

Engineering Analysis of the Economics of Predicted Pavement Life

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The problem of deteriorating infrastructure—including highways and the cost of proper maintenance—is a major point of debate for policy makers. With continued tight budgets and increasing deficits, policy makers are looking harder at the costs of building and maintaining a viable highway network. Economists and engineers sometimes disagree on pavement maintenance, design, and construction costs. For example, K. Small, C. Winston, and C. Evans, authors of *Road Work* (1989), have proposed that costs of highway maintenance could be reduced by billions of dollars by increasing the thickness of the nation's highways and by imposing a national system of weight-distance taxation. The authors of *Road Work* base their assertion that highway engineers underdesigned the nation's highways on a re-analysis of the AASHO Road Test data using a survival regression analysis. An analysis of the *Road Work* study concluded that the results are similar to those of the original AASHO Road Test when additional traffic is considered. *Road Work* may have used questionable assumptions regarding pavement service life, the role of thickness in pavement performance, and predicted traffic growth. As a result, the estimated savings in the maintenance of the nation's highways seem to be vastly overstated. The analysis concluded that current pavement management economics and thickness design, although not perfect, are reasonable.

Do the nation's pavement and infrastructure problems result from bad economic analysis and poor performance equations? That is the conclusion of *Road Work*, a 1989 publication that suggests that these are the reasons for our crumbling highway infrastructure, estimated to require billions of extra public dollars to maintain and improve (1). The book asserts that "the United States can no longer rely on current highway policy to finance and manage its roads" (1, p. 114). The book advocates a new national highway policy based on (a) pavement-wear taxes for heavy trucks, (b) congestion taxes for all vehicles and (c) construction of thicker pavements to achieve greater durability (1, p. vii). A recurrent theme of the book is that improper economic analyses, along with errors in the AASHO Road Test analysis, have led highway engineers to underdesign the thickness of existing pavements. The book suggests that by increasing the pavement thicknesses by only 1 or 2 in., billions of dollars would be saved.

The *Road Work* proposal for congestion taxes and a national weight-distance tax for each functional class of pavement based on axle loading, but with increased truck weight limits and reduced truck taxes, is of concern to many interested groups. The book is published by the Brookings Institution, noted for its economic studies. It was the work's lack of engineering input, however, that prompted a review of the

engineering aspects that were reported. The review of the *Road Work* analysis finds errors in application of pavement engineering principles and questionable assumptions, resulting in conclusions that are not supported by the analysis.

SCOPE

This paper reports an engineering examination of *Road Work* that compares actual highway engineering data with the assumptions, premises, and observations that led the authors of *Road Work* to their conclusions. This paper covers six main areas in which engineering expertise is required to develop a true economic analysis of the nation's highway pavements:

1. Examination of the reanalysis of the AASHO Road Test data,
2. Assumptions of pavement life and thickness,
3. The role of thickness in pavement life,
4. Routine maintenance costs,
5. Assumptions of traffic growth, and
6. Relative savings of reduced loadings versus increased thickness.

BACKGROUND

In the book and in a previous paper published in *American Economic Review* (2), Small and Winston have undertaken the ambitious task of performing a broad-based economic analysis of the nation's highway system with regard to structural pavement design. Their analysis is credible, especially concerning the original AASHO Road Test data. They note that the original analysis in the 1960s overestimated the life of thick rigid pavements because those pavements had not, then, showed distress. Since then, the AASHTO Design Guide has been revised in 1972, 1981, and 1985, with considerable effort to account for environmental factors (3).

Road Work articulates challenging and thought-provoking ideas that are worthy of consideration by highway officials in formulating future transportation policy. Several studies have shown that trucks do not pay their fair share of the costs imposed on the maintenance and construction of the highways they use. A recently conducted study by Texas Research and Development Foundation of the I-80 corridor in Pennsylvania concluded that trucks pay only 45 percent of the costs allocated to their use of that facility (4). *Road work* estimates that rural and urban truck operations pay only 29 and 14 percent, respectively, of their allocated share of maintenance

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and then suggests that their system of taxes would recover all costs (1, p. 59).

EXAMINATION OF REANALYSIS OF AASHO ROAD TEST

The *Road Work* reanalysis of the original AASHO Road Test data used modern regression analysis techniques with certain limitations and assumptions. Many original AASHO Road Test sections, particularly the thicker ones, never reached a 2.5 serviceability index at the end of the test (1,113,800 axle repetitions). In the *Road Work* analysis, any pavement section that had not yet reached a 2.5 serviceability index was considered a survivor; therefore, the serviceability index of that test section was censored.

In *Road Work*, the authors chose to analyze the data using the Tobit model, an econometric model originally developed by James Tobin in the early 1950s as a tool for the economic analysis of household expenditures (5). The model is functionally the same as that in a survival analysis. The model is frequently used when the data (for example the life of laboratory mice) have a measured lifetime, or when they survive the entire length of the experiment. The application of the Tobit-type model to the Road Test data is innovative and worthy of consideration.

