An Economic Replacement Model for Highway Surface Determination

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This paper attempts to point out basic inadequacies in the conventional cost approach to highway surface-type determination, and subsequently, presents an economic replacement model couched within a highway framework. The conventional method relies heavily on a static concept of cost, whereas the proposed replacement model recognizes the value of funds over time; the first-mentioned approach requires a predetermined estimate of surface life, whereas the latter method is equipped to make an objective determination of surface life; the replacement approach, in an attempt to recognize all costs associated with the surface structure over its life, includes an estimate of road user cost not present in the HRB method.

Specifically, the model provides a surface replacement solution in terms of an optimum economic time span for pavement type (i.e., rigid or flexible) based on the minimization of an average cost stream over time, where the cost stream is made up of the initial surface structure cost and the anticipated stream of maintenance and road user costs. In this paper the anticipated stream of maintenance costs is simple regression estimates of these costs over the life of selected rigid and flexible pavement structures. The final solutions yielded by the model, in terms of present worth calculations, indicate the comparative total amounts of money needed today to build, maintain, and operate either a flexible- or rigid-type surface structure over time.

• OFTEN in the economic determination of highway surface structures (i.e., rigid or flexible type), a comparison of alternative costs by the Highway Research Board's annual cost formulation is used[1]. Given highway location and design, highway officials must decide on "surface type," and such a decision should be couched in such terms as initial cost, estimated surface life, estimated future maintenance costs, and traffic volumes. This paper contends that the basis of most present methods of computing surface structure costs precludes proper consideration of these factors. On the other hand, is there a method of estimating highway costs which can account properly for the previously mentioned variables?

The basic aim of this paper, therefore, is briefly to discuss basic aspects of the HRB method of estimating highway costs in particular and subsequently present an economic model that attempts to recast factors crucial in highway decision making in a somewhat different framework.

HIGHWAY RESEARCH BOARD METHOD

The abbreviated HRB formula for computing annual road costs as presented by Breed (5, p. 94) is

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[1] Actually the HRB annual cost formulation has been reformulated as an approximation by Breed (5).

$$C = \left(\frac{A+S}{2}\right) r + \left(\frac{A-S}{n}\right) + B + \frac{E}{n} \qquad (1)$$

in which

C = average annual cost;
A = original capital cost;
B = annual maintenance cost;
r = rate of interest;
n = estimated life of surface;
S = estimated salvage value of highway at end of n years; and
E = required periodic maintenance during n.

The first term of the equation computes an average annual interest payment; the second term provides for straight-line depreciation; a combination of these terms yields a simple average annual capital cost figure (12, p. 491). The results are more valuable from a cost-accounting standpoint rather than an economic one, i.e., cost accounting in the sense that the model assumes the initial cost to be borrowed and repaid in amounts equal to annual average depreciation plus interest (6, pp. 177-178). The third and fourth terms describe the entire maintenance pattern as averages added to the average depreciation and interest figures for an estimate of total average annual cost. An average annual cost so derived for a particular type of surface structure is then compared with a similarly found value for a second type of surface structure. That type exhibiting minimum average annual cost is considered the optimum.

The following are the basic objections to this approach for highway surface structure costs:

1. The HRB method does not distinguish between value and cost. That is, the method in question defines a static pattern of cost allocation (which is useful to the cost accountant) rather than a pattern of changes in the usefulness or utility associated with a given facility (18, Chs. 8 and 9).

2. As a result of "averaging," the HRB formulation does not account for the intertemporal value of money over n.

3. The expected life (n) of a facility in no way reflects the period of economic or physical replacement.

4. The HRB formulation does not take into account the element of road user cost. If n is assumed to be some function of overall costs, then road user costs must be given consideration in addition to initial and maintenance costs, because the value of the highway (value expressed in terms of economic utility) would remain constant if, for some reason, no vehicles were allowed to use the facility. (The assumption is that in the short-run, technological innovations, various forms of obsolescence, climatic vagaries, and the like, are constant. Therefore, any changes in the value of the highway are necessarily engendered by road users. By the same token, any maintenance expenditures would exist only as a function of traffic volumes, and in the absence of such volumes would presumably be nil.)

ALTERNATE APPROACH

Important Considerations

In private industry, the introduction of new technology, cheaper sources of raw material, etc., enable an entrepreneur to compete more efficiently through price adjustment. These efficiency factors imply a lower unit cost structure facing an entrepreneur, which in turn implies a lower unit price structure facing consumers. The lowered price structure further implies that consumers are maximizing their expenditures. (This statement implies, from an economics standpoint, that the value of the monetary unit remains constant.) Highway surface determination, a concern of government, must rest on the total cost of a given surface structure over the life of that structure. Moreover, that surface is preferable whose entire structure has the lowest overall initial, maintenance, and road user costs. Stated differently, the goal should be the selection of that surface type possessing economic advantage. As in the case of private industry, the advantages stemming from a relatively low set of costs make sense only insofar as the public is now able to consume (or use) a given highway at some optimally minimum price.

Because the cost of building, maintaining, and operating highways is covered by road user taxes[2], the government becomes obligated, in an economic sense, to build roads that can be consumed at some relatively minimum price. This is true because the price paid by road users (which they view as the cost of vehicle operation, maintenance, time, etc.) will be a function of the initial road cost, maintenance cost, and anticipated surface life. Thus, in the proposed model, an estimate of road user costs is included.

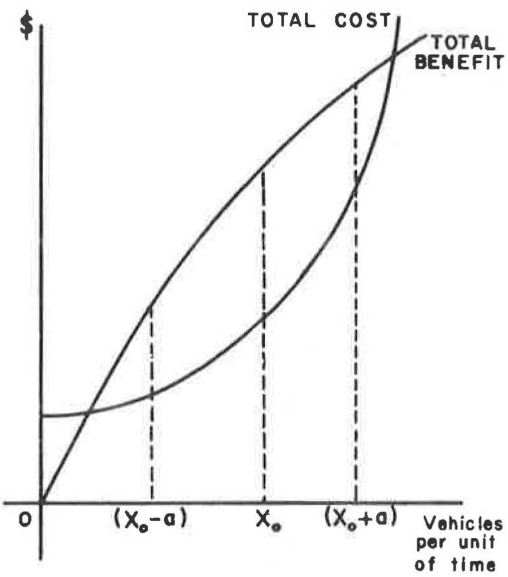

Figure 1. Total cost and benefit curves.

Model

The proposed model involves essentially the computing of the present worth of present and future highway construction, maintenance, and road user costs. In addition, the process indicates an optimal economic time for surface replacement as a function of minimum weighted average discounted costs. This "economic surface replacement time" is not necessarily the same as the actual physical replacement often dictated by engineering experience and consideration. To this extent it is basically an economic replacement model.

The economic significance of "minimum weighted average discounted cost" deserves some theoretical attention because it occupies a place of basic importance in the model. Figure 1 shows the hypothetical long-run path of total cost and total benefit associated with increasing numbers of vehicles per unit of time, using a given highway improvement. It is assumed that total cost is made up of initial, maintenance, and road user costs; total benefit may be viewed as a monetary expression of total savings resulting from an improvement in the highway system. Given these two functions, an optimum number of vehicles per unit of time may be found at the point where the difference between total cost and total benefit is maximum. In Figure 1 such a point might be X_0; that is, X_0 vehicles per unit of time derive maximum net benefit from a given highway improvement.

If it is assumed that the number of vehicles using this given improvement increases at some known rate, then it is possible to state that maximum net benefit will accrue, for example, in the 10th year. Moreover, it is demonstrable that for more than X_0 vehicles per unit of time, say $(X_0 + a)$ vehicles, total cost is rising at a faster rate than total benefits. By the same token, total benefits would be rising at a faster rate than total cost at $(X_0 - a)$ vehicles; thus, the justification for using X_0 as the point of optimality.

This reasoning may be enhanced through the use of the average and marginal curves shown in Figure 2. These four curves are derived from the total curves in Figure 1. The optimum number of vehicles, X_0, is found at the point where the marginal cost and marginal benefit curves intersect in Figure 2. These marginal curves are the derivatives of the total curves in Figure 1, and measure the cost and benefit associated with

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[2] In general, this is true whether the cost of highways is financed directly from the general fund, or financed by bond issues which, at some point in time, are paid off through taxation. This is not to imply, however, that the economic consequences are identical regardless of the method of financing.

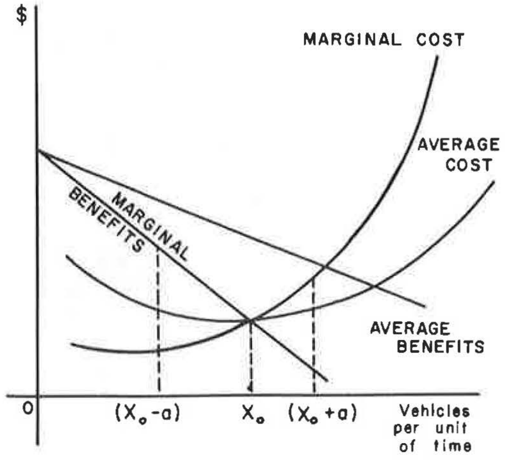

Figure 2. Average and marginal cost curves.

an additional or marginal unit; i.e., $(X_0+a) - X_0$. The marginal unit at $(X_0 - a)$ vehicles in Figure 2 will receive benefits in excess of costs as measured by the vertical distance between the marginal cost and marginal benefit curves. Hence, it would pay more units to use the improvement; i.e., up to the point where the cost to the last unit of vehicles is just offset by benefits. If the number of vehicles increases beyond X_0, then the cost to the marginal unit exceeds benefits; thus, vehicle expansion is economically unfeasible. Moreover, in terms of Figure 1, the addition of vehicle units beyond X_0 would produce a decline in total net benefit. The proposed model, therefore, suggests surface replacement in a time period correspondent to X_0 vehicles.

