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OPTIMAL HIGHWAY DURABILITY

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Congressional legislation since 1982 has reflected a consensus that U.S. highways are in serious need of repair. Fuel taxes have been raised, and there is new interest in taxes that vary by truck weight and distance traveled. At the same time, researchers have begun investigating optimal rehabilitation strategies.[1]

Neither a fuel tax nor a weight-distance tax, however, satisfactorily apportions the damage that vehicles inflict on highways. That damage depends critically on weight per axle. In our 1986a paper, we found that an axle-weight-based marginal-cost tax could go a long way toward raising funds for infrastructure repair and reducing the need for such repair in the future. We also found that such a tax would cause a substantial redistribution from the trucking industry to the public treasury, raising questions of political viability.

In this paper, we investigate the complementary question of the optimal durability of highways. We find that in order to minimize discounted lifetime costs, typical urban interstate highways should be designed with thicker pavements lasting much longer between repavings. Furthermore, although existing roads have marginal pavement-wear costs that are quite high, optimal high-volume urban interstates would not. Thus the need for marginal-cost taxation, and the accompanying diversion of trucking industry revenues, would be virtually eliminated on a large portion of the nation's highway network if the highways were built to optimal standards.

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[1] For example, Potter and Hudson (1981), Gomez-Ibanez and O'Keeffe (1985).

We begin by reformulating the standard model of optimal highway pricing and investment (see Winston, 1985, p. 78) to include highway durability as a long-run decision variable. The resulting pricing rule includes both a congestion charge related to scarce capacity, and a heavy-vehicle charge related to scarce durability. We derive expressions for marginal-cost user charges, optimal capacity, optimal durability, and long-run marginal pavement-wear cost. We then explore empirically those parts of the model related to durability.

I. Model

Our formulation of the model extends that of Keeler and Small (1977). We consider a one-mile, one-directional stretch of highway. It is used n days per year by vehicles in type-weight classes labeled $i=1,\ldots,I$, during distinct hours of the day labeled $h=1,\ldots,H$. Let $q=\{q_{ih}\}$ be the vector of hourly flow volumes, and let $P_{ih}(q)$ be the inverse demand curves giving perceived prices (user-incurred time and money costs plus user charges) as functions of flow volumes.

Each vehicle in class i contributes as much to congestion as v_i cars, and as much to road wear as ℓ_i single axles weighing 18,000 pounds: it is said to have v_i passenger car equivalents and ℓ_i equivalent standard axle loads (ESALs). We follow common practice in ignoring variation in these equivalence factors with respect to such influences as terrain, climate, and highway design. We therefore define two traffic variables affecting congestion and road wear, respectively:

hourly traffic volume $V_h = \sum_i v_i q_{ih}$, and annual traffic loadings $Q = n\sum_h \sum_i \ell_i q_{ih}$.

Highways are built with more lanes (more precisely, with greater capacity) to reduce the congestion caused by traffic volume; they are built thicker (greater durability) to reduce the road wear caused by traffic loadings. Let W and D measure capacity and durability, respectively: specifically, let W to be width in lanes, and let D be pavement thickness (or a weighted combination of various component thicknesses) in inches. We can then write average user cost C_{ih}, annualized highway maintenance cost m, and annualized highway capital cost k, for our one-mile highway segment as:

(1) $c_{ih} = c_{ih}(V_h,W)$

(2) $m = rM(Q,W,D)$

(3) $k = rK(W,D)$

where r is the interest rate, M is the present discounted value of all required highway maintenance expenses, and K is the capital cost of construction.

