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Economic Evaluation of Pavement Design Alternatives for Low-Volume Roads

DAVID R. LUHR AND B. FRANK McCULLOUGH

Pavement economics is a very important consideration in the design and management of pavements for low-volume roads. This is particularly true in considering the large mileages that constitute most low-volume-road systems and the sensitivity of total system cost to small changes in pavement design. A pavement management system called the Pavement Design and Management System (PDMS) is used to perform an economic analysis that compares three surfacing types (aggregate, surface treatment, and asphalt) at six different traffic levels for low-volume roads (5-200 vehicles/day in the design lane). Total cost was calculated for each case, which included initial construction, rehabilitation, maintenance, user, and salvage costs. It was found that, for the specific conditions analyzed, aggregate surfacing was optimum for traffic levels of less than five 18-kip equivalent single-axle loads (ESALs)/day, surface treatment was optimum for 5-20 ESALs/day, and asphalt was optimum for traffic with more than 20 ESALs/day. Additional analyses that considered marginal cost, cost-performance ratio, and the effect of terminal serviceability index indicated that a pavement structure that is optimum for a given level of traffic has significantly different costs than a pavement that is not in the optimum range. It is concluded that pavement costs can be greatly reduced for low-volume roads by determining and implementing an optimum design and rehabilitation strategy for a given set of conditions.

The terms "low-cost" and "low-volume" roads are often used together, sometimes interchangeably. However, the term "low-cost," meaning low cost per mile, should not be misconstrued to mean low total cost. Around the world, low-volume roads make up the greater part of the vast majority of road networks. This large road mileage, even when multiplied by a relatively small cost per mile, requires a tremendous annual investment for building and maintenance. The U.S. Interstate Highway System, even though it is costly on a per-mile basis, makes up less than 2 percent of the road mileage of the United States and therefore does not require nearly the resources needed by the United States for its low-volume roads.

Pavement design can be just as important for low-volume roads as for Interstate highways because total pavement costs for low-volume roads are more sensitive to pavement design than costs for Interstate highways. For example, a 1-in change in surfacing thickness for an Interstate highway may increase the cost per mile by 15 percent, but the same design change for a low-volume road could increase the cost per mile by 50 percent. When multiplied by the large mileage of a low-volume-road system, the effect of pavement design on total cost is very significant.

Because pavement design is so important to the overall cost of a low-volume-road system, every effort should be made by designers to determine the optimum pavement design and rehabilitation strategy for a given set of conditions. This task is made easier by the use of a pavement management system, which can assist the designer in determining optimum pavement management on the basis of total overall cost. This paper summarizes the results of an analysis that evaluated the economic consequences of a range of pavement design alternatives. A pavement management system was used to conduct the analysis, which included the consideration of optimum surface type, marginal cost, and level of maintenance.

BACKGROUND

The U.S. Forest Service operates one of the largest low-volume-road networks under the jurisdiction of a single agency in the world. This system contains approximately 260 000 miles, and 100 000 additional miles are planned for the long-term future. Approximately 11 000 miles are constructed and reconstructed annually, and the annual expenditure for construction, reconstruction, and maintenance exceeds $0.5 billion.

In an effort to manage this road system more efficiently, the Forest Service and the University of Texas at Austin have developed a pavement management system called the Pavement Design and Management System (PDMS) (1). This computer system optimizes pavement design and rehabilitation strategies on the basis of total overall cost, which includes initial construction, maintenance, rehabilitation, user, and salvage costs. The optimization is completed after the user has supplied information concerning material properties and costs, seasonal conditions, traffic, and road geometry. The PDMS is used in this paper not to optimize under a certain set of conditions but to explore the economic consequences of certain pavement design alternatives.

METHOD OF ANALYSIS

Total overall cost was calculated over a 20-year analysis period for several different scenarios.

Pavement Structure

Three different initial pavement designs were considered:

1. Type 1--An aggregate-surfaced road with 6 in of aggregate surfacing,
2. Type 2--A 6-in aggregate base with a 0.5-in surface treatment, and
3. Type 3--A 6-in base with a 4-in asphalt concrete surface.