TABLE 1 Test Section Data Used for Small and Winston Model

Pavement Thickness (in.)	Number of Test Sections		
	AASHO	CENSORED	OBSERVED
2.5	12	8	4
3.5	26	14	12
5	42	22	20
6.5	44	24	20
8	56	42	14
9.5	44	41	3
11	28	28	0
12.5	12	12	0
Total	264	191	73

As reported in an earlier paper (6), the authors of this paper have duplicated the results of the *Road Work* analysis using the Small data. The data used by Small consist of the original 264 rigid pavement test sections of the AASHO Road Test, but only 73 test sections reached the 2.5 present serviceability index (PSI) failure criteria. A tabulation of the test sections with respect to thickness is provided in Table 1.

Each data point is a recording of the number of axle repetitions when each section reached a 2.5 terminal serviceability index. If the present serviceability index is greater than 2.5, whether it is 2.6 or 4.5 PSI, no PSI value is given to any of these test sections in the Tobit analysis. In Table 1, note that of the 73 observed test sections only 3 of the 44 test sections of 9.5-in. thickness were included, and none of the 11-in. or 12.5-in.-thick test sections were included. Thus, the analysis depended heavily on pavements whose thickness was 8 in. or less. The resulting mean thickness of the observed test sections used in the *Road Work* analysis was only 5.8 in.

In Table 2, a comparison is made showing the Small and Winston results and the AASHO performance equation converted to natural logarithms. The most significant difference is the coefficient of the load term (A_2), which is only 3.24 in the Small and Winston term and 4.62 in the AASHO term. The equations predict the number of equivalent single 18,000-lb axle loads (ESAL) until a 2.5 serviceability index is reached. The significance of these equations for a typical 10-in. rigid pavement is a prediction of 9.3 million ESAL for the Small and Winston equation and 28.6 million for the AASHO equation. In the Small and Winston analysis, the 10-in. pavement would have to be increased to 12.5 in. to predict 26 million ESAL. The authors of *Road Work* believe that the disagreement between these equations caused the AASHO design model to overestimate the life of thick rigid pavements (2, p. 563).

SMALL ANALYSIS WITH ADDITIONAL ILLINOIS DATA

At the conclusion of the AASHO Road Test, many thicker rigid test sections were still in excellent condition, and the

TABLE 2 Comparison of AASHO and Small and Winston Performance Equations

EQUATIONS	COEFFICIENTS				PREDICTED ESAL (MILLIONS)
	(STANDARD ERROR)				
	A_0	A_1	A_2	A_3	
AASHO	13.53	7.08	4.53	3.17	28.6
SMALL & WINSTON	13.505 (0.307)	5.041 (0.329)	3.241 (0.260)	2.270 (0.242)	9.3

$$\text{Note: } \ln N = A_0 + A_1 \ln (D + 1) - A_2 \ln (L_1 + L_2) + A_3 \ln (L_2)$$

where D = thickness
 L_1 = load in Kips
 L_2 = number of axles

remaining sections were rehabilitated as new 10-in. rigid sections constructed in a controlled experiment (7). This rehabilitated roadway was incorporated into Interstate 80 to continue the research on this road test. For inclusion into the new study of the rehabilitated roadway, the rigid test sections had to be at least 8 in. thick and structurally sound, with no visible signs of deterioration. A few 8-in. sections, most of the 9.5-in. sections, and all of the 11- and 12.5-in. sections were retained as original test sections. The rehabilitated test facility included 47 original rigid test sections and 37 new 10-in. rigid test sections for a total of 84 experimental rigid sections.

The facility opened to traffic in November 1962 and carried an average daily traffic (ADT) of 3,500 vehicles per day. The traffic consisted of 71 percent passenger cars, 6 percent single-unit trucks, and 23 percent multiple-unit trucks. More than 96 percent of the heavy trucks used the outer lane and therefore only the outer lane was included in the analysis. In 1973 the ADT was 15,700. The average annual growth rate of ADT during the first 10 years was a high 26 percent.

Since the authors of *Road Work* acknowledge the Illinois data by reference, it was assumed that their analysis would also concur with the findings by the Illinois DOT report (1, p. 27). The data from the Illinois DOT study of the continuation of traffic on the Road Test sections were added to the *Road Work* data analysis, and surprising results were achieved. As previously reported (6), the authors of this paper have calculated new regression coefficients based on this Tobit-type reanalysis of the AASHO Road Test data.