The marginal cost curve bisects the average cost curve at the minimum point of the latter. The nature of their relationship to the total cost curve precludes a bisection of the average cost curve by the marginal cost curve at any point other than the minimum. However, that the marginal benefit curve cuts the average cost curve at its minimum point, occurs here by assumption. This critical assumption is that officials responsible for the highway improvement have correctly estimated benefits accruing over time in terms of the improvement, maintenance, and road user costs. For if they were to overestimate or underestimate the pattern of benefits, the average and marginal benefit curves would fall to the left and right, respectively, of the minimum point on the average cost curve. This paper is not concerned with these consequences, however, because the proposed replacement model always assumes that the optimum point is determined at average cost = marginal cost = marginal benefit.

Such a replacement approach has several advantages (1) over the conventional HRB method:

1. The proposed method stresses economic optimization rather than conventional financial considerations.
2. Separate forecasting of maintenance and road user costs is necessary, and these forecasts will automatically include estimates of technological innovation and obsolescence.
3. The selection of an economic surface replacement date by the proposed method is objectively determined as a function of all costs.
4. It is possible to ascertain the nature of an optimal pattern of maintenance costs once the other variables are known, and also optimal traffic volumes given the other variables.

The following are the general assumptions used:

1. Costs of rough-grading, right-of-way, landscaping, and structures are identical for both flexible and rigid surface structures, and therefore, may be omitted from the comparison.
2. All costs (i.e., capital, maintenance, and road user) are paid at the time in which they are incurred. Moreover, the present worth structure tells how much money would be needed today to meet both present and future costs. Thus, future annual highway costs paid at the time in which they are incurred are composed of maintenance and incremental road user costs only. Incremental road user cost is the additional cost resulting from an increase in traffic volumes. Normally, it would be reasonable to recognize that over time, unit vehicle-operating costs would tend to rise. However, for purposes of demonstrating this model, it is sufficient to assume that unit vehicle-operating costs remain constant. A further assumption is that a rising annual maintenance

cost curve implies restoration of the roadway to its initial state after each year. There fore, incremental road user cost will be considered a function of the sum of increments in traffic volumes, and may be stated as $(C_2' - C_1')$, $(C_3' - C_1')$, ..., $(C_n' - C_1')$ in which C_i' is total road user cost in time period i.

3. At the time of replacement, only resurfacing costs (rather than surface structure costs) need be considered because the lives of other items that constitute a surface structure are assumed to be infinite. (In this assumption, the problem of salvage value is brought under control because only resurfacing costs are equated to replacement costs, and the time span is considered infinite. On the other hand, some estimate of salvage value may be accounted for by adjusting the cost of resurfacing.)

4. The rate of interest used to discount future costs is 7 percent (Appendix). The selection of an appropriate rate of interest for economy studies is presented elsewhere (11, 14, 26).

Having stated the basic assumptions underlying the proposed replacement model, it is assumed further that, in constructing some typical mile of highway, the alternatives are (a) rigid surface structure, or (b) flexible surface structure. If A is the initial or first cost of either type of surface structure; A′ is the cost of resurfacing the structure when necessary; C_i is the projected annual maintenance cost and road user cost differences in the ith year; the factor $1/(1 + r)^{i-1}$ computes the present worth of future costs when given the rate of interest r; then,

$$K_n = A + C_1 + \frac{C_2}{1+r} + \frac{C_3}{(1+r)^2} + \ldots + \frac{C_n}{(1+r)^{n-1}} + \frac{A' + C_1}{(1+r)^n} + \frac{C_2}{(1+r)^{n+1}} + \ldots + \frac{C_n}{(1+r)^{2n-1}} \qquad (2)$$

This equation describes the complete stream of present and future costs when the highway is to be resurfaced every nth year and where K_n is the total present worth of that stream. When this formulation is applied to both rigid and flexible surface structure costs, the economically optimal facility is that whose total discounted costs (i. e., present worth) are a minimum, and may be selected by direct comparison. The mechanics of this model have been adopted from Churchman, Ackoff, and Arnoff (7); further discussion of replacement models is presented by Alchian (1), Bellman (4), Grant and Ireson (12), and Dean (10).

It is methodologically incorrect to compare total costs, based on a single life cycle, of two surface structures whose lives are estimated to be different. Consequently, it becomes necessary to establish cyclical iterations so that ultimately only an equal number of time periods are compared; i. e., finding the least common multiple. In actual applications to highway surface determination problems, however, the number of iterations can be high so that the entire valuation process, based on present worth factors, often tends toward infinity (general assumption 3). Now if this assumption of infinity is made (i. e., where the discount factors are a convergent series over time), then,

$$K_n = A + \frac{A' + \sum_{i=1}^{n} \left[\frac{C_i}{(1+r)^{i-1}} \right]}{1 - \left[\frac{1}{(1+r)^n} \right]} \qquad (3)$$

This equation shows how much money will be needed today initially to construct the road and resurface it every nth year. For economy studies, this approach is quite acceptable; on the other hand, from an accounting or financing standpoint, such a formulation would be meaningless.

(Actually, Eq. 3 results in a duplication of initial surface cost because this cost is implicit in A and explicit in A′. Perhaps more correctly, the equation should be

$$K_n = (A - A') + \frac{A' + \sum_{i=1}^{n} \left[\frac{C_i}{(1+r)^{i-1}} \right]}{1 - \left[\frac{1}{(1+r)^n} \right]} \tag{4}$$

This is because it is assumed that only the surface (wearing course) is replaced every n years. But this would not apply to rigid structures unless it is assumed that such a structure is resurfaced with concrete rather than asphalt. Throughout this study, however, it is assumed that K_n, as expressed in Eq. 3, is a good approximation of costs.)

The computation of K_n assumes that n is objectively determined. If, for a given surface structure type, K_n is a minimum, then it can be demonstrated that $K_{n+1} - K > 0$ and $K_{n-1} - K > 0$. These cost-minimizing inequalities may be verbalized in terms of weighted average costs where the sum of the discount factors are used as weights. Thus, one should resurface every n years if the weighted average of all previous costs in the nth year is less than the actual undiscounted cost in the nth + 1 year. In other words,

$$C_{n+1} > \frac{A + C_1 + \frac{C_2}{1+r} + \frac{C_3}{(1+r)^2} + \ldots + \frac{C_n}{(1+r)^{n-1}}}{1 + \frac{1}{1+r} + \frac{1}{(1+r)^2} + \ldots + \frac{1}{(1+r)^{n-1}}}$$

A complete mathematical analysis of these cost-minimizing rules is given by Churchman, et al. (7, pp. 485-7).

APPLICATION OF MODEL TO ACTUAL DATA

In testing the model as presented in the foregoing section, it was necessary to procure three types of data: (a) highway maintenance cost data, (b) projected road user cost, and (c) initial or first cost per mile. These data were obtained from Minnesota Highway Department records and traffic engineering forecasts. This section describes the treatment of the data, its inclusion in the model, and the results of the analysis.

Maintenance Cost Patterns

The proposed replacement model requires that a projected pattern of total surface maintenance costs be estimated over the life of a given surface type. In meeting this requirement, sample control sections of rigid and flexible highways were obtained from the total highway mileage in the State of Minnesota. In drawing a sample of control sections, three governing factors were present because the basic concern was the establishment of cost patterns over the surface life of a facility. First, only those control sections exhibiting a completed surface life (i.e., from time of initial construction to time of complete resurfacing) were considered. Secondly, though the flexible roads were predominantly low-type structures, it was decided on statistical grounds not to mix whatever scant information available on high-type flexible surfaces with that on low-type surfaces. Thirdly, all maintenance cost figures apply to one roadway. (Maintenance cost records are only available since 1939; therefore, all cost observations are contained in the 21-year span between 1939-60.)

Highway maintenance expenditures were divided into routine maintenance and special maintenance. Routine maintenance may be defined as the regular and normal maintenance to prevent and correct minor deterioration of the surface structure. Special maintenance is distinguished from routine maintenance in that the former is periodic and includes major restoration of a surface structure, and/or repair of structural failure. Normally, special maintenance also includes resurfacing; however, these costs have been deleted, insofar as possible, from the sample.

Figure 3 shows the pattern of routine maintenance costs for rigid surface structures. The parabolic regression curve is based on an averaging of per mile year-to-year costs over the life of 14 control sections. Moreover, these and other costs have been converted into constant dollars; i. e., the 1947-49 general price index = 100 was used to deflate the actual money costs, so that changes in the value of money would not appreciably affect the averaging process. Figure 4 is a summary of special maintenance costs for rigid surface structures. Because of the unexplained variability in these data, the semi-average method for determining trends was used. (The semi-average trend line is easily distorted by extreme values. Hence, Figure 4, at best, is a rough estimate of special maintenance costs.) Figure 5, which is the summation of Figures 3 and 4, is a completed estimate of annual per mile maintenance costs for rigid surface structures. Figures 6, 7, and 8 are similar cost estimates for a sample of 15 flexible surface control sections. Tables 1 and 2 summarize all estimated and extrapolated maintenance costs over a 30-year period.

Projected Annual Road User Costs

As stated earlier, C_i is composed of both annual maintenance and incremental road user costs per mile. It is assumed that incremental road user cost is a function of some linear change in traffic volumes. That is, if, for example, an ADT of 6, 500 is expected in year 1, and 8, 000 ADT is forecast for year 15, then the annual incremental increase in vehicles will approximate 107 vehicles in year 2, 3, . . . , 15. The incremental ADT figures should then be converted into "passenger car equivalent" so as to account for trucks and other commercial vehicles (2, p. 29). Once annual incremental traffic volumes are determined, the computation of annual per mile road user costs is a straightforward process (2, Sec. I)(Tables 3 and 4).

Case 1

A decision was made to redesign and reconstruct approximately 10 miles of highway in the State of Minnesota. The total per mile initial construction cost for a rigid surface structure was estimated at $96, 277; the same cost for a flexible surface structure was estimated at $89, 292. (For purposes of this study, any salvage value contained in the old road is assumed not to exist. In other words the old road is considered as if it were a newly constructed highway.) The present ADT in terms of passenger car equivalent is 2, 310 vehicles; the forecasted 1980 passenger car equivalent is 3, 376 vehicles. These PCE figures translated into annual per mile road user costs are given in Table 3. (The constant unit cost shown in this table as well as in Table 4 reflects not only fuel, tires, and oil but also repairs, depreciation, time, and comfort and convenience. There is some question as to whether these latter costs should be included or excluded from the total unit cost for purposes of this study. As can be seen, exclusion of these costs will result in longer surface replacement times than given in Tables 5 through 8.) To these annual road user cost figures are added the estimated annual per mile maintenance cost figures for both rigid and flexible surface structures given in Tables 1 and 2. The model, as applied to these various costs for Case 1, is given in Tables 5 and 6. [The general form for Tables 5 through 8 has been borrowed directly from Churchman, et al. (7, p. 488).] The time of surface (not "surface structure") replacement for both rigid and flexible surfaces as a function of weighted average costs is 11 years. Both tables show that continued use of the existing surface beyond the 11th year violates the cost-minimizing principles discussed earlier.