These three pavement structures were meant as a general range of pavements for low-volume roads. The initial construction costs assumed for a two-lane roadway were as follows:

Pavement Type	Cost ($/mile)
1	15 000
2	25 000
3	90 000

The deterioration of the pavement structures was predicted by performance models in PDMS. The inputs assumed for this analysis included average properties of the asphalt and base layers and a relatively poor subgrade. Seasonal conditions representative of a northern climate (frozen in winter with a thaw during spring) were also assumed.

Traffic

Three basic vehicles were used to represent mixed traffic for this roadway:

Vehicle	Type	Percentage of Total Vehicles
1	Passenger car	70
2	Single-unit truck with one 18-kip single-axle load	10
3	Truck-trailer combination with two 34-kip tandem-axle loads	20

Six different levels of total vehicles per day in the design lane were chosen: 5, 10, 25, 50, 100, and 200 vehicles/day. These figures represent vehicles per day in the design lane; to compare them with traffic volumes based on average daily traffic (ADT), the numbers should be multiplied by 2, since a two-lane road is being considered. This analysis, therefore, uses a range of traffic volumes from 10 to 400 ADT to represent low-volume roads. This is similar to traffic levels considered in a previous study on low-volume-road economics (2).

The PDMS uses a new performance prediction algorithm to calculate the pavement deterioration caused by each vehicle type separately, thereby eliminating the need to convert mixed traffic into an equivalent number of 18-kip single-axle applications. This procedure was adopted after it was shown that axle equivalence factors are not very precise (1). However, to give an indication of how much traffic is being used in this analysis, the number of 18-kip equivalent single-axle loads (ESALs) expected over a 20-year period for each traffic level is summarized below:

Traffic Level (vehicles/day)	No. of ESALs
5	19 400
10	38 800
25	97 100
50	194 000
100	388 000
200	777 000

Rehabilitation and Maintenance

The PDMS program predicts the time at which the present serviceability index (PSI) will reach the "failure" level or terminal serviceability index (TSI). When a failure occurs before the end of the 20-year analysis period, rehabilitation is used and the additional cost is added to the total cost.

In this analysis, the rehabilitation cost assigned for an aggregate-surfaced (type 1) road is $6000/mile. This cost is for 3 in of added aggregate, 1 in of which is considered level-up. The rehabilitation cost for the surface treatment (type 2) pavement is $6500/mile for 1 in of surface treatment overlay, 0.5 in of which is considered level-up. For the asphalt pavement (type 3), a 2-in overlay (1 in as level-up) is $30 000/mile.

Annual routine maintenance is considered a function of PSI. If a pavement is new or recently rehabilitated, the PSI is high and a small annual routine maintenance cost is assigned. If the PSI is low, then a high maintenance cost is used and a linear relation is assumed for points between. In this study, the routine maintenance cost at the failure PSI level is $2000/mile for the aggregate-surfaced pavement, $2500/mile for the surface treatment pavement, and $4500/mile for the asphalt pavement.

Vehicle Operating Cost

Vehicle operating cost is considered a function of PSI for each vehicle type. This information was obtained from the literature for asphalt roads (3), but certain assumptions and estimations were made in determining the vehicle operating costs for aggregate-surfaced roads. The vehicle operating costs used for this study, expressed as additional costs incurred for a PSI of less than 4.0, are given in Table 1.

Total Cost

The total cost for each pavement type is calculated over the analysis period, including the initial construction, rehabilitation, maintenance, and user costs. Salvage value is calculated as a percentage of the cost of rehabilitating, depending on what percentage of the PSI above failure remains at the end of the analysis period.

All costs in PDMS are considered on a net present worth basis, and future costs are discounted back to present worth. Because the system does not consider inflation, a real (not nominal) discount rate is used. For this study, a discount rate of 4 percent was assumed.

Total cost was calculated for each pavement type for each of the six traffic levels. Figure 1 shows PSI versus time during the 20-year analysis period for the traffic level of 5 vehicles/day in the design lane. This figure gives an idea of how the total costs will vary as a function of the performance of each pavement type.

RESULTS OF ANALYSIS

Optimum Surface Type

Figures 2-4 show the total cost ($\log_{10}$ scale) ver-

Table 1. Additional vehicle operating cost for PSI of less than 4.0.