Some writers have stressed that traffic loadings affect maintenance costs <u>and</u> user cost through lower speeds, increased vehicle maintenance, and so on. There is a crucial difference, however, in how these two types of cost are affected by traffic. Traffic affects highway maintenance cost mainly through the frequency of resurfacing: the heavier the traffic, the more often resurfacing is required. User costs, however, vary cyclically between resurfacings. Only their time pattern, not their total amount, is affected if traffic is constant over time and if resurfacing is done at predetermined levels of pavement quality (D.M. Newbery, 1985). The effect of traffic on the present value of user costs over the entire life of the road is therefore likely to be small. In addition, this relationship is not well understood. Thus we omit Q and D from the arguments of c_{ih}. Including them would, if anything, further strengthen our conclusion that current pavement design is of suboptimal durability.

In accordance with the road pricing and investment literature, the standard net benefit maximization problem is

$$\text{(4)} \qquad \underset{q,W,D}{\text{Max}} \; NB \equiv n\sum_{hi}\int_0^{q_{ih}} P_{ih}(q')dq_{ih}' - n\sum_{hi} q_{ih}c_{ih}(V_t,W)$$

$$- rM(Q,W,D) - rK(W,D).$$

This yields the following first-order conditions:

$$\text{(5a)} \qquad P_{ih} - c_{ih} = v_i \sum_j q_{jh}(\partial c_{jh}/\partial V_h) + \ell_i r(\partial M/\partial Q), \; i=1,\ldots,I, \; h=1,\ldots,H$$

$$\text{(5b)} \qquad r\partial(M+K)/\partial W = -n\sum_{hi} q_{ih}(\partial c_{ih}/\partial W)$$

$$\text{(5c)} \qquad \partial K/\partial D \quad = -\partial M/\partial D \; .$$

Equation (5a), the pricing rule, gives a user charge consisting of the usual congestion charge plus a charge for road wear. (Note that this assumes the charge for road wear cannot be varied over the life of the pavement; if it could, we would have to formulate an optimal control problem to determine it.) Equation (5b), the optimal capacity rule, equates the extra cost of building and maintaining a wider road to the incremental benefit of reduced congestion. The optimal durability rule is equation (5c). It minimizes $M+K$ with respect to D by equating the extra capital cost of building a thicker road to the incremental benefit of reduced maintenance cost.

This paper is concerned only with durability and the effects of traffic loadings, not with capacity and congestion. Hence it is equation (5c), along with the last term in equation (5a), that we explore empirically in this paper.

We now specify the maintenance cost in more detail. As a good approximation, a pavement can be considered to have a lifetime $N(D)$ giving the number of ESALs that can pass over it before it must be resurfaced [U.S. Federal Highway Administration (FHWA), 1982, p. IV-42]. Standard practice requires building all lanes of a highway to the same thickness, and repaving all lanes as soon as one of them, normally the outer lane, needs it (J.A. Gomez-Ibanez and M. M. O'Keeffe, 1985, p. C-10). The number of traffic loadings between resurfacings is therefore $N(D)$ divided by the proportion λ of traffic loadings that occur in the outer lane. Letting $C(W)$ be the cost of resurfacing, M is the present value of an infinite sequence of expenditures $C(W)$ every T years beginning at time T:[2]

$$M(Q,W,D) = C(W)/(e^{rT}-1) \tag{6}$$

where

$$T = N(D)/(\lambda Q) \ . \tag{7}$$

The wear-related user charge per ESAL-mile, $r(\partial M/\partial Q)$, is then:

$$SRMC = \alpha C(W)\lambda/N(D) \tag{8}$$

where $\alpha \equiv (rT)^2 e^{rT}/(e^{rT}-1)^2$. Hereafter we refer to this as simply the marginal cost. Note that α is between 0 and 1; it approaches 1 as rT becomes very small, in which case SRMC is just the undiscounted resurfacing cost divided by the number of traffic loadings between resurfacings.