It it is assumed that all resurfacing, regardless of existing surface structure type, is done with asphalt, and a 2-in. overlay for a single roadway will cost approximately $13, 962 per mile, then the minimum total amount of money needed today to cover all future costs including surface replacement every 11 years for the rigid surface structure is estimated as K_{11} = $96, 277 + ($13, 962 + $63, 859)/(1-0. 4751) = $244, 536. A similar calculation for the proposed flexible surface structure would be K_{11} = $89, 292 + ($13, 962 + $66, 506)/(1-0. 4751) = $242, 594. A direct comparison of these results indicates that in terms of today's money, the proposed flexible surface structure can be constructed, maintained, and its surface replaced every 11 years, for $1, 942 less than the minimum cost of the proposed rigid surface structure.

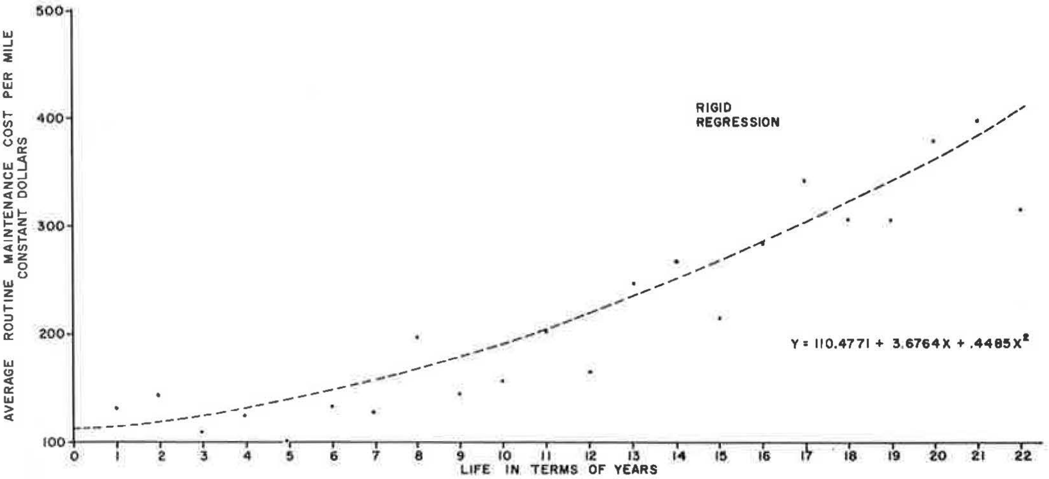

Figure 3. Time series relating routine maintenance costs to rigid surface structure life (one roadway).

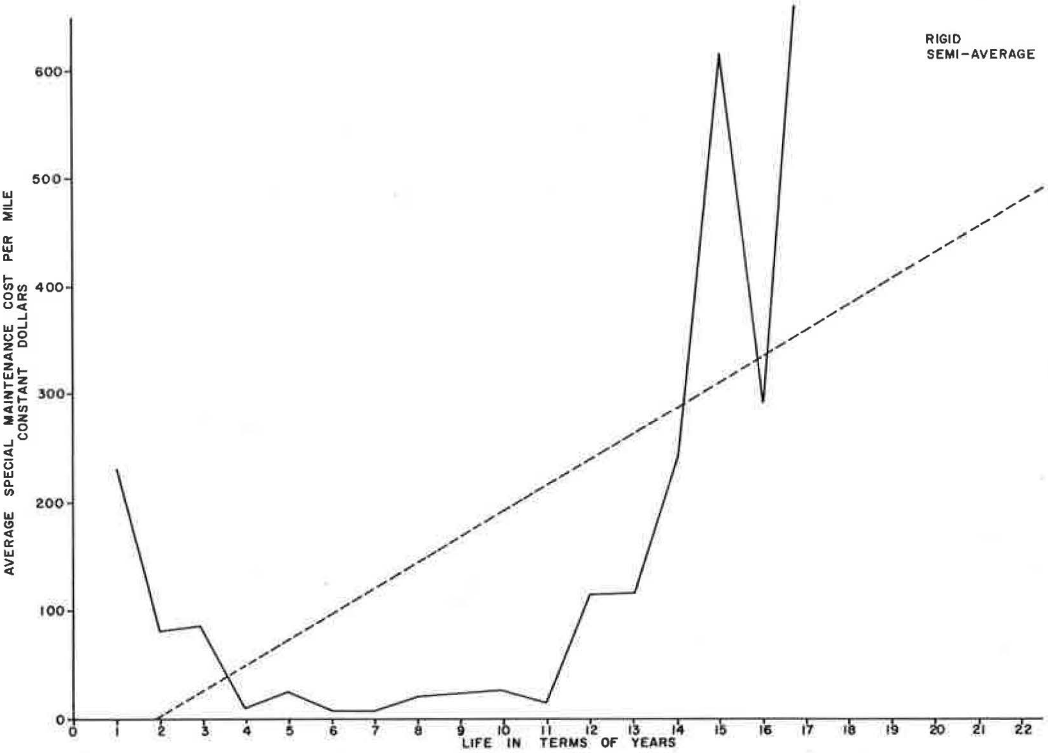

Figure 4. Semi-average trend line describing path of special maintenance costs over rigid surface structure life (one roadway).

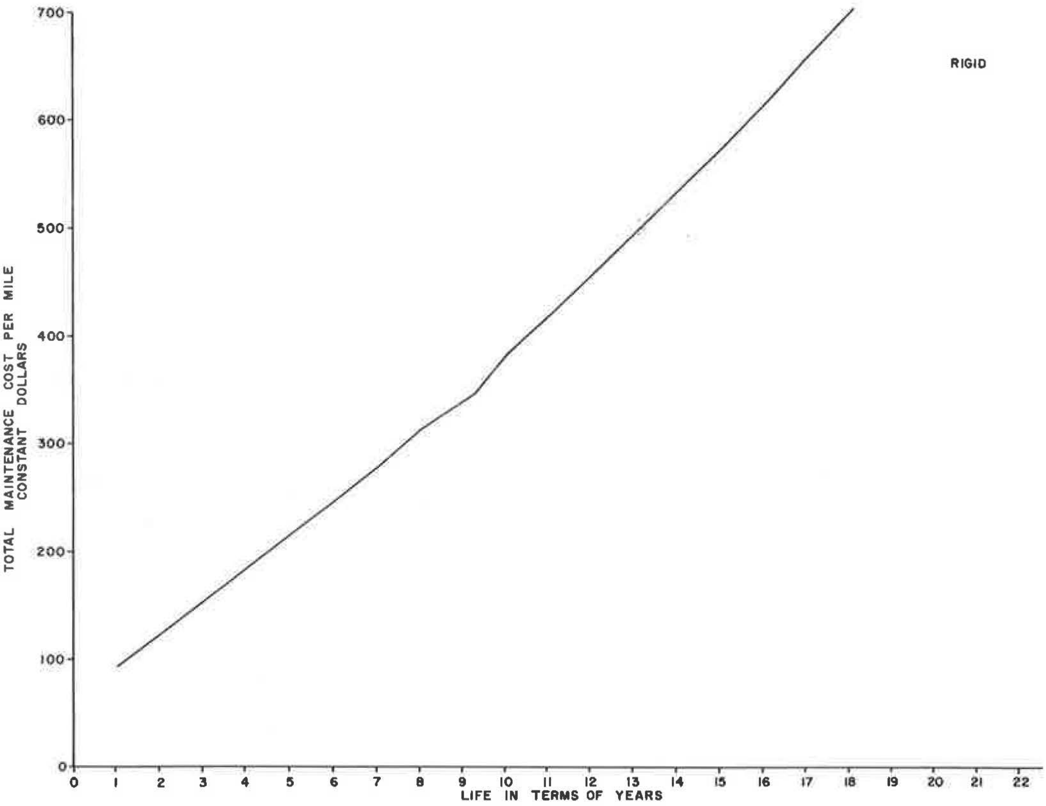

Figure 5. Sum of Figures 2 and 3, showing estimated total average maintenance costs for rigid surface structure life (one roadway).

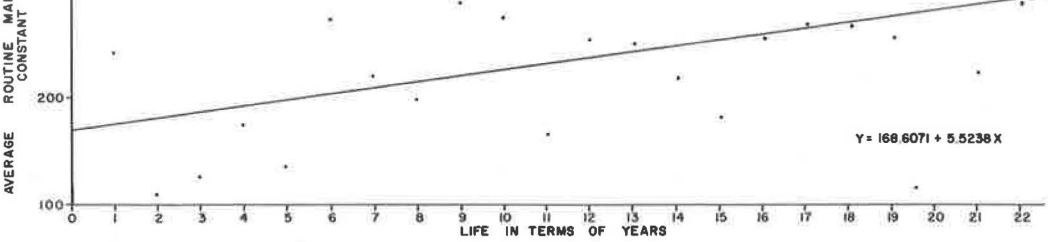

Figure 6. Time series relating routine maintenance cost to flexible surface structure life (one roadway).