The results in Table 3 show that, revised, the Small and Winston equation is now much closer to the original AASHO equation (using 2.5 terminal serviceability) than it is to the *Road Work* analysis. The coefficient of the load factor term, which was calculated in *Road Work* to be 3.24, is now 4.46. The significance of this change is that a typical 10-in.-thick rigid pavement will now have a predicted lifetime of 24.1 million ESAL versus the 9.3 million ESAL previously predicted by the Small and Winston analysis. Figure 1 shows the

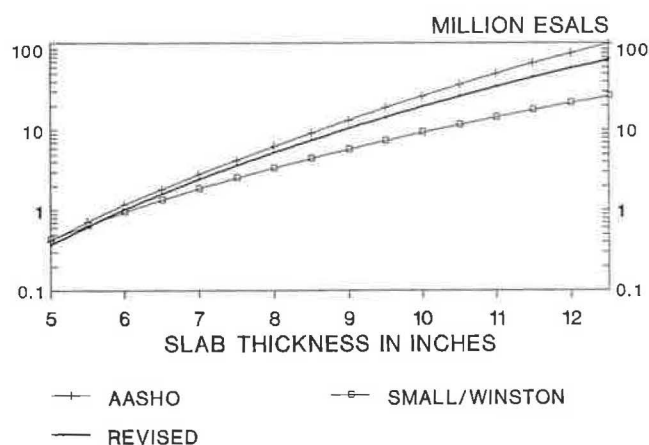


FIGURE 1 Comparison of 18,000 single-axle repetitions by thickness.

differences in the predicted repetitions of an 18,000-lb axle by pavement thickness.

When compared with the performance of the new 10-in.-thick rigid test sections of the Illinois study shown in Figure 2, the *Road Work* equation underestimates the life of thick rigid pavements far more than the original AASHO equation overestimates the life of the same pavements. The foundation of the subsequent *Road Work* economic calculations is based on this limited analysis, which assumes that a four-to-one savings will result for increased cost associated with increasing thicknesses.

ASSUMPTIONS OF PAVEMENT LIFE AND THICKNESS

To complete their economic analysis of the highway system the authors of *Road Work* had to rationalize a pavement thickness and service life for reference, against which in-

TABLE 3 Comparison of Small and Winston and Revised Performance Equations

EQUATIONS	COEFFICIENTS (STANDARD ERROR)				PREDICTED ESAL (MILLIONS)
	A ₀	A ₁	A ₂	A ₃	
AASHO	13.53	7.08	4.53	3.17	28.6
SMALL & WINSTON	13.505 (0.307)	5.041 (0.329)	3.241 (0.260)	2.270 (0.242)	9.3
SMALL & WINSTON REVISED	14.02 (0.379)	6.72 (0.277)	4.46 (0.247)	3.09 (0.257)	24.1

Note: $\ln N = A_0 + A_1 \ln (D + 1) - A_2 \ln (L_1 + L_2) + A_3 \ln (L_2)$

where D = thickness
L₁ = load in Kips
L₂ = number of axles

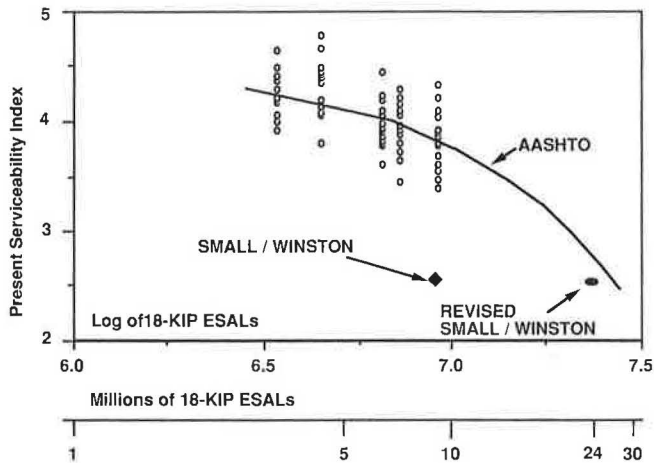


FIGURE 2 Performance of 10-in. rigid sections of rehabilitated AASHO Roadway.

creased thicknesses could be compared to show economic gain. Unfortunately, the thickness and service life values they selected as the basis for the future comparisons were understated, and thus the results are skewed toward higher savings.

Assumed Pavement Life

First, the *Road Work* authors define pavement service life in terms of the time lapse until resurfacing. Although the source of their service life is not clearly referenced, the authors of *Road Work* assume that the service life for rigid freeway pavements is 13.5 years and that for flexible pavements it is 10 years. These assumptions are significant, for most of the "maintenance savings" is achieved by doubling these assumed service lives to "optimum" service lives (1).

Based on two case studies that the authors of this paper have completed, it is believed that the *Road Work* assumptions regarding pavement service life are suspect. In a recent study of the Interstate 80 corridor in Pennsylvania, the average age of the original 10-in. rigid pavements was calculated as 22 years until resurfacing or reconstruction (4). However, there was no way to determine the serviceability index of those pavements at the time of resurfacing or reconstruction.

A data base for monitoring the long-term performance of CRCP sections in Texas (8) was examined for the age of rigid freeway pavements at resurfacing. It was determined that there was an average time lapse of 15.9 years until sections had received their first overlay, or a 17.8 percent greater service life than projected in *Road Work*. If all the unresurfaced pavements 15 years or older were resurfaced today, the average time to resurfacing in the Texas data base would calculate to 18.6 years, or 37 percent more than the *Road Work* assumption.