Note that we neglect any pavement wear that is unrelated to traffic. Here we follow Gomez-Ibanez and O'Keeffe (1985) who, after reviewing conflicting claims in the literature, conclude that time and weather mainly aggravate the effects of traffic loadings, having little independent effect. We also neglect the rather small routine maintenance expenditures on such such items as patching cracks and filling

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[2] We ignore complications arising if, because pavement structure changes with each rehabilitation, T varies over the pavement's life.

potholes. Finally, we ignore the occasional but expensive major reconstruction that may be required after many resurfacings, or if resurfacing is overly delayed.[3]

We now state a procedure to calculate optimal durability. (Because this analysis is not concerned with congestion, it is not neccessary to calculate optimal width.) It is convenient to define $k_m = C(W)/W$ and to specify the capital cost in the simple form $K(W,D) = k_0 + k_1 W + k_2 WD$. Differentiating this equation and the maintenance cost equation (6) with respect to D, and using (7), the optimal durability rule (5c) becomes:

$$\text{(9)} \qquad \frac{rT}{\alpha} \cdot \frac{k_2}{k_m} = \frac{1}{N(D)} \cdot \frac{dN}{dD} \ .$$

Since T depends on D through (7), this equation cannot be solved for optimal durability D^* in closed form. Instead, we numerically minimize $[M(Q,W,D) + K(W,D)]$ with respect to D. Dropping terms that are unaffected by D, this amounts to choosing D^* so as to minimize

$$\text{(10)} \qquad k_m/(e^{rT}-1) + k_2 D$$

with T depending on D through equation (7).

II. Empirical Parameters

We consider a six-lane urban interstate highway (W=3), for which the U.S. FHWA (1983, p. II-16) assumes the fraction of trucks in the outer lane to be λ=0.7.

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[3] Current maintenance policies are effectively taken as given. Maintenance policy, or course, can also be optimized (see Gomez-Ibanez and O'Keefe, 1985), resulting in a tradeoff between road maintenance and durability. However, such maintenance policies are not always practical. Hence in developing optimal durability rules, we posit a simple maintenance policy, which corresponds closely to current practice.

The maintenance parameter k_m is taken to be the per-lane cost of repaving a six-lane expressway in an outlying urban residential area, as given in U.S. FHWA (1983, p. II-10) and adjusted to 1984 prices using the FHWA Construction Cost Index (U.S. Department of Commerce, 1983 and 1985, p. S-7). The result is $113,400 per lane-mile.

Pavement Life and Pavement Thickness: N(D)

The relation between pavement life N and thickness D was studied as part of major road test carried out by the American Association of State Highway Officials (AASHO) between 1958 and 1960. This test remains today the most important and widely used source of experimental information on the subject. Using test tracks in northern Illinois, investigators measured the effects of axles of various weights on pavement deterioration for over 200 different design combinations. Two kinds of pavements were studied: rigid (portland cement concrete) and flexible (bituminous concrete, commonly called asphalt). The former is more common for heavy-duty roads.

The results, published in Highway Research Board (1962), were incorporated into the standard pavement design guide (American Association of State Highway and Transportation Officials, 1981, pp. 59-62, 102-106) on which most states base their design practice (U.S. FHWA, 1982, p. IV-42). The design guide suggests adjustments for different soils and climates; hence our results apply directly only to soils and climates similar to those of the test tracks.

AASHO specified a complicated non-linear equation relating a precisely defined measure of pavement quality, π, to the number of applications n of an axle of weight L_1 (in thousands of pounds) and type L_2 ($L_2 = 1$ for single axles, 2 for tandem).[4] Essentially, the equation gives the time path of road deterioration. It is specified as

$$(11) \qquad \pi = \pi_0 - (\pi_0 - \pi_f)(n/\rho)^{\beta}$$

where π_0 is initial pavement quality; π_f is a predetermined "terminal" pavement quality at which the pavement is considered to be worn out; and ρ and β depend parametrically on L_1, L_2, and D as described below. By setting $n = \rho$, we see that ρ is just the number of axle passages (of weight L_1 and type L_2) that will cause the pavement to wear out. The parameter β controls the shape of the pavement history curve (plotting pavement quality against cumulative axle loads); that curve is concave if $\beta > 1$, convex if $\beta < 1$, and linear if $\beta = 1$.

