.834		3.32
(D-max)[b]	33.723	5.871	0.472	2.73
2. (W-max)	54.498	5.870		3.31
(D-max)	53.946	5.927	0.552	2.60
3. (W-max)	22.008	5.789		3.38
(D-max)	21.597	5.798	0.411	2.89
4. (W-max)	22.807	4.178		3.28
(D-max)	22.451	4.211	0.348	2.58
5. (W-max)	68.082	9.680		3.35
(D-wax)	66.743	9.719	1.339	2.73
6. (W-max)	34.842	3.063		3.30
(D-max)	33.760	3.127	1.082	2.38
7. (W-max)	33.256	8.138		3.35
(D-max)	32.952	8.161	0.304	2.89
8. (W-max)	33.927	5.740		3.14
(D-max)	33.091	5.812	0.836	2.45
9. (W-max)	34.388	5.899		3.51
(D-max)	33.934	5.916	0.454	2.91

[a]Figures are capitalized values per mile of highway in $millions.
[b]W-max = welfare maximization; D-max = profit maximization.

TABLE 2 SCENARIO DEFINITIONS

Scenario Number	Demand Elasticity	Discount Rates r_w, r_p (%)	Toll ($0.00)	Maintenance Effectiveness Parameter A
1 (base)	1.0	8, 10	0.20	1/775000
2	0.5	8, 10	0.20	1/775000
3	2.0	8, 10	0.20	1/775000
4	1.0	12, 14	0.20	1/775000
5	1.0	4, 6	0.20	1/775000
6	1.0	8, 10	0.10	1/775000
7	1.0	8, 10	0.30	1/775000
8	1.0	8, 10	0.20	1/1550000
9	1.0	8, 10	0.20	2/775000

profits generated by the highway under each maintenance and reconstruction scenario (Equation 10). Profits are discounted using r_p for both policies.

The third column presents the difference in present discounted net welfare between the socially optimal versus the profit-maximizing policies for each scenario as taken from Column 1, which uses a discount rate of r_w for both policies. These differences range between roughly $0.5 million per mile of highway in the base case, down to $0.3 million per mile of highway in Scenario 7, and up to $1.3 million per mile of highway in Scenario 5.

CONCLUSIONS AND POLICY IMPLICATIONS

The results in the previous section give some idea of the quantitative difference between the profit-maximizing and the welfare-maximizing highway quality for a representative typical case. It is clear that there is a potentially important physical difference in the average quality of a highway maintained to maximize profits versus social welfare. But to draw any substantive conclusions from this analysis, it is suggested that the figures in the third column of Table 1 are more relevant. The figures quantify the dollar value of this physical difference in terms of aggregate social welfare.

As noted, this difference in social value ranges from about $0.3 million to about $1.3 million in capitalized value per mile of highway, depending on the scenario of the sensitivity analysis. To see the significance or use of this type of quantitative finding regarding the policy question of whether a highway like the hypothetical example should be privatized, it is necessary to return to the economic points raised previously and to consider how the highway would be privatized and subsequently regulated by the government. Recall that their are three major characteristics of the highway supply, quantity, quality, and price, which determine the efficiency of the highway market. It is not hard to imagine how the government might privatize either new or existing highway facilities and still easily maintain control over both the quantity (e.g., number of lanes available in a given market) and price (i.e., toll) of the highway supply in the market *(2)*.

It is less easy to see how the government could maintain control over the quality of privately owned roads. Thus, of the three characteristics determining the efficiency of the privatized highway market, quality poses the main problem.

It is therefore tempting to think of quality as the main potential economic cost of a policy of highway privatization. The preceding analysis was motivated by a desire to try to put a quantitative upper limit on what that cost might be. In the example, $1.3 million would appear to be a good approximation of what that limit might be, in present, capitalized value per mile.