The authors of *Road Work* reference the source of their data as coming from interviews with highway engineers and their analyses (1, p. 39). Resurfacing is often justified for reasons other than loss of serviceability. If the Texas and Pennsylvania data are any indication, the *Road Work* analysis has significantly underestimated the referenced service life.

Assumed Pavement Thickness Based on Pavement Life

Second, the book's authors readily admit that they lack specific data on existing pavement thicknesses. They believe that because of the wide variation in climate and soil type, existing pavements can be more accurately described by the interval between resurfacing than by attempting to identify actual thicknesses. Using their method (which we suggest is faulty) for predicting years of pavement life from road thickness and traffic loadings, they then work backward to estimate the existing national road thickness for given functional classes, pavement types, and traffic level intervals (1, p. 39).

Although this circular method of calculation makes for nice, neat, and convenient data for analysis, other variables exist in the real world that also must be considered. The *Road Work* authors' simplification disregards these variables, with the net result that ultimate costs are understated and expected savings are overstated.

Assumed Costs a Function of Thickness

The *Road Work* equation for total pavement cost (TPC), which is optimized in their economic analysis, is

$$TPC = k_2 D + k_m \frac{1}{[e^{rT(D)} - 1]}$$

where

- D = thickness,
- k_2 = pavement construction cost per lane-mile per unit of road thickness,
- k_m = resurfacing cost per lane-mile,
- r = interest rate, and
- T = time between resurfacing (which depends on D).

The only variables in the *Road Work* equation that affect savings in what the authors term total pavement cost are changes in the assumed pavement thickness, the assumed existing service life, and the optimal service life, determined only by thickness and ESAL (1, p. 38). By basing the analysis on an assumed short pavement service life and comparing the results with an optimal service life affected only by thickness and ESAL, the authors argue that significant savings can be realized. But since the assumed values are highly questionable, we suggest that the projected "maintenance savings" are greatly overstated.

ROLE OF THICKNESS IN PAVEMENT LIFE

The authors of *Road Work* exaggerate the role of thickness in the life of a pavement. As has been stated, to simplify their analysis, the authors have consciously excluded all structural terms and factors except pavement thickness. Admittedly, many engineers and nonprofessionals feel that making pavements thicker might have extended the service life of some pavements that did not achieve a 20- or 25-year design life. Rather than as a result of improper thickness design, premature pavement failure is often the result of such factors as

(a) incorrect traffic forecasting, (b) the failure of subgrade support, (c) increased truck weights, (d) lack of proper maintenance, or (e) poor construction practices. Increasing pavement thickness is not a cure-all for each of these problems and may be economically unsound.

Contrary to the assumptions in *Road Work*, thickness is not necessarily the major determinant of pavement service life longevity. Data in Michigan and Texas and from the AASHO Road Test document cases in which thinner rigid pavements—in nearly the same locations, under the same traffic, and in the same weather—have outlasted thicker rigid pavements (8,9). Moreover, the decision to rehabilitate pavements is not necessarily based only on the loss of serviceability (roughness), as is the assumption in *Road Work*. In fact, the FHWA Rigid Pavement Distress Model, which is based on empirical data, assigns only 40 percent of the decisions to rehabilitate on loss of serviceability. The remaining 60 percent are assigned to faulting, pumping, loss of skid resistance, joint deterioration, cracking, depression, or swell (10). Both loading and environment influence pavement life. Many pavement engineers believe that, in reality, the interaction of heavy truck loadings in combination with environmental conditions has the greatest influence on actual pavement service life.

ROUTINE MAINTENANCE COSTS

Pavements deteriorate with age. The *Road Work* authors assume that a flexible pavement closed to truck traffic will last 25 years, whereas a rigid pavement will not deteriorate at all, since they have found “no evidence of significant aging in rigid pavements” (1, p. 28). Although this assumption makes for easy analysis, it ignores what state highway engineers experience throughout their careers: pavements deteriorate with age and require routine maintenance throughout their lifetimes.

If routine maintenance costs were constant throughout the lifetimes of pavements, those costs possibly could be excluded from the economic analysis. In reality, as pavement distress becomes greater, more maintenance is required. Often the forecast cost for continued routine maintenance makes an economic case for early resurfacing. In the Pennsylvania I-80 corridor study, the authors estimated that the cost of routine maintenance over the 25-year lifetime for that rural Interstate highway was equivalent to 10 percent of the life-cycle cost of the initial roadway construction (4).

The *Road Work* definition of maintenance savings apparently includes only those costs strictly related to resurfacing; other operations that highway departments normally categorize as routine maintenance are excluded. It is this failure to include these routine maintenance costs in an economic analysis that results in an overstatement of the calculated optimum pavement lifetime and in an inflation of the resultant maintenance savings. This is particularly important in the *Road Work* authors' analysis, since the savings are based wholly on extended pavement service lifetimes. Also, the longer the pavement service lifetime is extended, the greater is the amount of routine maintenance required.