Using measurements of average pavement quality on new pavements, the AASHO researchers set π_0 at 4.5 for rigid pavement, 4.2 for flexible. They chose π_f to be 1.5, representing a very badly deteriorated pavement; whereas 2.5 is the value at which resurfacing is usually recommended.

The AASHO researchers specified β and ρ parametrically as:

$$(12) \quad \beta = b_0 + B_0(D+1)^{-B_1}(L_1+L_2)^{B_2}(L_2)^{-B_3}$$

$$(13) \quad \rho = A_0(D+1)^{A_1}(L_1+L_2)^{-A_2}(L_2)^{A_3}$$

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[4] For flexible pavements, where seasonal differences in pavement vulnerability are large, n is a seasonally weighted number of applications, the weights having been developed from a separate analysis. (This means that our results for the user charge on flexible pavements must be interpreted as pertaining to a seasonally varied charge.)

where b_0 was predetermined (through a somewhat arbitrary and unclear procedure), and the A's and B's were estimated. For rigid pavements, D is just the pavement thickness in inches; for flexible pavements, D is a linear combination of pavement, base, and sub-base thicknesses known as structural number.[5]

The AASHO estimates of these equations, one for rigid and one for flexible pavements, are given in Highway Research Board (1962, pp. 40, 152). Recall that N(D) is defined as the number of single axles of weight 18,000 pounds that lower π to 2.5. Hence to compute N(D) based on AASHO's equations, we substitute the values $L_1=18$ and $L_2=1$ into (12) and (13), then solve (11) for the value of n that yields $\pi=2.5$.

An Alternative Estimate of N(D)

Although the AASHO road test was carefully done and probably deserves its reputation as the best evidence yet on road deterioration, the statistical estimation of the coefficients in equations (11)-(13) was seriously flawed. The AASHO researchers first fitted equation (11) 548 times, once for each of 548 different combinations of L_1, L_2, and D. Using the resulting estimates of β and ρ as dependent variables, they then estimated equations (12) and (13). The fits to (11) were frequently poor and tended to overestimate pavement lifetimes, as seen in various examples graphed in Carey and Irick (1962) and in the appendix of Canadian Good Roads Association (1962). Various arbitrary constraints, averages, and data

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[5] The coefficient in the linear combination are .44, .14, and .11. These were estimated by the AASHO researchers along with other parameters of (12) and (13) in a complex multistage procedure (Highway Research Board, 1962, pp. 36-40). Note that one way to increase the structural number by amount ΔD is to increase pavement thickness by $(\Delta D/.44)$.

exclusions were used to compensate (Highway Research Board, 1962, pp. 313-319). The resulting coefficient estimates are certainly inefficient and probably severely biased.

To correct the problem, we estimated part of the equation system (11)-(13) ourselves, using the original AASHO data (published in Appendix A of Highway Research Board, 1962). Since our interest is solely in the number of axle applications lowering π to 2.5, we simply redefined ρ in (13) to be this quantity. (This is equivalent to setting $\pi_f = 2.5$ in (11).) As it happens, the AASHO data contain direct observation of ρ as redefined in this way, so more were able to bypass equations (11)-(12) and estimate (13) directly. That is, the dependent variable was simply the natural logarithm of the number of applications (seasonally weighted in the flexible case) after which π was observed to be 2.5. We used a limited dependent variable (Tobit) model to reflect the fact that for those pavement sections not deteriorating to π=2.5 over the duration of the test, we observe only a lower limit on the pavement life.[6]

Our estimates are shown along with AASHO's in Table 1. Recall that the dependent variables are slightly different, so the two sets of estimates are not strictly comparable. Nevertheless, two potentially important differences are suggestive. First, our estimates show a somewhat less steep relationship between pavement life and axle load -- closer to a third-power law than to the fourth-power law conventionally used to approximate the AASHO findings (U.S. FHWA, 1982, p. IV-43; Croney, 1977, pp. 54, 494). More germane to the present

[6]To our knowledge only one other study, that of Shook and Finn (1963) for flexible pavements, has used as a variable the directly measured number of applications to a predetermined pavement quality. This is surprising since that is the quantity of greatest interest in highway design. Shook and Finn's study did not take into account the selection bias from ignoring pavement sections that outlasted the experiment. It also had certain other differences that make comparisons difficult.