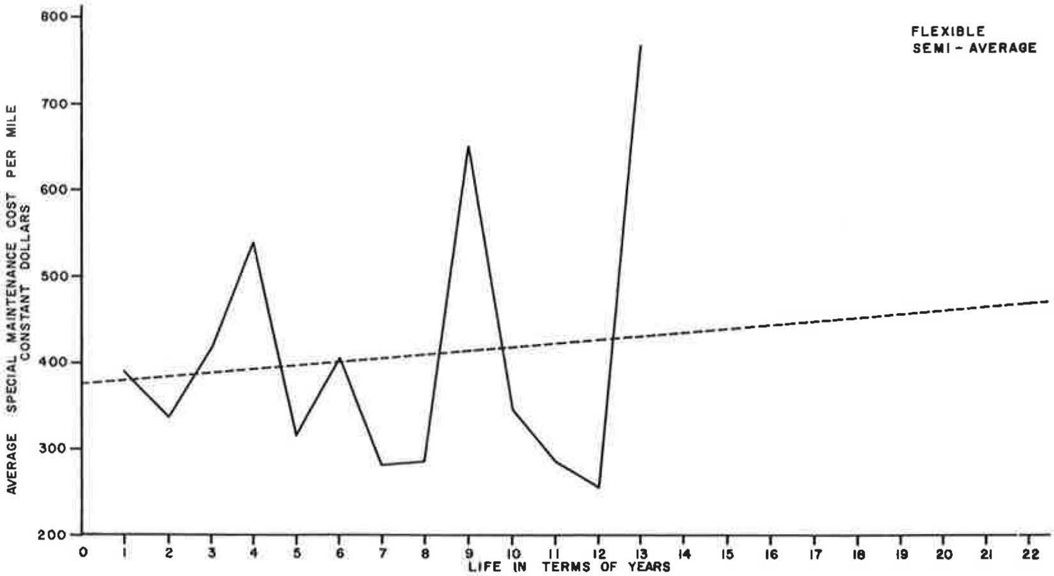

Figure 7. Semi-average trend line describing path of special maintenance costs over flexible surface life (one roadway).

Case 2

Case 2 involves a section of road located in the northern part of Minnesota, and is described in Tables 4, 7, and 8. The same maintenance cost figures and the unit road user costs are assumed to be applicable here as in Case 1. The present PCE on this roadway was estimated to be 1,968 vehicles, and the 1980 PCE forecast estimated 3,412 vehicles. The total initial per mile cost for a rigid surface structure is estimated at $71,254; the total initial per mile cost for a flexible structure is estimated to be $44,285. Tables 7 and 8 show, on the basis of all cost estimates, that the proposed rigid and flexible surfaces should be replaced each 8 and 6 years, respectively. Thus,

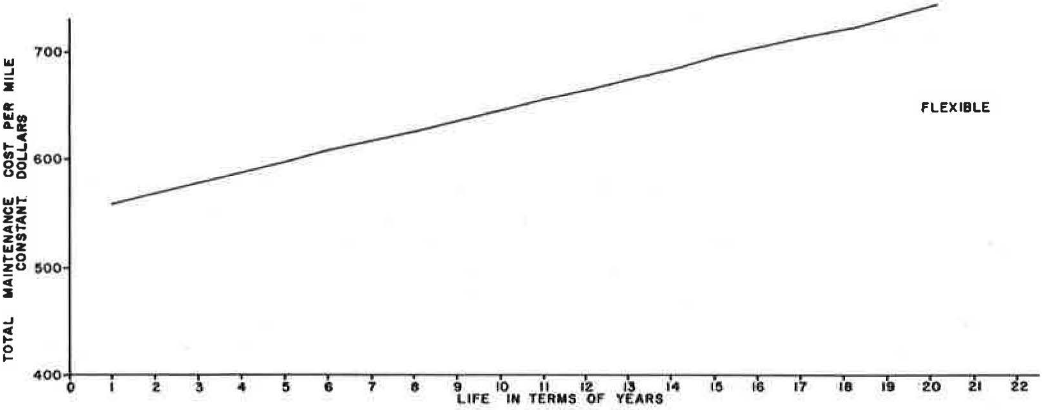

Figure 8. Sum of Figures 6 and 7, showing estimated total average maintenance costs for flexible surface structure life (one roadway).

TABLE 1

TOTAL ESTIMATED PER MILE MAINTENANCE COSTS FOR FLEXIBLE SURFACE STRUCTURES

Year	Estimated Costs (constant dollars)		
	Per Mile Routine Maintenance	Per Mile Special Maintenance	Per Mile Total Maintenance
1	175	379	554
2	180	383	563
3	186	388	574
4	191	392	583
5	197	396	593
6	202	400	602
7	208	404	612
8	213	408	621
9	219	413	632
10	224	417	641
11	230	421	651
12	235	425	660
13	241	429	670
14	246	433	679
15	252	438	690
16	257	442	699
17	263	446	709
18	268	450	718
19	274	454	728
20	280	458	738
21	285	463	748
22	291	467	758
23	296	471	767
24	302	475	777
25	307	479	786
26	313	483	796
27	318	488	806
28	324	492	816
29	329	496	825
30	335	500	835

TABLE 2

TOTAL ESTIMATED PER MILE MAINTENANCE COSTS FOR RIGID SURFACE STRUCTURES

Year	Estimated Costs (constant dollars)		
	Per Mile Routine Maintenance	Per Mile Special Maintenance	Per Mile Total Maintenance
1	116	-21	95
2	120	2	122
3	126	26	152
4	133	49	182
5	140	73	213
6	149	96	245
7	159	120	279
8	169	143	312
9	180	167	347
10	193	190	383
11	205	214	419
12	220	237	457
13	235	261	496
14	251	284	535
15	267	308	575
16	285	332	617
17	304	355	659
18	322	379	701
19	343	402	745
20	364	426	790
21	386	449	835
22	409	473	882
23	433	496	929
24	457	520	977
25	483	543	1,026
26	510	567	1,077
27	537	590	1,127
28	566	614	1,180
29	595	637	1,232
30	625	661	1,286

the total minimum of all present and future costs associated with the rigid structure is K_8 = \$71,254 + (\$13,962 + \$50,149)/(1-0.5820) = \$224,630. The total minimum present and future costs for the proposed flexible structure is K_6 = \$44,285 + (\$13,962 + \$31,095)/(1-0.6663) = \$179,308. A direct comparison of K_8 and K_6 shows that the proposed flexible structure is \$45,322 less than the rigid structure when its replacement cycle is 6 years.

SUMMARY AND CONCLUSIONS

An attempt has been made to present an economic replacement cost model that properly takes into account present and future costs associated with surface structure types, and reveals, on the basis of these costs, some minimally optimal total cost. The presumption, of course, is that some optimal n is determinate. In the cases presented, n appears unrealistically low for replacement in terms of highway experience. However, the surface life dictated by the replacement model is based primarily on economic rather than engineering considerations. Hence, from the standpoint of this study, n signifies a point of minimum cost, and need have no implications for actual surface replacement.

The methods for arriving at various estimates of maintenance and road user costs in this study are by no means definitive, nor are they intended to be. Estimating pro-

TABLE 3

ESTIMATED ANNUAL INCREMENTAL ROAD USER COST[1], CASE 1

Year	PCE	Annual Incremental Road User Cost ($)
1	0	0
2	55	1,795
3	110	3,589
4	165	5,384
5	220	7,179
6	275	8,974
7	330	10,768
8	385	12,563
9	440	14,358
10	495	16,152
11	550	17,947
12	605	19,742
13	660	21,536
14	715	23,331
15	770	25,126
16	825	26,921
17	880	28,715
18	935	30,510
19	990	32,305
20	1,045	34,099
21	1,100	35,894
22	1,155	37,689
23	1,210	39,484
24	1,265	41,278
25	1,320	43,073
26	1,375	44,868
27	1,430	46,662
28	1,485	48,457
29	1,540	50,252
30	1,595	52,046
31	1,650	53,841
32	1,705	55,636
33	1,760	57,431
34	1,815	59,225

[1] For 365 days per year, per one-mile length, at a unit cost of $0.0894.

TABLE 4

ESTIMATED ANNUAL INCREMENTAL ROAD USER COST[1], CASE 2

Year	PCE	Annual Incremental Road User Cost ($)
1	0	0
2	75	2,447
3	150	4,895
4	225	7,342
5	300	9,789
6	375	12,237
7	450	14,684
8	525	17,131
9	600	19,579
10	675	22,026
11	750	24,473
12	825	26,921
13	900	29,368
14	975	31,815
15	1,050	34,263
16	1,125	36,710
17	1,200	39,157
18	1,275	41,605
19	1,350	44,052
20	1,425	46,499
21	1,500	48,947
22	1,575	51,394
23	1,650	53,841
24	1,725	56,288
25	1,800	58,736
26	1,875	61,183
27	1,950	63,630
28	2,025	66,078
29	2,100	68,525
30	2,175	70,972
31	2,250	73,420
32	2,325	75,867
33	2,400	78,314
34	2,475	80,762

[1] For 365 days per year, per one-mile length, at a unit cost of $0.0894.

cedures will vary, no doubt, from analyst to analyst depending on available data, degree of desired sophistication, etc. Moreover, the actual maintenance cost data used in this paper are in some instances incomplete, and therefore, do not lend themselves to a high degree of cost accuracy. One potential point of danger is the inclusion of annual incremental road user costs. This value is extremely sensitive to ADT estimates. It need not, however, seriously affect the outcome of a cost comparison because the same road user costs are part and parcel of the estimates compared. Nonetheless, the more accurate the ADT forecast (?), the more significant road user costs become in the analysis.