The current AASHTO Design Guide suggests five methods of performing an economic analysis of alternate design strategies. The recommended present worth method, similar to

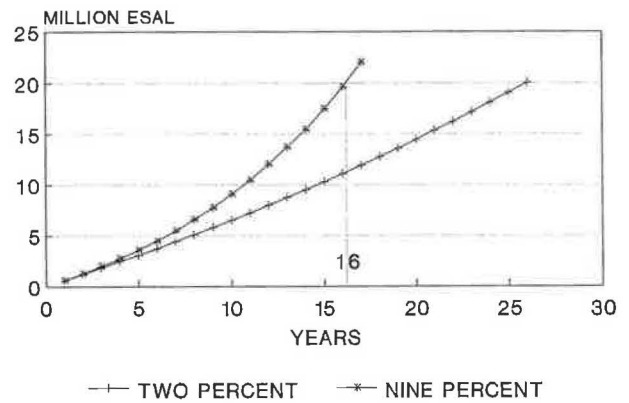


FIGURE 3 Comparison of predicted ESAL growth rate.

the *Road Work* analysis, describes a method for including the effects of routine maintenance costs as described by Baldock (11).

TRAFFIC GROWTH FORECAST

The *Road Work* authors acknowledge that their analysis is sensitive to traffic growth (1, p. 67). It has been generalized that average daily traffic growth rates are roughly comparable to the growth rate of the gross national product (GNP) (12). A conservative ADT growth rate for the assumed existing pavement service life would therefore range from 3.5 to 4 percent. A 3.5 percent ADT growth on rural Interstate highways is equated by the FHWA to a growth rate of 9 percent for ESAL loadings (12).

For their model, the authors of *Road Work* have assumed a growth rate of only 2 percent for all vehicles, noting that the number was chosen from the *AASHTO Guide for Design of Pavement Structures* (1, pp. 65,68). Yet the AASHTO Design Guide specifically states that a 2 percent growth rate for all vehicles is “a poor assumption” (3, p. D-24). The anomaly is that, in comparing costs to show savings, the assumed existing pavement service life reflects a much higher actual growth rate, whereas the calculated optimal 26-year service life uses only a 2 percent growth rate.

Road Work's hypothetical optimal Interstate pavement having a thickness of 10.41 in. would be designed (according to the authors' method) to achieve a service life of 26 years. As shown in Figure 3, if that design were based on 20 million ESAL using a 2 percent annual ESAL growth rate, and if a 9 percent annual ESAL growth rate were actually experienced, the pavement would have accumulated the same 20 million ESAL in only 16 years. The projected source of savings in their model, then, would be reduced from a 12.5-year gain until resurfacing to a gain of less than 3 years.

RELATIVE SAVINGS OF REDUCED LOADINGS VERSUS INCREASED THICKNESS

As mentioned earlier, the maintenance savings purported in *Road Work* are strictly a function of the estimated reduced time until the pavement requires resurfacing. It does not re-

flect the bulk of traditional state highway maintenance costs, including routine maintenance, lighting and signing, or initial construction (other than the additional asphalt or concrete required to achieve optimal thickness). The *Road Work* findings purport an \$8 billion savings in maintenance costs. The source of the savings comes from two areas: (a) reducing truck loadings by shifting freight to trucks with more axles to reduce pavement damage, (b) doubling the assumed existing service life to achieve optimal service life.

As reported in *Road Work*, "The source of the welfare gain is the 38 percent decrease in truck loadings (ESAL-miles) resulting from our policy, almost all of which is due to shifts among truck types" (1, p. 53). The reduction of ESAL-miles would be accomplished by replacing current truck-user taxes with marginal cost taxes based on axle-weight per mile of use on each pavement type. Hypothetically, this change would thus induce truckers to use vehicles with more axles on more cost-efficient routes. Considering the tremendous capital investment in present fleets, is it realistic to expect in the distant future the industry to replace the fleets and shift usage to vehicle configurations that offer financial advantages only?

The authors of *Road Work* conduct sensitivity analyses individually of the assumptions of initial pavement life and traffic growth. However, these sensitivity analyses are compared only with the results of their policy, which assumes a 38 percent ESAL reduction of loading. A realistic analysis would be a combination of higher initial pavement life, much higher traffic growth, and the effects of current pricing.

CONCLUSION

New analyses are always valuable, and the authors of *Road Work* are to be complimented on their innovative application of the Tobit model to the analysis of the AASHO Road Test data. Statistically, the Tobit regression analysis procedure can be an effective technique for data analysis in a Road Test-type experiment and potentially could be superior to ordinary least-squares regression analysis. However, when interpreting the results, it is important to look at the data to see what really can be inferred. In this application, because of the small percentage of failed pavements (72 percent censored), the small number of axle repetitions, and the large variance in performance, the Tobit analysis does not yield good prediction equations, especially for thick rigid pavements. However, when it is used with additional data for thicker rigid sections that carry additional loads in the Illinois data, the Tobit analysis produces results very close to those of the performance equations and design guides in current use by professional highway engineers.