Table 1. Estimates of Equation (13)

Coefficient	Rigid Pavements		Flexible Pavements[a]	
	Ours[b]	AASHC[c]	Ours[b]	AASHO[c]
$\ln A_0$	13.505 (.307	13.47	12.062 (.237)	13.65
A_1	5.041 (.329)	7.35	7.761 (.245)	9.36
A_2	3.241 (.260)	4.62	3.652 (.147)	4.79
A_3	2.270 (.242	3.28	3.238 (.189)	4.33
Number of observations	264		284	
No. censored observations[d]	191		45	
Standard error of regression	.367		.651	

[a]Using seasonally weighted axle applications

[b]Estimated using Tobit model of error structure. Dependent variable is the natural logarithm of the number of axle applications to pavement serviceability index of 2.5. Standard errors are given in parentheses.

[c]From Highway Research Board (1962, pp. 40, 152); the intercept has been converted from base 10 to natural logarithms. Dependent variable was the natural logarithm of an estimated parameter respresenting the number of axle application to pavement serviceability index of 1.5. Standard errors were not reported.

[d]A censored observation is one for which only a lower bound on the dependent variable is observed, due to the finite duration of the test.

paper, calculations of N(D), obtained by substituting $L_1 = 18$ and $L_2 = 1$ into our estimate of equation (13), reveal that our estimates imply far shorter pavement lifetimes for thick pavements -- 65 percent shorter for the standard 10-inch rigid slab used on most interstates. These results are only slightly altered if we reestimate our equation using a cutoff of π=1.5, and measure lifetime to this value.

The reader is cautioned that the very definition of traffic loadings Q from a mixture of vehicle types and weights depends on these estimated parameters, and hence comparisons of predicted lifetimes are inherently ambiguous. In particular, the AASHO procedures would attribute somewhat more cumulative ESALs to a traffic history with a high proportion of very heavy trucks than ours would, because

AASHO's estimate of A_2 is larger. Nevertheless, there is other evidence that the AASHO results overstate lifetimes of thick pavements. A Canadian critique noted that the estimated curves for thick flexible pavements fit the data poorly (Canadian Good Roads Association, 1962, p. 130). And further records on some of the test pavements, later incorporated into Interstate Route 80, show that the thicker rigid pavements lasted only about half as long as the AASHO equations predicted (Elliott, 1981, p. 8 and Figure 1). These observations on real highways lend support to the belief that our estimates correct serious biases in the original AASHO work.

Other Parameters

The construction cost parameter k_2 is derived from the average contract price for either portland cement concrete or bituminous concrete, delivered and spread in place. Conversations with highway engineers and an asphalt company official indicated that this is probably an accurate reflection of the marginal cost of added pavement thickness. Cost per unit of delivered material is given in U.S. FHWA (1985, p. 2); for bituminous concrete, we assume a density of 130 pounds per cubic foot, then divide by 0.44 to obtain cost per square foot per unit increase in D (see footnote 5). We assume a standard 12-foot lane width. The result, per lane-mile per unit of D, is \$10,670 for rigid and \$20,684 for flexible pavements. Other sources were consulted to verify that these cost are reasonable.

The interest rate r should represent the alternative real cost of public funds, which are at least partly obtained by diverting private-sector funds earning the before-tax corporate real rate of return. We use 10 percent, and check for sensitivity within the range 6-12 percent.[7]

III. Results: Durability

Table 2 shows optimal durability as a function of annual traffic loadings Q. Since pavement quality depends on <u>cumulative</u> loadings, little would be gained by incorporating traffic growth into our model. The three values of Q shown are roughly the 5th, 50th, and 95th percentile values for six-lane interstate highway mileage in the U.S.[8] Several points deserve attention.