Throughout this study, the assumption that maintenance expenditures restore the roadway to its initial state and, therefore, make possible the use of a constant unit road user cost is not wholly satisfactory. What would be more desirable, of course,

TABLE 5

CASE 1, RIGID SURFACE, A = 96,277, r = 7%

No. of Years	C_i	$\frac{1}{(1+r)^{i-1}}$	$C_i\left[\frac{1}{(1+r)^{i-1}}\right]$	$A+\Sigma C_i\left[\frac{1}{(1+r)^{i-1}}\right]$	$\Sigma\left[\frac{1}{(1+r)^{i-1}}\right]$	Weighted Average
	(1)	(2)	(3)	(4)	(5)	(6)
1	0	1.0000	0	96,277	1.0000	96,277
2	1,890	0.9346	1,766	98,043	1.9346	50,679
3	3,711	0.8734	3,241	101,284	2.8080	36,070
4	5,536	0.8163	4,519	105,803	3.6243	29,193
5	7,361	0.7629	5,616	111,419	4.3872	25,396
6	9,187	0.7130	6,550	117,969	5.1002	23,130
7	11,013	0.6663	7,338	125,307	5.7665	21,370
8	12,842	0.6228	7,998	133,305	6.3893	20,864
9	14,670	0.5820	8,538	141,843	6.9713	20,347
10	16,499	0.5439	8,974	150,817	7.5152	20,068
11	18,330	0.5084	9,319	160,136	8.0236	19,958
12	20,161	0.4751	9,579	169,715	8.4987	19,970
13	21,993	0.4440	9,765	179,480	8.9427	20,070
14	23,827	0.4150	9,888	189,368	9.3577	20,237
15	25,661	0.3878	9,951	199,319	9.7455	20,452
16	27,496	0.3625	9,967	209,286	10.1080	20,705
17	29,332	0.3387	9,935	219,221	10.4467	20,985
18	31,169	0.3166	9,868	229,089	10.7633	21,284
19	33,006	0.2959	9,767	238,856	11.0592	21,598
20	34,844	0.2765	9,634	248,490	11.3357	21,921

TABLE 6

CASE 1, FLEXIBLE SURFACE, A = $89,292, r = 7%

No. of Years	C_i	$\frac{1}{(1+r)^{i-1}}$	$C_i\left[\frac{1}{(1+r)^{i-1}}\right]$	$A+\Sigma C_i\left[\frac{1}{(1+r)^{i-1}}\right]$	$\Sigma\left[\frac{1}{(1+r)^{i-1}}\right]$	Weighted Average
	(1)	(2)	(3)	(4)	(5)	(6)
1	0	1.0000	0	89,292	1.0000	89,292
2	2,349	0.9346	2,195	91,487	1.9346	47,290
3	4,152	0.8734	3,626	95,113	2.8080	33,872
4	5,958	0.8163	4,864	99,977	3.6243	27,585
5	7,762	0.7629	5,922	105,899	4.3872	24,138
6	9,567	0.7130	6,821	112,720	5.1002	22,101
7	11,370	0.6663	7,576	120,296	5.7665	20,861
8	13,175	0.6228	8,205	128,501	6.3893	20,112
9	14,979	0.5820	8,718	137,219	6.9713	19,683
10	16,784	0.5439	9,129	146,348	7.5152	19,474
11	18,588	0.5084	9,450	155,798	8.0236	19,417
12	20,393	0.4751	9,689	165,487	8.4987	19,472
13	22,196	0.4440	9,855	175,342	8.9427	19,607
14	24,001	0.4150	9,960	185,302	9.3577	19,802
15	25,805	0.3878	10,007	195,309	9.7455	20,041
16	27,611	0.3625	10,010	205,319	10.1080	20,313
17	29,414	0.3387	9,963	215,282	10.4467	20,608
18	31,219	0.3166	9,884	225,166	10.7633	20,920
19	33,023	0.2959	9,772	234,938	11.0592	21,244

TABLE 7

CASE 2, RIGID SURFACE, A = \$71, 254, r = 7%

No. of Years	C_i	$\frac{1}{(1+r)^{i-1}}$	$C_i\left[\frac{1}{(1+r)^{i-1}}\right]$	$A+\Sigma C_i\left[\frac{1}{(1+r)^{i-1}}\right]$	$\Sigma\left[\frac{1}{(1+r)^{i-1}}\right]$	Weighted Average
	(1)	(2)	(3)	(4)	(5)	(6)
1	0	1. 0000	0	71, 254	1. 0000	71, 254
2	2, 542	0. 9346	2, 376	73, 630	1. 9346	38, 060
3	5, 017	0. 8734	4, 382	78, 012	2. 8080	27, 782
4	7, 494	0. 8163	6, 117	84, 129	3. 6243	23, 213
5	9, 971	0. 7629	7, 607	91, 736	4. 3872	20, 910
6	12, 450	0. 7130	8, 877	100, 613	5. 1002	19, 727
7	14, 929	0. 6663	9, 947	110, 560	5. 7665	19, 173
8	17, 410	0. 6228	10, 843	121, 403	6. 3893	19, 001
9	19, 891	0. 5820	11, 577	132, 980	6. 9713	19, 075
10	22, 373	0. 5439	12, 169	145, 149	7. 5152	19, 314
11	24, 856	0. 5084	12, 637	157, 786	8. 0236	19, 665
12	27, 340	0. 4751	12, 989	170, 775	8. 4987	20, 094
13	29, 825	0. 4440	13, 242	184, 017	8. 9427	20, 577
14	32, 311	0. 4150	13, 409	197, 426	9. 3577	21, 098
15	34, 798	0. 3878	13, 495	210, 921	9. 7455	21, 643

TABLE 8

CASE 2, FLEXIBLE SURFACE, A = \$44, 285, r = 7%

No. of Years	C_i	$\frac{1}{(1+r)^{i-1}}$	$C_i\left[\frac{1}{(1+r)^{i-1}}\right]$	$A+\Sigma C_i\left[\frac{1}{(1+r)^{i-1}}\right]$	$\Sigma\left[\frac{1}{(1+r)^{i-1}}\right]$	Weighted Average
	(1)	(2)	(3)	(4)	(5)	(6)
1	0	1. 0000	0	44, 285	1. 0000	44, 285
2	3, 001	0. 9346	2, 805	47, 090	1. 9346	24, 341
3	5, 458	0. 8734	4, 767	51, 857	2. 8080	18, 468
4	7, 916	0. 8163	6, 462	58, 319	3. 6243	16, 091
5	10, 372	0. 7629	7, 913	66, 232	4. 3872	15, 097
6	12, 830	0. 7130	9, 148	75, 380	5. 1002	14, 780
7	15, 286	0. 6663	10, 185	85, 565	5. 7665	14, 838
8	17, 743	0. 6228	11, 050	96, 615	6. 3893	15, 121
9	20, 200	0. 5820	11, 756	108, 371	6. 9713	15, 545
10	22, 658	0. 5439	12, 234	120, 695	7. 5152	16, 060
11	25, 114	0. 5084	13, 768	133, 463	8. 0236	16, 634
12	27, 572	0. 4751	13, 099	146, 562	8. 4987	17, 245

is an objective measure of the change in the unit cost as a function of maintenance expenditures; i.e., as a roadway deteriorates, presumably unit road user cost will rise. Moreover, one might expect changes in vehicle speed to significantly affect unit road user cost. Unfortunately, such information is not readily obtainable.

In the final analysis, the basic intent of this paper has been to describe an additional method for surface-type determination, and, at the same time, emphasize the advantages of an economic replacement approach relative to conventional financing methods. Though the presentation of the proposed model has purposely avoided the inclusion of much detail, it is hoped that this principle of methodology has aided rather than hindered this effort.

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Appendix

The responsibility of government, when confronted with highway alternatives, is to choose an alternate that yields for its constituency the greatest possible return per dollar of expenditure. This makes sense because funds expended for a given highway alternate are no longer available for alternatives. Moreover, such an expenditure in the public sector precludes an equivalent expenditure in the private sector.

It is suggested that only from the standpoint of financing highway projects should the concern with a bond rate, or some other rate on borrowed funds, be paramount; on the other hand, when cast in a strict economic framework, the predominant considerations given to highway projects, as well as to private projects, should be couched in terms of opportunity costs. This is to state that the important costs for an economic comparison of two or more highway projects, or a comparison of public with private projects, are those revealed when the projects are allowed to compete with each other for funds. These opportunity costs may be defined as foregone returns from employing factors of production for a given project rather than some alternate project. Thus, when considering alternative resource-using activities, and when guided by the opportunity cost principle, a pattern of optimal resource allocation within and between the public and private sectors may be established.

This principle can best be illustrated by assuming the existence of a firm whose investment expenditure program lists five independent projects. Further, the project costs and prospective rates of return on each project are those given in Table 9 to their prospective rates of return, and the various combinations of these prospective rates of return, and the various combinations of these projects to their combined rates. In addition, Figure 9 shows the firm's supply of available investment funds (S). This hypothetical supply curve describes the willingness of the firm to invest different sums of money at various rates of return. It is clear, then, that the firm is unwilling to invest any sum of money at less than a 1 percent rate of return; the firm is willing to invest $600 for at least a 4 percent rate of return, $1, 800 for a 24 percent minimum rate of return; etc.

The positive slope of the S-curve is engendered by the firm's inability to take advantage of tomorrow's investment opportunities when funds are expended today; i.e., the firm, in some sense, foregoes tomorrow's return in favor of today's gain. Thus, if the firm has only $2, 000 for investment purposes, its willingness to commit this sum in total today is tempered by the realization that any potential returns from tomorrow's investment opportunities are necessarily foregone. Hence, the firm, before it will consider such an expenditure, must be assured of a minimum rate of return in the neighborhood of 30 percent (Fig. 9).