The *Road Work* analysis uses questionable assumptions for estimating pavement service life and traffic growth. The questionable assumptions, the exclusions of variables other than thickness, and faulty analysis of thickness design result in overstated maintenance savings. The book presents no credible engineering evidence that increasing the nation's pavement thickness by small amounts would sharply cut overall highway costs.

In summary, although the AASHTO Design Guide analysis may slightly overestimate the life of thick rigid pavements, it is still valid and the prediction equations are reasonably ac-

curate. The current thickness design and techniques of economic analysis of alternate design strategies in use by the nation's highway engineers are satisfactory. Continued emphasis on pavement management systems and techniques have resulted in locally revised performance equations for specific geographic locations. There is no magic cure for offsetting the deterioration of the nation's crumbling highway infrastructure. A practical solution to the problem requires improving understanding and accountability while increasing reimbursement of the cost for the damage caused by axle loads.

REFERENCES

1. K. A. Small, C. Winston, and C. A. Evans. *Road Work: A New Highway Pricing and Investment Policy*. The Brookings Institution, Washington, D.C., 1989.
2. K. A. Small and C. Winston. Optimal Highway Durability. *American Economic Review*, Vol. 78, June 1988, pp. 560-569.
3. *AASHTO Guide for Design of Pavement Structures 1986*. AASHTO, Washington, D.C., 1986.
4. R. Harrison, M. T. McNerney, M. Euritt, and W. R. Hudson. Truck Versus Rail Freight System Cost Comparison: CONRAIL and I-80 Corridors. Texas Research and Development Foundation, Austin, 1991.
5. J. Tobin. *Estimation of Relationships for Limited Dependent Variables*. Paper 117. Cowles Foundation for Research in Economics, Yale University, New Haven, Conn., 1958.
6. W. R. Hudson and M. T. McNerney. A Comparison and Reanalysis of the AASHO Road Test Rigid Pavement Data. In *Transportation Research Record 1307*, TRB, National Research Council, Washington, D.C., 1991.
7. R. J. Little and L. J. McKenzie. *Performance of Pavement Test Sections in the Rehabilitated AASHO Test Road*. FHWA-IL-PR-76. Illinois DOT, Springfield, 1977.
8. C.-P. J. Chou, B. F. McCullough, W. R. Hudson, and C. L. Saraf. *Development of a Long Term Monitoring System for Texas CRCP Pavement Network*. Research Report 472-2. Center for Transportation Research, The University of Texas at Austin, Oct. 1988.
9. *Special Report 61E: The AASHO Road Test—Report 5—Pavement Research*, HRB, National Research Council, Washington, D.C., 1962.
10. *State Highway Cost Allocation Guide*, Vol. II, Technical Appendix. Report HHP-15 and TSC DTS-42. FHWA, U.S. Department of Transportation, 1984.
11. R. H. Baldock. The Annual Cost of Highways. In *Highway Research Record 12*, HRB, National Research Council, Washington, D.C., 1963.
12. *FHWA Pavement Newsletter*, Issue 12. Office of Highway Operations, FHWA, U.S. Department of Transportation, Washington, D.C., Aug. 1988.

DISCUSSION*

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In discussing our book (1), McNerney and Hudson focus mainly on one of its conclusions—that lifecycle pavement costs could be reduced by designing pavements for greater durability.

*This discussion was based on the original paper, which was later revised.

They contest our analysis of pavement wear and a variety of other assumptions. Their own analysis of pavement wear, however, uses data that already have their preferred equation built in, and they neglect to mention that we report extensive sensitivity analyses of the very assumptions they challenge (1). In no case does altering key assumptions overturn our findings, and in several cases it strengthens them.

Contrary to the authors' assertion, our book does not advocate increased weight limits.

We discuss the authors' main criticisms in turn.

REANALYSIS OF PAVEMENT WEAR

Current design procedures are heavily dependent on the original road-test analysis by the AASHO. Our reanalysis of the AASHO data introduced survival or Tobit analysis to account for the statistical effects of censored data. "Censored" is a technical term meaning that, for certain observations, the variable being explained is known only to lie in a certain range; here, the number of axle loads to failure is censored for those pavement sections that outlasted the duration of the test. These censored observations still provide valuable information, and McNerney and Hudson are simply wrong to assert here and in their previous paper with Dossey (2) that they are omitted from our analysis.

In that paper, the authors approve of our methodology but attempt to apply it to an enlarged sample that merges the AASHO data with supplementary data from in-use Illinois pavements. However, these supplementary data are of a fundamentally different character from the AASHO data. First, in the new data each pavement section received a mixture of various axle weights. The equation being estimated describes the effect of just one axle weight, so it cannot be applied to in-use data without specifying some aggregation rule. What is worse, the supplementary data used by the authors contain no information about the traffic mixture except an aggregate measure of ESALS, calculated from the original AASHO equation (3, p. 34).