		Additional Cost ($/vehicle-mile)		
Surface Type	PSI	Medium Car or Pickup	Single-Unit Three-Axle Truck	Truck and Trailer (3-S2)
Bituminous	3.5	0.006	0.023	0.33
	2.5	0.026	0.092	0.140
	1.5	0.057	0.210	0.339
	0.5	0.108	0.441	0.732
Aggregate	3.0	0.014	0.046	0.067
	2.0	0.040	0.124	0.186
	1.5	0.054	0.186	0.287
	1.0	0.072	0.268	0.433

Figure 1. PSI curves for three surface types: traffic including all three vehicle types at 5 vehicles/day.

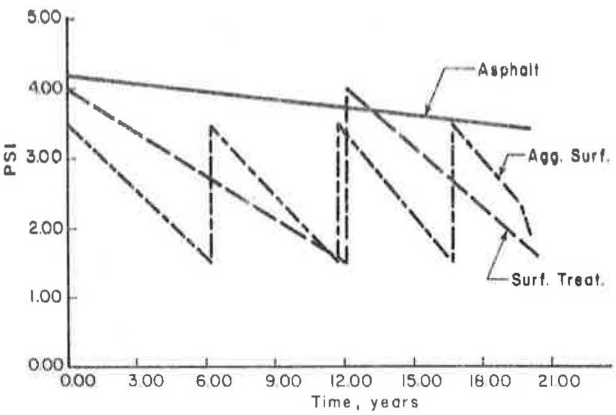
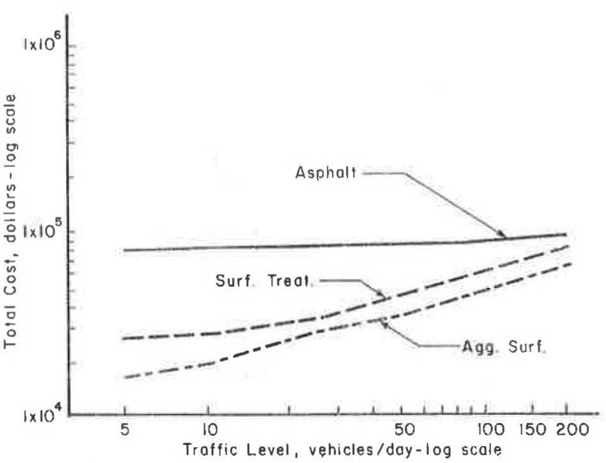


Figure 2. Total cost versus traffic for vehicle 1 traffic.



sus vehicles per day ($\log_{10}$ scale) in the design lane. Figure 2 shows the case in which only the portion of the traffic that contains vehicle 1 is being considered. This figure shows that for the traffic levels considered the lowest total cost is achieved with the aggregate-surfaced road. However, it also shows that an increase of traffic to more than 200 vehicles/day will bring the total cost of the aggregate-surfaced road very near the cost of the surface treatment and asphalt concrete pavements.

Figure 3 considers that portion of the traffic that contains two vehicle types (vehicles 1 and 2). These results show that at a volume of about 45

Figure 3. Total cost versus traffic for vehicle 1 and vehicle 2 traffic.