First, our equations imply optimal rigid pavement thicknesses that are approximately 1 to 3 inches greater than obtained using the AASHO pavement-wear equations in the same optimization model. This is a result of the different predicted pavement lifetimes already discussed.

Second, our calculations imply that current practice for both rigid and flexible pavements yields substantially less durable roads than would be optimal. The

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[7] Although real rates of return on bonds historically have averaged only about 4 percent, real pre-tax rates of return in the private sector can be much higher. As our sensitivity analysis shows, using an interest rate lower than our assumed 10 percent just strengthens our conclusions still further.

[8] Derived from data in Gomez-Ibanez and O'Keeffe (1985, pp. 57, C-3, and C-9). Compared to-six-lane urban interstates, six-lane rural interstates have about half the vehicle traffic, but twice the percentage of trucks, hence roughly the same traffic loadings. Median traffic levels on four-lane interstates are about half as large for urban areas and one-third as large for rural areas; however a higher proportion of trucks travel in the outer lane.

Table 2. Optimal Durability

Q(1000s ESALs/yr)	D^* (inches slab thickness or structural number)			
	Rigid Pavements		Flexible Pavements	
	Ours[a]	AASHO[b]	Ours[a]	AASHO[b]
250	8.7	7.9	5.2	5.1
1,000	11.5	9.8	6.4	6.1
2,500	13.8	11.1	7.3	6.9

[a]N(D) computed using our estimates of modified equation (13), as given in Table 1.

[b]N(D) computed using AASHO's estimates of equations (11)-(13), as reported in Highway Research Board (1962, pp. 40, 152).

FHWA's Highway Performance Monitoring System, used in annual Congressional reports, assumes certain "default" thicknesses for current roads (U.S. FHWA, 1983, p. II-10). The typical "heavy" rigid pavement is 10 inches: about 1-1/2 inches below optimum for the median traffic level, at which a 10-inch pavement would last only half the optimal 26 years. Similarly, the typical "heavy" flexible pavement (structural number 5.3) should, according to our results at median traffic, be built at structural number 6.4 instead, thereby raising its life from 8 to 29 years.[9]

[9]These values are typical not only of existing highways, but of current design practice. On the design chart for flexible pavements in one standard text (Oglesby and Hicks, 1977, p. 672), the range given for structural number does not even go up as high as 6.4. The Pennsylvania Pavement Design Procedure calls for heavy rigid pavements to be 10 inches thick, and heavy flexible pavements to have structural number 5.5. Highway engineers tell us that most states building rigid pavements to interstate standards use between 9 and 11 inches thickness. A new revision of the AASHTO design guide, currently in preparation, attests to the inadequacy of these practices in light of experience by recommending stricter design standards, pointing out that many roads built since the AASHO road test have not lasted to their design life.

Third, optimal design is quite sensitive to traffic. Over the 10-fold range of traffic loadings shown, optimal rigid pavement thickness varies from approximately 9 to 14 inches, corresponding to pavement lives of 3-1/2 to 28 million ESAL applications in the outer lane. In fact, to a rough approximation, optimal design calls for durability to be adjusted so as to hold constant the lifetime in years, which varies only between 31 and 26 years over these traffic volumes.

Fourth, the results are surprisingly insensitive to the key parameters determining the tradeoff between capital and maintenance costs. Table 3 shows optimal pavement life at the median traffic level using our parameter estimates, as the cost ratio k_2/k_m varies from 50 to 200 percent of its original value and as the interest rate varies from 6 to 12 percent. All scenarios lead to optimal lifetimes greater than the current 13 or 8 years characterizing "heavy" rigid or flexible pavements, respectively. Indeed, at the original cost parameter ratio, the

Table 3.