The results are miraculous. Although the supplementary data can provide no information about effects of various axle loads, the authors claim that including them reinstates the AASHO fourth-power law for their relative damaging power, as compared with a third-power law that we obtained by the same technique without the supplementary data. More generally, one must be suspicious of the remarkable coincidence that the original AASHO equations, which the authors acknowledge to have resulted from faulty statistical analysis on inadequate data, turn out to be about right after all.

There is substantial external evidence that the AASHO equations misrepresent heavy rigid pavements. To cite just two examples, experience with the Illinois Tollway indicates that the AASHO equations overpredicted pavement lifetimes by a factor of three (4, p. 39), whereas, on a national sample, the AASHO equations overpredicted average lifetimes in wet-freeze climates (like that at the AASHO test site) by a factor of 1.9 for unreinforced and 2.8 for reinforced rigid pavements (5, p. 7). These lifetimes are measured in equivalent axle loads, so the results have nothing to do with the accuracy of traffic forecasts. Widespread concern over rapid pavement deterioration has led many states, such as Pennsylvania and

Florida, to strengthen their design standards, and AASHO itself (now AASHTO) to build more conservatism into its revised design guides.

To this evidence we add that the Illinois Department of Transportation (3), in its own analysis of the supplementary data used by McNerney and Hudson, reports that the AASHO equations drastically underpredict the lifetimes (in ESALS) of heavy rigid pavements. For example, the 11-in. rigid pavements deteriorated at approximately the rate predicted by the AASHO equations for 10-in. pavements, whereas 12.5-in. pavements performed only as 10.75-in. pavements were supposed to (3, p. 32). The Illinois researchers conclude, as we do, that the rigid pavement lifetimes are much less sensitive to thickness than stated in the AASHO equations (3, p. 35).

It is worth noting that only a modest portion of the benefits we project from our recommended policies come from our reanalysis of the AASHO data. Another portion comes from increasing the durability of flexible pavements, where our pavement-life equation does not differ much from that of AASHO. The greatest portion comes from using pricing incentives to alter the mix of vehicle types and thereby reduce the pavement-damaging power of trucks. We now turn to the authors' criticisms of our analyses.

ANALYSIS NEGLECTS INFLUENCE OF AGE AND ENVIRONMENT ON PAVEMENT LIFE

Our extensive discussion of the issue of factors affecting pavement life (1, pp. 28–31) is based on the same premise as that stated by McNerney and Hudson: it is the interaction between loadings and environmental conditions that determines pavement service life. In the case of flexible pavements, the World Bank has provided quantitative estimates, which are incorporated in our analysis. The effect is to increase the cost-minimizing pavement thickness. The reason is that the World Bank equation, consistent with most evidence, assumes that age has a more deleterious effect if the pavement already has been weakened by heavy use; hence, the stronger the aging effect, the more important it is to forestall such weakening through initial design. In the case of rigid pavements, the evidence for aging effects is inconclusive and no quantitative estimate is available, so we assumed that age-related deterioration is negligible.

ANALYSIS UNDERSTATES EXISTING PAVEMENT THICKNESSES

McNerney and Hudson wrongly state that we lack data on pavement thicknesses of existing roads. As we make clear, FHWA provided such data, but we deemed them unsatisfactory for our purposes (1, pp. 19, 39–41). Instead, we start with information about the lifetimes of existing pavements. We then calculate (for each road or pavement classification) the corresponding thickness, or more precisely, the corresponding parameter that makes the AASHO equation represent that pavement. There is nothing circular in this and nothing more mysterious than solving a nonlinear equation for a unknown parameter.

In questioning our lifetime assumptions, the authors cite cases that, besides being selective, offer an invalid comparison. Our pavement lifetime is defined as the time taken for the pavement to deteriorate to a predetermined value of the pavement serviceability index, namely 2.5. Times to actual resurfacing may be quite different, especially if maintenance is deferred for budgetary reasons.

Even if actual lifetimes of existing pavements are 30 percent higher than we assumed, our results would be only modestly altered according to one of our sensitivity analyses (1, p. 67). The cost-minimizing pavement design would still require an increase in annualized capital expenditures (relative to current practice) of about 62 percent of that in our base case; pricing and revenue implications would be virtually unchanged.

ANALYSIS IGNORES ROUTINE MAINTENANCE

Routine maintenance costs could be incorporated into our model in the same way as are user costs, since both occur in cycles corresponding to periodic resurfacing. In one of our sensitivity analyses (1, p. 67), we found that accounting for user costs strengthened all our conclusions considerably: durability should be even greater, prices higher, and overall cost savings larger. Including routine maintenance would have a similar, but much smaller, effect on our results.

ANALYSIS UNDERSTATES TRAFFIC GROWTH

Contrary to the assertion of McNerney and Hudson, our sensitivity analysis showed that the growth rate of traffic loadings has only a small effect on our results [1, p. 68]. The reason is that our data on traffic loadings refer to today, not the date the road was built. Hence, assuming a higher rate of traffic growth implies that traffic was lighter until now and will be heavier subsequently than in the base case. This assumption has offsetting effects on the time of resurfacing.