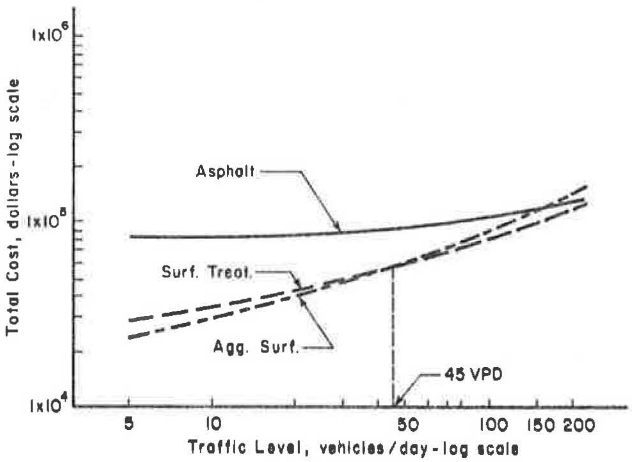
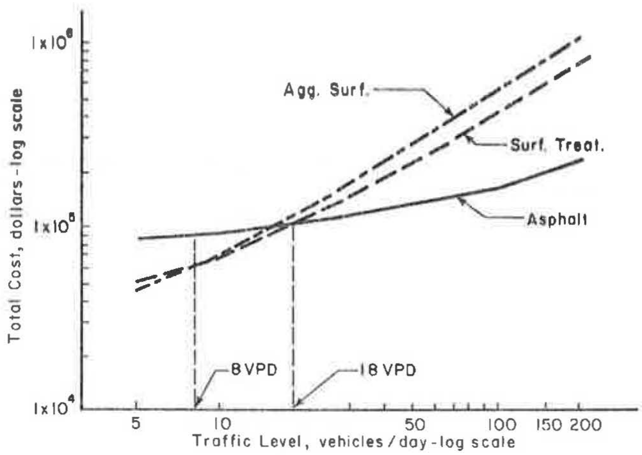


Figure 4. Total cost versus traffic for traffic including all three vehicle types.



vehicles/day the surface treatment pavement becomes less costly than the aggregate-surfaced pavement. This level of traffic is approximately equal to five 18-kip ESALs/day. At approximately 150 vehicles/day, the pavement also becomes cheaper than the aggregate-surfaced road; at a volume greater than 200 vehicles/day, it appears that the asphalt pavement will become the least costly (approximately 20 ESALs/day). The case for all three vehicle types in the traffic is shown in Figure 4. The point at which the surface treatment becomes cheaper than the aggregate surfacing is about 8 vehicles/day, which is equivalent to 5 ESALs/day. The asphalt pavement becomes least costly at 18 vehicles/day, or approximately 10 ESALs/day.

The reason the aggregate-surfaced and surface treatment pavements eventually become more expensive than the asphalt concrete pavement is that for increased traffic these pavements are underdesigned and have frequent rehabilitations and thus high maintenance and user costs. It is difficult to make general conclusions from an example analysis such as this one, but, for the data considered, Figures 3 and 4 show that at traffic levels greater than 5 ESALs/day aggregate surfacing is no longer economical and that at levels greater than 10-20 ESALs/day the asphalt pavement is most economical.

A new performance parameter used with PDMS is the performance area. This term quantifies the areas under the PSI versus time curve (Figure 1) and is expressed in units of PSI (years). A pavement that provides better overall performance will have a higher performance area than one with lower overall performance. Another, similar term is the cost-performance ratio. This is calculated by taking the total cost for a given pavement structure and dividing by the performance area. This parameter expresses the efficiency at which a pavement structure provides performance and is very similar in concept to a cost-benefit ratio.

The cost-performance ratio was calculated for each pavement type and the case of all three vehicles in the traffic. The results are shown in Figure 5. This figure shows that the surface treatment is always more efficient at providing performance than the aggregate-surfaced road and that the asphalt pavement is most efficient at traffic volumes greater than 10 vehicles/day or approximately 5 ESALs/day. In a comparison of Figure 5 and Figure 4, it can be seen that the aggregate-surfaced and surface treatment pavements become more uneconomical at lower traffic levels when cost-performance ratio is considered than when total cost is considered. This indicates that, even though some situations may result in a higher total cost, the efficiency of providing performance may be better.

The practicality of providing the most efficient performance without regard to total cost would arise if the designer had an unlimited budget. Because this is seldom the case, especially with low-volume roads, the principal parameter for deciding optimum surface type should be total overall cost. Performance area and cost-performance ratio can be very useful in selecting the best of several designs that all satisfy the conditions required by the designer.

Marginal Cost

Marginal cost is an important parameter in pavement economics, particularly with respect to roadway financing and pricing. Marginal cost refers to the change in total cost as the result of a unit change in some input. For example, if 1000 applications of a certain vehicle caused a $500 increase in the total cost of maintaining the pavement, then the marginal cost of each application of that vehicle would be $0.50.