If quality might be the major potential economic cost of highway privatization, what would be the major economic benefit? Some might argue that the major benefit would be to obtain more funding for highway construction to get more highways built sooner than they otherwise would be. However, any highway that could be successfully privatized without government subsidy would be by necessity self-financing, and therefore could be built by the government without recourse to tax revenues or the government budget. The government can borrow money at least as cheaply as private developers can. The timing advantage of privatization therefore would, in theory, only exist if the relevant government agency lacks sufficient borrowing authority. Highways that would require government subsidy to be privatized due to capitalized toll profits being insufficient to cover construction costs might not have any timing advantage over government ownership, because government funds would have to be used or committed to get the project started.

Rather, it would seem that the main potential economic benefit from highway privatization might be to improve the production efficiency as opposed to allocational efficiency with which highway quantity and quality are produced. Going back to the hypothetical example, suppose the highway does not yet exist or does exist but is badly deteriorated and in need of reconstruction. The government plans to construct or reconstruct the highway. Now suppose that a private developer could construct or reconstruct the highway 10 percent more efficiently than the government could due to greater production efficiency or greater management flexibility and profit incentive. But the private developer would subsequently maintain the highway so as to maximize its profits rather than to maximize the economic welfare of the society, whereas the government would maintain the highway to maximize welfare.

If the government's estimated cost for the highway construction or reconstruction project is greater than $13 million/mi, the savings in more efficient highway production by a profit-maximizing private highway owner would more than offset the economic loss of the subsequent less efficient highway quality maintenance, even assuming the government would pursue a welfare-maximizing highway maintenance policy. The construction cost savings would exceed 10 percent of $13 million, whereas the capitalized cost of the difference between profit-maximizing versus welfare-maximizing highway quality maintenance would be estimated at only $1.3 million or less (indeed, only $0.5 million in the base case).

Considering the magnitude of the highway that was studied in the numerical example (six lanes, 40,000 veh/day), it appears likely that construction costs could exceed this upper limit threshold of $13 million/mi, although for a reconstruction project it is more questionable whether the cutoff point would be exceeded. Of course these benefit-cost numbers are illustrative, depending on the assumption that private producers would be 10 percent more efficient than government producers and considering only the concern for highway pavement quality.

In fact, in this example, the economic argument for privatization could be stronger. It has been noted that the $1.3 million potential cost of privatization quantified in the foregoing analysis was an upper limit, because it is taken from the worst case in the sensitivity analysis of Table 1 and it is based on the difference between the profit-maximizing and welfare-maximizing maintenance policies. There are several reasons why the actual quality cost of privatization might be less than this upper limit.

First, although it would appear reasonable to assume that a private highway owner would seek to maximize profits from the highway, it is nevertheless true that in general, to the extent that other objectives (such as gross revenue maximization) enter the private owner's decisionmaking, his quality maintenance policy would be likely to approach more closely the welfare-maximizing policy. One case where this point would be important is the case in which the private owner of the highway also owns major real estate parcels served by the highway. Then the external benefit of improved highway quality would be to some extent internalized within the highway owner because the value of the owner's real estate is improved by the quality of the access to it.

Second, it is perhaps less reasonable to assume that a government owner would adopt the maintenance policy that maximizes welfare. Numerous constraints and limitations, legal, political, and otherwise, enter into the information processing and decision-making capabilities of government agencies, causing the resulting policies to diverge from economic efficiency. Indeed, as noted in the example case the profit-maximizing pavement maintenance policy exceeds the current standards applied to Interstate highways by government owners (even when not constrained by insufficient funding).

Finally, it should be noted that it may be possible for the government to regulate, subsidize, or otherwise control the privatized highway so that it does produce the welfare-maximizing highway quality without destroying its incentives for production efficiency *(2)*. It is significant that in Table 1 the difference in profit between the welfare-maximizing and the profit-maximizing policies is not great. Nevertheless, a regulatory process would likely be difficult and tricky, and not without cost in terms of the deadweight burden of regulatory administration.

SUMMARY

Given the likely difficulty of obtaining efficient highway quality over the long run from privately owned highways, it is important in considering and evaluating highway privatization proposals to attempt, as was done in this paper, to put quantitative limits on the potential economic costs of suboptimal highway quality that could result from privatization. The analysis here indicates that this cost may not be too great in some circumstances. But different conclusions might be reached in other examples and with other assumptions.

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