PRICING INCENTIVES WILL NOT AFFECT TRUCKERS' BEHAVIOR

The authors argue that truckers will not respond to axle-weight-based taxes because they are unwilling to trade extra investment now for benefits realized "only in the distant future." This reasoning is false: to the trucking firm, whose taxes would depend on axle weights, the financial benefits from reconfiguring their fleets would be an immediate reduction in taxes. In Oregon, where such taxes are in effect for trucks exceeding 80,000 pounds, truckers have responded rapidly.

REFERENCES

1. K. A. Small, C. Winston, and C. A. Evans. *Road Work: A New Highway Pricing and Investment Policy*. Brookings Institution, Washington, D.C., 1989.
2. W. R. Hudson, M. T. McNerney, and T. Dossey. Comparison and Reanalysis of AASHO Road Test Rigid Pavement Data. In

- Transportation Research Record 1307*, TRB, National Research Council, Washington, D.C., 1991, pp. 122-128.
3. R. J. Little and L. J. McKenzie. *Performance of Pavement Test Sections in the Rehabilitated AASHO Test Road*. Report FHWA-IL-PR-76. Illinois DOT, Springfield, 1977.
4. B. H. Welch, M. W. Witzak, D. C. Zimmer, and D. G. Hacker. Pavement Management Study: Illinois Tollway Pavement Overlays. In *Transportation Research Record 814*, TRB, National Research Council, Washington, D.C., 1981, pp. 34-40.
5. M. Liu, M. I. Darter, and S. H. Carpenter. Evaluation of 1986 AASHO Design Guide for Jointed Concrete Pavements. In *Transportation Research Record 1207*, TRB, National Research Council, Washington, D.C., 1988, pp. 1-20.

AUTHORS' CLOSURE

Although we consider the Tobit regression an innovative approach to predicting pavement life, we nevertheless believe, even after further review, that the Tobit analysis is inferior to the AASHO Road Test analysis. The AASHO Road Test analysis of serviceability loss was a complicated two-step process that accounted for the sharp change in the slope of serviceability curve as pavements reached serviceability near 3.5 PSI. The comprehensive analysis performed by the road test staff showed that a direct linear regression of PSI loss was ineffective in predicting pavement loss.

However, the authors of *Road Work* have used a direct Tobit regression, which, in some cases, would theoretically be an improvement over a direct Ordinary Least Squares (OLS) regression when predicting lifetimes. Still, we do not believe it an accepted statistical practice to apply a Tobit regression technique with more than 70 percent of the data as right-censored observations. The Tobit technique is not a full information regression (the serviceability of the censored observations is discarded); rather, it is a bias estimator. Thus, the regression can be highly influenced by only a few observations and the period at which the test ends.

The combination of a Tobit regression that uses only 28 percent full information observations and extrapolates the predicted pavement life more than 10-fold produces fragile results. Using the 12 additional years of real traffic on only a few test sections, our analysis shows that the *Road Work* results are so fragile that, regardless of whether the traffic stream is converted using a *Road Work* or AASHO formula, the results are closer to the AASHO analysis than to the *Road Work* analysis.

Pavement materials and pavement performance are highly variable over time. The AASHO design guide gives specific guidance on how to design pavement to a 90 percent reliability design life using two standard deviations. The AASHO regression has a reported standard deviation of 0.17 on the LOG scale. Therefore, a 10-in. pavement with a 28.6-million ESAL predicted life will have a 90 percent reliability of achieving a 13.1-million ESAL design life. Using this reliability measure, the AASHO Road Test equation does not overpredict design life.

A shortcoming of the *Road Work* analysis is its reported standard deviation of the regression. On initial inspection, the reported standard errors of 0.306 for the intercept, 0.329 for the thickness coefficient, and 0.259 for the load coefficient appear innocuous. However, calculating a 90 percent reliability measure, considering this in a natural log value, makes

the analysis seem inappropriate. If the two standard deviations of only the thickness coefficient are used, that alone is enough to change the predicted 18-kip ESAL load on a 10-in. pavement from 9.34 million repetitions to 1.9 million repetitions. If the intercept, load, and thickness coefficients are all taken at two standard deviations at the same time for 90 percent confidence, the design repetitions for a 10-in. pavement is reduced from 9.34 million to 0.22 million. Obviously, this is not a robust regression. Using this reliability measure, the Winston-Small pavement would have to be several feet thick to achieve a 90 percent reliable, 9-million ESAL design life.

A single-step regression of serviceability loss of the AASHO test data is an oversimplification that provides no useful in-

formation. The complex analysis of the rigid pavement data performed by Irick at the road test is far superior to any direct regression technique, be it Tobit or OLS. Using the oversimplification of the serviceability loss by direct regression of the AASHO Road Test only shows a lack of understanding of both the complex action of pavement deterioration and the complexity of the original AASHO regression analysis. The direct Tobit regression is definitely not an improvement to the AASHO Road Test analysis.

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