In this study, a marginal cost analysis was possible because total cost was calculated for three different conditions: (a) vehicle 1 only, (b) vehicles 1 and 2, and (c) vehicles 1, 2, and 3. The change in total cost from condition a to condition b is due to the additional applications of vehicle 2. Dividing the additional cost by the number of applications of vehicle 2 will yield the marginal cost for vehicle 2. The same process is used to calculate the marginal cost for vehicle 3 by using conditions b and c.

Figure 6 shows the marginal cost for vehicle 3 for different traffic levels. Two vertical lines are drawn to indicate at what traffic levels the surface treatment and asphalt pavements become optimum (lowest in total cost) (Figure 4). Figure 4 shows that the aggregate-surfaced road is lowest in total cost up to the vertical line on the left. Between the two vertical lines the surface treatment is the lowest in total cost, and past the vertical line on the right the asphalt pavement is the lowest in total cost. Figure 6 shows that, if the pavement type is near the optimum traffic level, it will have a decreasing marginal cost. After the pavement type is no longer optimum, the marginal cost will increase (see aggregate-surfaced and surface treatment pavements in Figure 6). At traffic levels that are below optimum for a given pavement type, the marginal cost will be nearly constant and then will decrease as the traffic level becomes closer to optimum (see asphalt pavement in Figure 6).

The same concept is shown in Figure 7, which has the marginal cost for vehicle 2. The vertical line in this figure represents the traffic level where the surface treatment pavement became optimum for two vehicles (Figure 3). The aggregate-surfaced

Figure 5. Cost-performance ratio versus traffic for traffic including all three vehicle types.

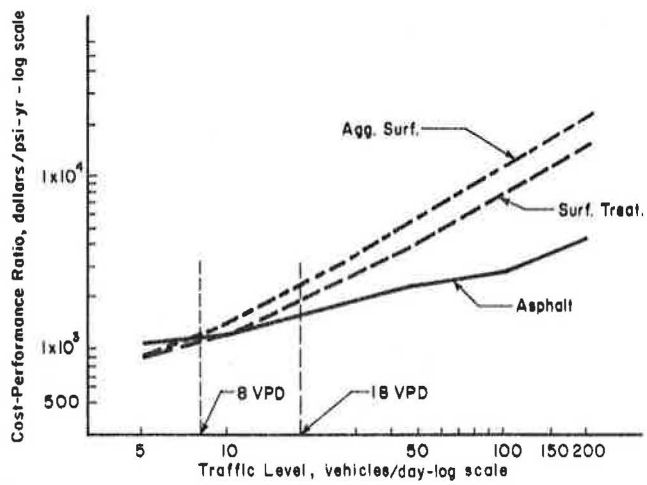


Figure 6. Marginal cost per mile versus traffic for vehicle 3 traffic.

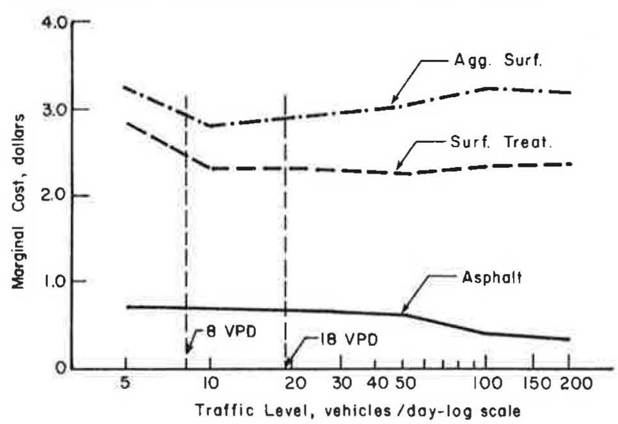
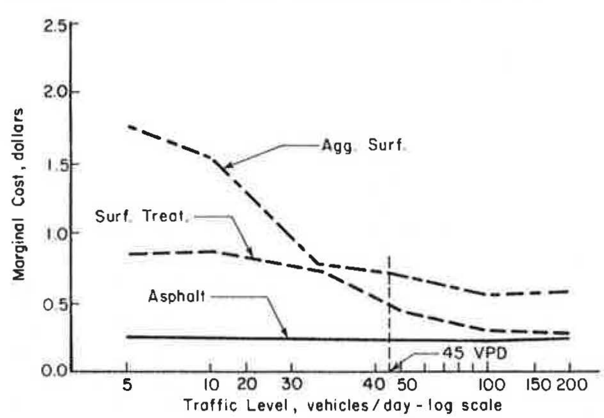


Figure 7. Marginal cost per mile versus traffic for vehicle 2 traffic.



pavement decreases in marginal cost until after the surface treatment becomes optimum and then increases. The surface treatment marginal cost is relatively stable until it nears the optimum traffic level and begins to decrease. The asphalt pavement is relatively unchanged over the entire range of traffic levels since it does not become optimum at this low traffic level (Figure 3).