TABLE 9

ALTERNATIVE INVESTMENT PROJECTS AND PROSPECTIVE RATES OF RETURN

Project	Total Cost ($)	Rate of Return (%)	Actual Return ($)
1	200	12	24
2	300	8	24
3	400	2	8
4	500	7	35
5	600	16	96

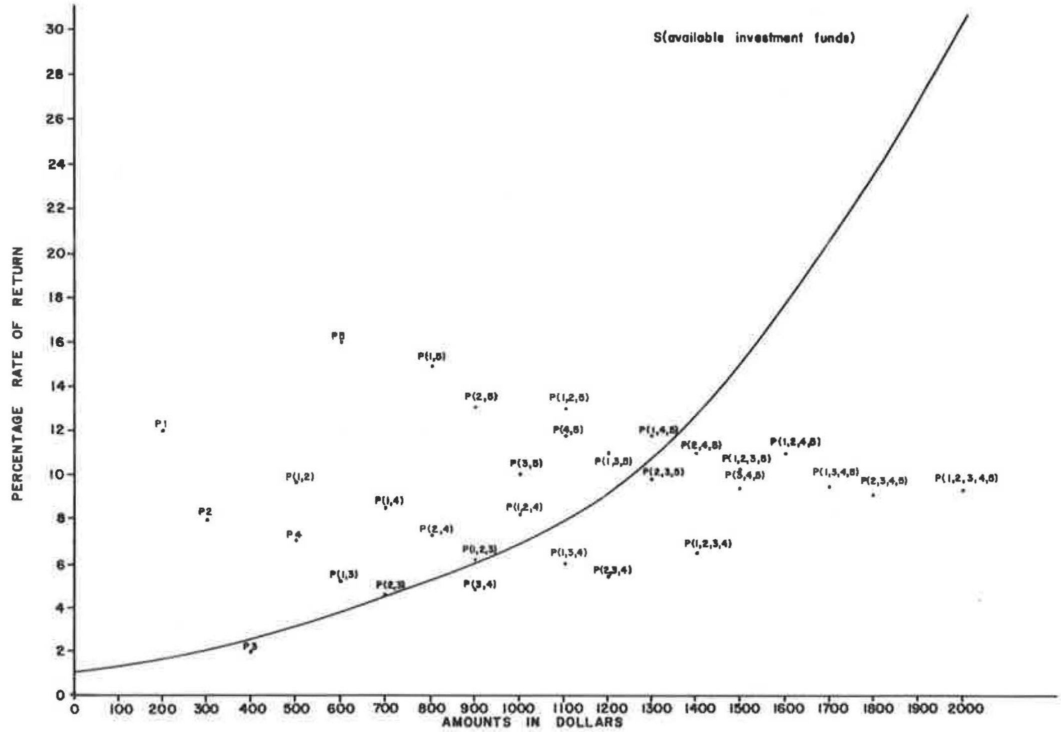

Figure 9. Prospective rates of return on combinations of five projects, relative to supply of available investment funds.

The S-curve, therefore, is a reflection of opportunity cost and economic uncertainty.

Figure 9 is designed to indicate the minimum rate of return the firm is willing to accept from a given project or combination of projects in terms of its opportunity cost picture. There are two separate methods for finding an acceptable minimum rate of return from Figure 9:

1. It is assumed that no limitations on available investment funds exist, and only like combinations are considered; e.g., p(1, 2), p(1, 4),... , are compared but not p(1, 3, 4) to p(1, 2);

2. It is assumed that limitations on available investment funds exist, and all projects and their combinations whose total cost equals the available investment funds are considered.

Examining Figure 9 in terms of the first method, and considering projects 1, 2, 3, 4, and 5 individually, the firm will consider the 2 percent yield on p 3 to be the accepted minimum rate if it decides to invest in all five projects. But unfortunately, the prospective rate of return on p 3 is below that rate which the firm must have if it is to invest $400 as shown by the S-curve. Hence, it may be concluded that the firm will consider individually p 1, p 2, p 4, and p 5, and the minimum rate of return acceptable to the firm is the 7 percent yielded by p 4.

Again, if the firm is considering the five projects but interested only in combinations of any three projects, Figure 9 shows ten such possible combinations and their prospective rates of return. Because their combined rates of return do not at least equal the rates at which the firm is willing to invest various sums of money, five of the possible ten combinations are immediately eliminated from consideration. Of those remaining, p(1, 2, 3) yields the lowest rate of return (6.2%) that the firm is willing to accept.

Employing the second method (2), where the assumed restriction is one of limited

funds, it is assumed that the firm's investment budget will allow only an expenditure of $1,100. There are three possible combinations which demand this entire sum; namely, p(1, 2, 5), p(4, 5), and p(1, 3, 4). Given the S-curve, it is obvious that the combination p(1, 3, 4) will be dropped from consideration. Of the two eligible combinations, p(4, 5) points to 11.9 percent as the minimum rate of return acceptable to the firm.

The establishment of an acceptable minimum rate of return is as necessary and basic in highway economy studies as in other economy studies, whether private or public. The use of a low discount rate for economy studies makes possible the justification of projects whose rates of return fall below the S-curve. Of course, if it can be successfully argued that the prospective minimum attractive rate of return on taxpayer dollars is low (i.e., 0-3%), then a low rate would be appropriate in highway economy studies. However, empirical evidence has been presented by writers mentioned in the text which suggests an appropriate rate of return of about 5 to 8 percent for such studies.

Discussion

HAROLD W. HANSEN, Senior Planning Engineer, Portland Cement Association, Chicago, Illinois — In capsule form, the author's procedure accepts estimates of current spending for highway purposes with confidence but, because of the vagaries connected with estimating future spending, discounts these by means of price deflators in the form of "present worth factors." (These factors permit calculating the amount of money that must be set aside today at interest which is compounded annually to produce the amount of money estimated to be required in some future year.) After discounting, cost data are accumulated in consecutive years and divided by present worth factors accumulated for the same years. The difference in rate of change of these two parts of the equation results in values which may be plotted to produce a curve that starts at a high value during the early years of the analysis period, declines to some minimal value, and then tends to rise again. The age at which cost has a minimal value is regarded by the author as the "economic life."

The elements of estimated cost used by the author include (a) pavement construction cost, (b) routine and periodic pavement maintenance expense, (c) future resurfacing costs, and (d) the motor-vehicle user "costs" for those vehicles estimated to be added to the traffic stream during the analysis period.

In the example given, the author uses $0.0894 as the unit cost of motor-vehicle operation. This is made up of the elements given in Table 10.

Inclusion of motor-vehicle operating costs constitutes the bulk of the computed "costs" in the author's example and contributes importantly to the short "economic life" which results. Yet the "economic life" computed by the author's model has no demonstrated relationship to the known physical life of pavements in Minnesota.

TABLE 10

UNIT COST OF MOTOR-VEHICLE OPERATION

Element	Estimated Cost ($/veh-mi)
Fuel	0.0211
Tires	0.0040
Oil	0.0021
Maintenance and repairs	0.0120
Depreciation	0.0150
Time	0.0352
Total	0.0894

Principles

The author's four assumptions are derived from concepts by Churchman, et al. (7, pt. 7), whose discussion is primarily on replacement models, which they begin by describing "relevant costs" in replacement theory considerations: "In the problem of choosing between two machines... costs that are the same for the two machines can be excluded in the comparison." When this principle is applied to highways it must be interpreted to mean that road user costs can be excluded except where

TABLE 11

COST COMPUTATION USING MINNESOTA ECONOMIC REPLACEMENT MODEL WHERE THERE IS NO INCREASE IN TRAFFIC IN FUTURE YEARS[1]

Year	Estimated Maintenance Expenditure Trend ($ per mi)	Present Worth Factor (at 7% interest)	Deflated Maintenance Expenditure ($ per mi)	Accumulated Total Maint. and Capital Cost ($)	Accumulated Present Worth Factor (at 7% interest)	Col. 5 Divided By Col. 6 ($)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	0	1.0000	0.00	96,277.00	1.0000	96,277.00
2	95	0.9346	88.79	96,365.79	1.9346	49,811.74
3	122	0.8734	106.55	96,472.34	2.8080	34,356.24
4	152	0.8163	124.08	96,596.42	3.6243	26,652.43
5	182	0.7629	138.05	96,735.27	4.3872	22,049.43
6	213	0.7130	151.87	96,887.14	5.1002	18,996.73
7	245	0.6663	163.24	97,050.38	5.7665	16,830.03
8	279	0.6228	175.56	97,225.94	6.3893	15,216.99
9	312	0.5820	181.58	97,407.52	6.9713	13,972.64
10	347	0.5439	188.73	97,596.25	7.5152	12,986.51
11	383	0.5084	194.72	97,790.97	8.0236	12,187.91
12	419	0.4751	199.07	97,990.04	8.4987	11,530.00
13	457	0.4440	202.91	98,192.95	8.9427	10,980.23
14	496	0.4150	205.84	98,398.79	9.3577	10,515.27
15	535	0.3878	207.47	98,606.26	9.7455	10,118.13
16	575	0.3625	208.44	98,814.70	10.1080	9,775.89
17	617	0.3387	208.98	99,023.68	10.4467	9,478.94
18	659	0.3166	208.64	99,232.32	10.7633	9,219.50
19	701	0.2959	207.42	99,439.74	11.0592	8,915.85
20	745	0.2765	205.99	99,645.73	11.3357	8,790.43
21	790	0.2584	204.14	99,849.87	11.5941	8,612.12
22	835	0.2415	201.65	100,051.52	11.8356	8,453.43
23	882	0.2257	199.07	100,250.59	12.0613	8,311.75
24	929	0.2109	195.93	100,446.52	12.2722	8,184.88
25	977	0.1971	192.57	100,639.09	12.4693	8,070.94
26	1,026	0.1842	188.99	100,828.08	12.6535	7,968.39
27	1,077	0.1722	185.46	101,013.54	12.8257	7,875.86
28	1,127	0.1609	181.33	101,194.87	12.9866	7,792.25
29	1,180	0.1504	177.47	101,372.34	13.1370	7,716.55
30	1,232	0.1406	173.22	101,545.56	13.2776	7,647.88
31	1,286	0.1314	168.98	101,714.54	13.4090	7,585.54
32	1,341	0.1228	164.67	101,879.21	13.5318	7,528.87
33	1,397	0.1147	160.24	102,039.45	13.6465	7,477.33
34	1,454	0.1072	155.87	102,195.32	13.7537	7,430.38
35	1,512	0.1002	151.50	102,346.82	13.8539	7,387.58
36	1,571	0.0937	147.20	102,494.02	13.9476	7,348.50
37	1,631	0.0875	142.71	102,636.73	14.0351	7,312.86
38	1,692	0.0818	138.40	102,775.13	14.1169	7,280.29
39	1,754	0.0764	134.00	102,909.13	14.1933	7,250.54
40	1,817	0.0714	129.73	103,038.86	14.2647	7,224.34
41	1,881	0.0668	125.65	103,164.51	14.3315	7,198.44
42	1,946	0.0624	121.43	103,285.94	14.3939	7,175.67
43	2,012	0.0583	117.30	103,403.24	14.4522	7,154.84
44	2,079	0.0545	113.30	103,516.54	14.5067	7,135.77
45	2,147	0.0509	109.28	103,625.82	14.5576	7,118.33
46	2,216	0.0476	105.48	103,731.30	14.6052	7,102.35
47	2,286	0.0445	101.73	103,833.03	14.6497	7,087.72
48	2,357	0.0416	98.05	103,931.08	14.6913	7,074.32
49	2,429	0.0389	94.49	104,025.57	14.3702	7,062.06
50	2,502	0.0363	90.82	104,116.39	14.7665	7,050.85
51	2,576	0.0339	87.33	104,203.72	14.8004	7,040.60
52	2,651	0.0317	84.04	104,287.76	14.8321	7,031.22
53	2,727	0.0296	80.72	104,368.48	14.8617	7,022.64
54	2,804	0.0277	77.67	104,446.15	14.8894	7,014.79
55	2,882	0.0259	74.67	104,520.82	14.9153	7,007.62
56	2,961	0.0242	71.66	104,592.48	14.9395	7,001.06
57	3,041	0.0226	68.73	104,661.21	14.9621	6,995.08
58	3,122	0.0211	65.87	104,727.08	14.9832	6,989.63
59	3,204	0.0198	63.44	104,790.52	15.0030	6,984.63
60	3,287	0.0184	60.48	104,851.00	15.0214	6,980.10

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[1] Based on Table 5.