Optimal Pavement Life in Years: Sensitivity Analysis

(our parameters, Q=1 million)

	Rigid Pavements			Flexible Pavements		
	k_2/k_m			k_2/k_m		
r	.038	.076	.152	.067	.135	.269
.06	54	41	28	62	48	34
.10	34	26	18	38	29	21
.12	29	22	15	32	25	18

interest rate would have to be over 20 percent to justify the current 10-inch standard for rigid pavements, even at this median traffic level.

Three additional checks on these results were performed. First, we redid all the calculations assuming overlays at a critical pavement quality of π=1.5 instead of π=2.5, since then we could use AASHO's estimated equation (13) directly and ignore equations (11)-(12). This change made hardly any difference to the results using our estimates, but it substantially increased the discrepancy between using our estimates and using AASHO's. Apparently, pavements deteriorate very quickly once they reach the level π=2.5 -- a fact also noted by the Canadian Good Roads Association (1962, pp. 136, 158) -- but the AASHO estimation procedure tended to misrepresent this by underestimating β.

As a second check, for the case of rigid pavements, we tried the pavement deterioration model that is used in the FHWA's Highway Performance Monitoring System (U.S. FHWA, 1983). That model appears to be a simplified approximation to the AASHO equations, with some adjustment to U.S. average soil and climate conditions (Gomez-Ibanez and O'Keeffe, 1985, p. C-7). Its results generally fell between those from our equations and those from AASHO's.

Our third check was to see whether the results are sensitive to the precise functional form of equation (13). Since the terms (D+1) and (L1+L2) involve a rather arbitrary mixing of units, we tried replacing them with (D) and (L1), both separately and together. We also tried translog forms in which log(ρ) is specified as a quadratic function of log(D), log(L2), and log(L1); or alternately of log(D+1), log(L2), and log(L1+L2). Of all these variants only the second translog form, for which equation (13) is a special case, fit better than equation (13), and even then the improvement was not statistically significant. In most cases, using the alternative estimates in our optimizations model resulted in only trivial changes in optimal pavement thickness; when there were sizeable changes, they were in the direction of even thicker pavements. For example, at the median traffic level, using the second translog form raised the optimal value of D for both rigid and flexible pavements by about 0.8 inches. Hence our conclusions are, if anything, strengthened by the use of more flexible functional forms for the relationship between pavement design and lifetime.

We do not claim that our model captures all the effects on pavements that highway engineers should and do take into account. Better materials and construction practices may make current designs more durable than the road test data would predict. Nevertheless, highway design has not heretofore been carried out within an explicit economic optimization framework, so there is no necessary reason that it should have turned out to be optimal. Furthermore, to the extent that design guides based on the original AASHO results have influenced actual design practice, the faulty statistical analysis behind those results has misled engineers into thinking that heavy pavements will last longer than they do.

We also recognize that the controversy over the independent effects of time and weather needs better resolution before accepting recommendations to build pavements to last up to 30 years. There is, however, some evidence that even light pavements can last this long when not subjected to heavy trucks. The Pasadena Freeway in southern California, originally built as the auto-only Arroyo Seco Parkway, lasted 35 years without resurfacing. At that time, its inner lanes of thin flexible pavement had finally weathered enough to require rehabilitation; its outer lanes, of 6-1/2 to 9-inch-thick portland cement concrete, were still sound (Matthews and Baumeister, 1976, pp. 10-11). Parts of the Wilbur Cross Parkway in Connecticut, an 8-inch rigid pavement carrying no trucks, lasted for 35 years, and most of the Merritt Parkway in Connecticut was overlayed only after 30 years and largely because of damage by studded snow tires (Hudson and Seeds, 1984). It is worth noting also that a well-known British text on highway design recommends that rigid pavements be built to last at least 40 years for all classes of road (Croney, 1977, p.25).