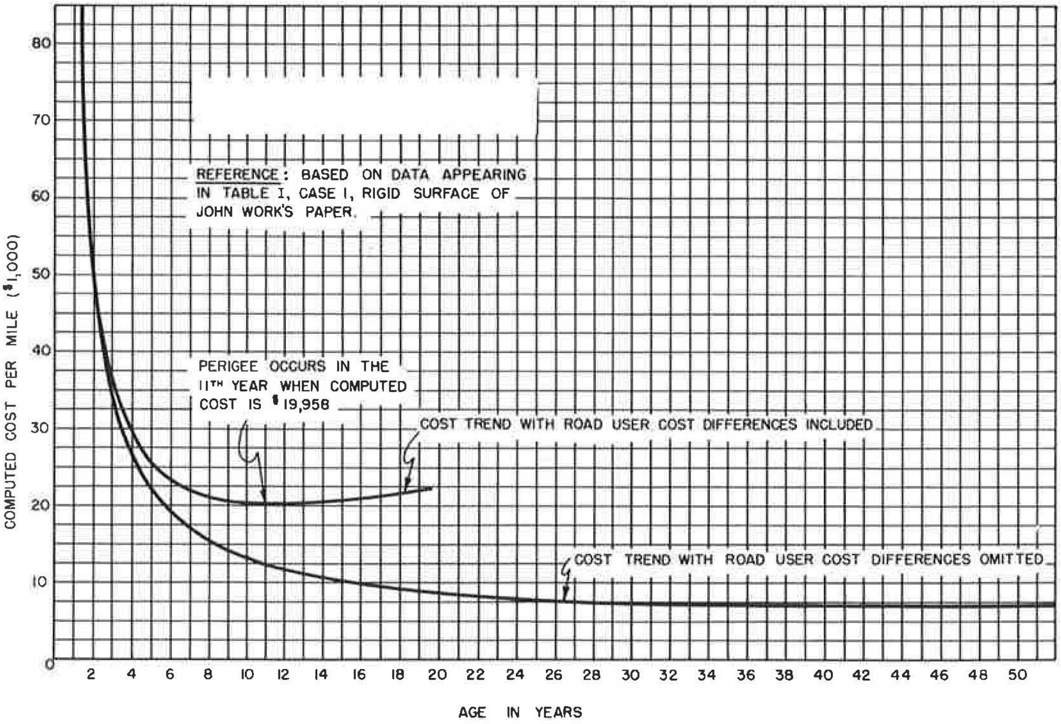

Figure 10. Economic replacement model for highway surface determination (based on Table 5).

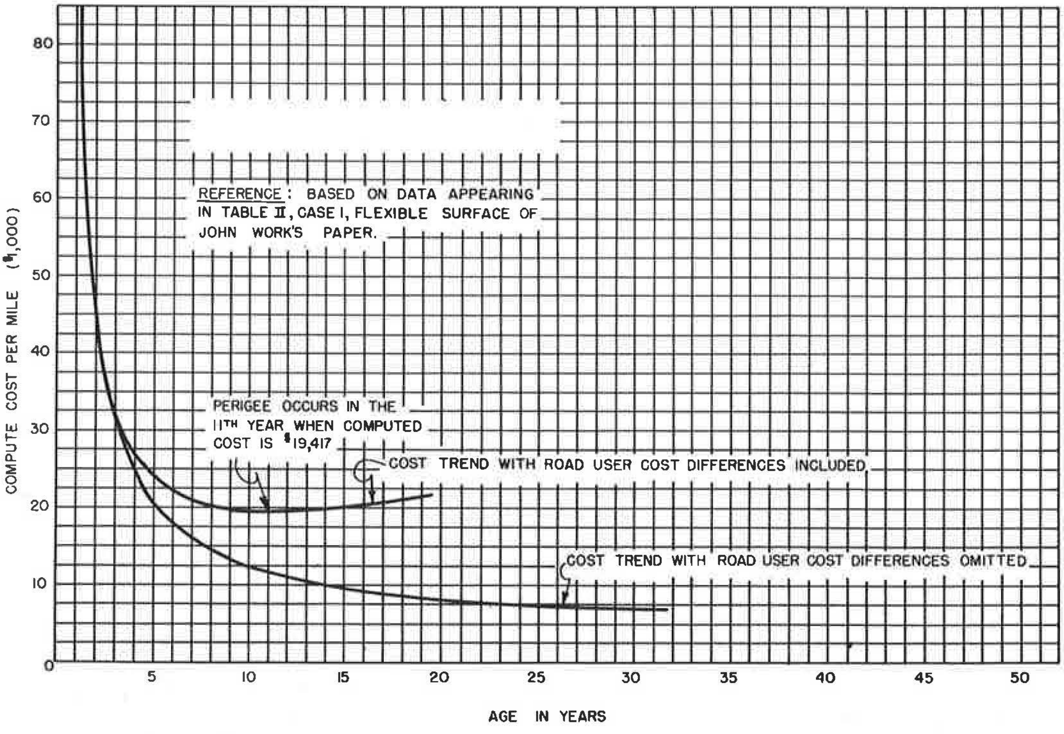

Figure 11. Economic replacement model for highway surface determination (based on Table 6).

TABLE 12

COST COMPUTATION USING MINNESOTA ECONOMIC REPLACEMENT MODEL WHERE THERE IS NO INCREASE IN TRAFFIC VOLUME IN FUTURE YEARS[1]

Year	Estimated Maintenance Expenditure Trend ($ per mi)	Present Worth Factor (at 7% interest)	Deflated Maintenance Expenditure ($ per mi)	Accumulated Total Maint. and Capital Cost ($)	Accumulated Present Worth Factor (at 7% interest)	Col. 5 Divided By Col. 6 ($)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	0	1.0000	0.00	89,292.00	1.0000	89,292.00
2	554	0.9346	517.77	89,809.77	1.9346	46,422.91
3	563	0.8734	491.72	90,301.49	2.8080	32,158.65
4	574	0.8163	468.56	90,770.05	3.6243	25,044.85
5	583	0.7629	444.77	91,214.82	4.3872	20,791.12
6	593	0.7130	422.81	91,637.63	5.1002	17,967.45
7	602	0.6663	401.11	92,038.74	5.7665	15,960.93
8	612	0.6228	381.15	92,419.89	6.3893	14,464.79
9	621	0.5820	361.42	92,781.31	6.9713	13,309.03
10	632	0.5439	343.74	93,125.05	7.5152	12,391.55
11	641	0.5084	325.88	93,450.93	8.0236	11,647.00
12	651	0.4751	309.29	93,760.22	8.4987	11,032.30
13	660	0.4440	293.04	94,053.26	8.9427	10,517.32
14	670	0.4150	278.05	94,331.31	9.3577	10,080.60
15	679	0.3878	263.32	94,594.63	9.7455	9,706.49
16	690	0.3625	250.12	94,844.75	10.1080	9,383.13
17	699	0.3387	236.75	95,081.50	10.4467	9,101.58
18	709	0.3166	224.47	95,305.97	10.7633	8,854.71
19	718	0.2959	212.46	95,518.43	11.0592	8,637.01
20	728	0.2765	201.29	95,719.72	11.3357	8,444.09
21	738	0.2584	190.70	95,910.42	11.5941	8,272.34
22	748	0.2415	180.64	96,091.06	11.8356	8,118.81
23	758	0.2257	171.08	96,262.14	12.0613	7,981.07
24	767	0.2109	161.76	96,423.90	12.2722	7,857.09
25	777	0.1971	153.15	96,577.05	12.4693	7,745.18
26	786	0.1842	144.78	96,721.83	12.6535	7,643.87
27	796	0.1722	137.07	96,858.90	12.8257	7,551.93
28	806	0.1609	129.68	96,988.58	12.9866	7,468.35
29	816	0.1504	122.73	97,111.31	13.1370	7,392.19
30	825	0.1406	116.00	97,227.31	13.2776	7,322.65
31	835	0.1314	109.72	97,337.03	13.4090	7,259.08

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[1] Based on Table 6.

a measurable difference in road user costs between alternative pavement types is shown.

For reasons not fully explained, the author included road user costs (although he limited this to the added costs associated with increased traffic volume during future years). In his summary and conclusions, he states: "One potential point of danger is the inclusion of annual incremental road user cost. This value is extremely sensitive to ADT estimates. It need not, however, seriously affect the outcome of a cost comparison because the same road user costs are part and parcel of the estimates compared." By this statement and the data in the report it is clear that the alternatives being compared include equal amounts of road user costs, which by the original premise could have been omitted.

Inclusion of road user cost differences is not only unnecessary but also seriously beclouds some fundamental considerations. This deficiency in the author's approach is particularly significant because road user cost differences represent the preponderance of the costs given in Tables 5 through 9. To illustrate, the value $34, 844 shown in the 20th year in the first column (C_i) in Table 5 is made up of $745 in maintenance costs (Table 2) plus $34, 099 of road user cost differences (Table 3).