IV. Results: Marginal Cost

Table 4 presents the marginal cost of highway wear from equation (8), at the FHWA default values of D for light, medium, and heavy pavements, and at our estimated D^* for the median traffic level. Marginal cost depends on Q through equation (7), but not very strongly empirically; we present results for the median Q. Again, several comments are in order.

Table 4

Short-Run Marginal Cost of Highway Wear

(our parameters, Q=1 million)

	Rigid Pavements		Flexible Pavements	
	D[a]	SRMC[b]	D[c]	SRMC[b]
Light	6.5	17.5	2.0	1275.6
Medium	8.0	6.9	3.7	39.1
Heavy	10.0	2.2	5.3	3.8
Optimal	11.5	0.8	6.4	0.6

[a]Slab thickness in inches.

[b]Cents per ESAL-mile

[c]Structural number

for high-volume roads. At median traffic levels for six-lane urban interstates, the long-run marginal cost (SRMC at D*) is less than one cent per ESAL-mile.

First, our 1986a paper on highway user charges used a marginal-cost estimate of 9 cents per ESAL-mile from U.S. FHWA (1982, p. E-25) as a rough national average. It appears this is reasonably representative of medium-strength rigid pavements or medium to heavy flexible pavements, and thus might be a satisfactory choice for a single uniform axle-weight-based user charge. However, it would be too high for the heavily traveled interstate system. The marginal-cost user charge for 10-inch rigid pavements is 2.2 cents per ESAL-mile: an amount that, for the typical fully loaded five-axle tractor-trailer combination, would extract payments comparable to current fuel taxes.

Second, trucking industry representatives are right in claiming that trucks would not be very damaging if pavements were designed optimally in the first place -- at least for high-volume roads. At median traffic levels for six-lane interstates, the long-run marginal cost (SRMC at D*) is less than one cent per ESAL-mile.

However, this point is qualified by the third observation: short-run marginal costs as defined by (8) vary tremendously over the range of highway types traveled by trucks. Thin pavements are extremely vulnerable and user charges over $10 per ESAL-mile can be justified in extreme cases. Clearly, an efficient pricing policy must take this variation into account. We note in passing that thin pavements are likely to be found in older urban cores sometimes subjected to heavy loads from construction traffic and garbage collection.

Finally, the results indicate that highways are subject to strong durability economies: long-run average cost declines markedly with traffic loadings. In fact, when traffic loadings are increased by a factor of 10, long-run <u>marginal</u> cost falls by approximately a factor of 7; therefore long-run <u>average</u> cost must fall even faster. This suggests that even in a world of optimal capital stock, marginal-cost user charges for highway wear would show great variation among roads with different amounts of traffic.

Because of durability economies, efficient wear-related user charges would not fully cover the costs of construction and highway maintenance in the long run. Thus other charges, such as license and registration fees, would still be needed to cover total costs. We discuss more fully the financial implications of wear-related user charges in two other papers (Small and Winston, 1986a, 1986b).

V. Conclusion

Using models of pavement deterioration very close to those developed for the AASHO road test, and estimating them from the road test data, we find evidence that existing design equations overestimate the life of thick pavements. Furthermore, current and past pavement design practice has led to underinvestment in pavement durability according to standard economic optimization procedures. At traffic levels found on six-lane interstate highways, optimal pavements would be substantially thicker, and would last two to four times as long, as current standard heavy-duty pavements. The current suboptimal practices may have resulted from basing decisions on the statistically flawed design equations, and/or from failing to incorporate economic optimization considerations into the design framework.

The marginal pavement-wear cost of heavy vehicles on existing roads is quite high, as claimed by an increasing number of researchers and policy makers. Arguments for steeply graduated user charges based on axle weights are valid for existing roads, and would remain valid for many optimal roads: indeed, the argument is overwhelming for thin pavements, which are extremely vulnerable to heavy axles. However, highway investment shows substantial durability economies. If marginal cost pricing were accompanied by optimal investment, the high-volume roads carrying much of the nation's freight traffic would have user charges that, for most vehicles, would be lower than existing fuel taxes.

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