Accordingly, maintenance cost is only slightly more than 2 percent of the computed C_i at 20 years. From this point it becomes increasingly more difficult to trace the relationship because of the application of present worth factors to some of the data. Suffice it to say, the $248, 490 given in Col. 4 for the 20th year is comprised of only $96, 277 of initial pavement construction costs. The remaining $152, 213 is made up of about $148, 844 in road user cost and $3, 369 in maintenance cost.

Failure to take into account the fact that maintenance expenditures represent a considerable portion of the overall outlay for highway purposes is being less than realistic. To institute techniques that minimize a major cost is hardly in accord with the principles of sound management. The techniques proposed by the author downgrade maintenance expense to an insignificant role. Accordingly, the method would be insensitive to situations in which maintenance cost on some part of the system is high or exorbitant. Because of this insensitivity, these procedures could not be relied on to determine the more economic alternative where maintenance expenditure is a factor.

In addition to minimizing maintenance costs, the author has introduced into his analysis costs (road user cost differences) that have no real bearing on pavement-type decision making. These costs materially hinder a direct view of the salient factors which should be evaluated in an economic analysis.

Table 11 and Figure 10 show how the data in Table 5 appear with road user cost differences omitted. Although the recomputed table and curve cover a 60-year period, the perigee (point nearest to zero) has not been reached. Furthermore, the curve is so flat that the procedure is decidedly not definitive. Nevertheless, using these data the technique now indicates the economic life is in excess of 60 years. Here again, in the 60th year maintenance costs make up only 0. 05 percent of the computed cost ($104, 851) due to the application of present worth factors as price deflators for maintenance costs.

Table 12 and Figure 11 show similar data for the flexible surface used in Table 6.

Maintenance Expenditures

The "governing factors" outlined in the paper are such that it is difficult to obtain realistic and representative pavement maintenance costs. Restricting the selection to control sections "exhibiting a completed surface life" tends to limit the sample to roads with abnormal problems which were reconstructed earlier than the average of all existing sections. In the case of rigid pavements, which in Minnesota are showing very long service lives, the sample is almost entirely limited to projects constructed before 1930.

Depending on how the analysis is made, the data used by the author could be analyzed to make it appear that per-mile costs decline as age increases.

The author does not indicate that he has taken account of the major factors that influence highway maintenance costs. Without determining the relationship of traffic volume (particularly the frequency and weight of heavier axle loads) to the cost of maintaining State highways, unwarranted generalizations will result.

JOHN W. WORK, Closure — In the main, Mr. Hansen unfortunately misconstrues the intent and fundamental idea of the paper. Therefore, this rejoinder, which forms a basis for clarification rather than debate, comments in turn on the three major points that he makes.

First, Mr. Hansen correctly states that the replacement model determines the economic life of a pavement surface as a function of an average cost stream, a cost stream composed of pavement construction costs, routine and periodic pavement surface maintenance costs, and incremental road user costs. He states further that this economic life bears no "... relationship to the known physical life of pavements in Minnesota." This contention is based on the fact that the lives of rigid and flexible pavements in Minnesota, and throughout the country generally, are thought to be, on the average, approximately 25 years and 18 years, respectively. In the paper, two examples were used to demonstrate the workings of the replacement model when applied to highway surface structures; these examples indicated surface replacement time for specific rigid and flexible surface structures ranging from 6 years to 11 years. Mr. Hansen finds such estimates of surface life vexing—particularly when applied to rigid surfaces. Yet, the paper states very clearly in two places that the concepts of economic surface life and physical surface life are entirely different and that these values need not be expected to correspond.

Physical surface life, as measured by serviceability index, reflects a period (perhaps an average) between initial construction and surface replacement. Obviously, such determination of surface life is based on subjective judgments. Moreover, fluctuations in available highway funds might have an influence on the decision to resurface a roadway at some given point in time. In any event, the important thing to note is that physical life simply tells "what is," rather than "what ought to be," as regards resurfacing. Economic surface life, on the other hand, is independent of judgment in that it is a function of all highway costs. Specifically, economic surface life, as determined by the replacement model, is found at the point of minimum weighted average discounted cost.

Unless one knows what standards dictate road life, hence resurfacing time, the physical or service life average conveys little meaningful information for highway economy studies. Moreover, the nature of physical road life precludes any basic economic consideration.

Figure 12, which is similar to Figure 2, describes what is meant by economic surface life, and what is probably meant by physical or service life. The coordinates are similar to those used in the original paper. The economic life of a surface is found at the point of minimum average cost, where

$$AC = MB = MC \qquad (5)$$

in which AC represents average cost, MB represents marginal benefit, and MC represents marginal cost. X_0 vehicles per unit of time is found to be the optimum number of vehicles in terms of initial, road user, and maintenance costs. Additional vehicles will find cost exceeding benefit. This fact notwithstanding, additional vehicles do come onto a facility and continue doing so until vehicle congestion becomes great or the road surface becomes completely worn. Physical surface life, then, is usually an indeterminate point somewhere in the range of X_n vehicles. To put it differently, observable physical life may greatly exceed economic life; but in terms of road user benefits and opportunity costs, which are basic to highway economy studies, the area beyond point X_0 is meaningless.

It is hoped that the foregoing serves to make clear the fact that there certainly is no demonstrable relationship between the economic life and the physical life of road surfaces. It was never intended that the paper should convey anything other than the differences. After all, economic life, as used in the paper, is mathematically determinable as a function of economic costs; physical life, as employed by Mr. Hansen, has no such determinants.

Mr. Hansen's second major criticism revolves around the inclusion of incremental road user cost and "like" road user cost patterns in the determination of an optimum surface struc-

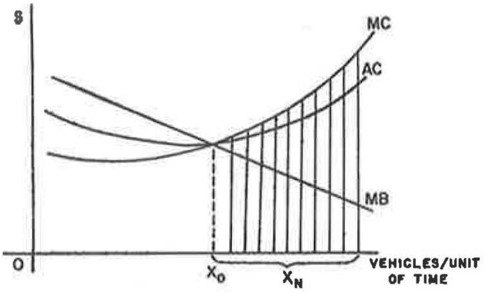

Figure 12.

ture. In support of this criticism, he quotes a passage that leads him to contend that: (a) road user cost differences need not have been included in a comparison of rigid and flexible surfaces because they were assumed to be equal in either case; (b) inclusion of road user cost differences is not only unnecessary but also seriously beclouds some fundamental considerations; (c) road user cost differences are large to the extent of making maintenance cost seem insignificant by comparison; (d) road user cost differences"... have no real bearing on pavement-type decision making."

It appears that this second major criticism and its ramifications rest on a quoted passage not applicable to the surface replacement model. On the contrary, that passage has a specific reference to the problem of choosing between machines (or highways) when the replacement time has already been determined or assumed. In the surface replacement model, the goal is to determine an optimum surface replacement time as a function of all relevant costs; i. e., all costs which vary with the age of the highway surface. The exclusion of road user costs (differences) from the model because they are equal in a comparison of surface types would produce misleading results. This is to say, the replacement time would be stated as a function of only initial and maintenance costs, and as a function of just these costs, replacement time would be ridiculously long, as Mr. Hansen discovered by constructing Tables 11 and 12, and Figures 10 and 11.

The inclusion of a road user cost element tends to complete the "economy study" matrix. In the paper, assumptions and reasons for the inclusion of a road user cost element are stated. Thus, there seems to be no reason for repetition. Suffice it to suggest that Mr. Hansen's reluctance to accept an element of road user cost in the replacement model stems partly from a misunderstanding about the role of equal cost patterns in economy studies, and a concentration upon highway financing rather than upon highway economics. These factors serve to seriously undermine the cogency of this particular criticism.

The third and final major criticism centers its emphasis on maintenance cost as a replacement model factor. The discusser's first contention is that maintenance expenditures make up a significant portion of total highway expenditures, but the replacement model works to make maintenance expenditures appear relatively small. Should he not have expected this result in view of the present worth formulation employed? Each year's maintenance expenditure (surface maintenance only) is converted into present worth terms, the value of which grows at a smaller and smaller rate over time. (The rate at which this occurs, of course, depends on the rate of discount.) This is in contrast to conventional financing procedures, which do not account for the value of money over time; hence, any summation of these unadjusted conventional maintenance values over the physical life of a surface (e.g., 25 years) will constitute a large percentage of total highway cost.

In the replacement model, incremental road user cost is also included as a major cost element. In the two examples presented, incremental road user cost was rising at a much faster rate than the estimated surface maintenance cost. Consequently, maintenance expenditures as a percentage of initial outlay and incremental road user cost appear relatively small. This occurrence gives rise to Mr. Hansen's statement: "Failure to take into account the fact that maintenance expenditures represent a considerable portion of the overall outlay for highway purposes is being less than realistic. To institute techniques that minimize a major cost is hardly in accord with the principles of sound management. The techniques proposed by the author downgrade maintenance expense to an insignificant role."

The fact is that total maintenance expenditures, from an accounting standpoint, do indeed "represent a considerable portion of the overall outlay for highway purposes," when one considers only the costs of building and maintaining a roadway. But initial and surface maintenance expenditures only make sense from an economics standpoint when they are properly related to the cost of using and consuming the roadway. Would Mr. Hansen contend that it is "sound management" to build and/or maintain roadways that had no traffic? The author sees no reason to be disturbed by the relative size of surface maintenance cost, inasmuch as it is assumed that this cost varies in some direct functional way with incremental road user cost.

Mr. Hansen's questioning of the real meaningfulness of the maintenance cost data used in the paper is partly valid in the sense that the data were neither good nor complete in all instances, as stated in the paper. Moveover, the surface maintenance data used in the model were not subjected to powerful analytical techniques. He further states that "Restricting the selection to control sections 'exhibiting a completed surface life' tends to limit the sample to roads with abnormal problems which were reconstructed earlier than the average of all existing sections." If this is true, maintenance cost patterns would be distorted. On the other hand, if the data were ideal the selection of control sections showing completed surface lives would be excellent for ascertaining surface maintenance cost patterns.

It should be stated that the paper represents an initial attempt to apply replacement theory techniques to the problems of highway surface determination. As yet, the model remains crude. It is hoped that in the future constructive criticism by thoughtful analysts will serve to overcome any shortcomings the model may have.