From the results shown in Figures 6 and 7, the following observations are made:

1. If the pavement is overdesigned, the marginal cost will remain approximately constant.
2. If the pavement is correctly designed (i.e., optimum for a given traffic level), the marginal cost will be decreasing.
3. If the pavement is underdesigned, the marginal cost seems to increase, but the range of data in this study does not make this point clearly.

The marginal cost analysis seems to indicate that it is very important to design the proper pavement structure for the proper condition (i.e., optimum design). Otherwise, the marginal costs imposed by the different vehicles may be much larger than can be afforded (or financed) by a transportation authority.

The marginal cost in Figures 6 and 7 for the aggregate-surfaced and surface treatment pavements is quite large when compared with the marginal cost for the asphalt pavement. This is due to the fact that the increased loads of vehicles 1 and 2 have a larger effect on weak pavements than on strong ones. This, of course, would be expected. However, it must be remembered that marginal cost in this analysis did not consider the initial construction cost. Pavements that have aggregate surfacings or surface treatments are often designed for "stage construction", in which the road is gradually built up over a number of years. In this case, some of the cost attributed to marginal cost may be better classified as construction cost, which would reduce the marginal cost for the stage construction pavements.

TSI Level

Pavements can be maintained at many different levels of performance. It is often difficult for the pavement designer to determine what level of TSI will be optimum for a given set of conditions.

As part of this study, an economic analysis was made for three different levels of TSI: 2.5, 2.0, and 1.5. This analysis was done only for asphalt pavement. Since rehabilitation would occur at different levels of serviceability index, rehabilitation costs were made a function of TSI. The assigned rehabilitation costs were $30 000 for a TSI of 1.5, $25 000 for a TSI of 2.0, and $20 000 for a TSI of 2.5.

The total cost for three different TSI values versus traffic is shown in Figure 8. The results show very little difference in total cost regardless of the TSI used. The reason for this is that the additional cost of more frequent rehabilitations for a TSI of 2.5 is offset by reduced maintenance and user costs. The vertical line in Figure 8 is the traffic level at which the asphalt pavement became optimum (Figure 4). The trend indicated by this figure is that when the pavement is overdesigned the additional maintenance of a TSI equal to 2.5 results in higher total costs. However, in the optimum range for the asphalt pavement, the higher level of maintenance becomes the most economical. This is another example of how costs can be reduced if the optimum pavement strategy is used.

Figure 8. Total cost for asphalt pavement at three PSI levels for traffic including all three vehicle types.

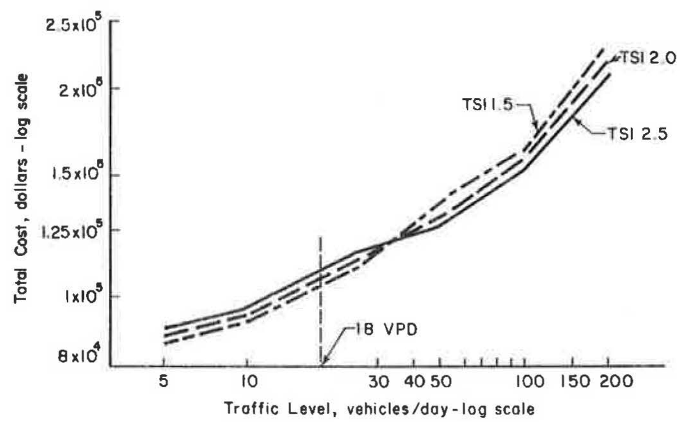


Figure 9. Cost-performance ratio for asphalt pavement at three PSI levels for traffic including all three vehicle types.

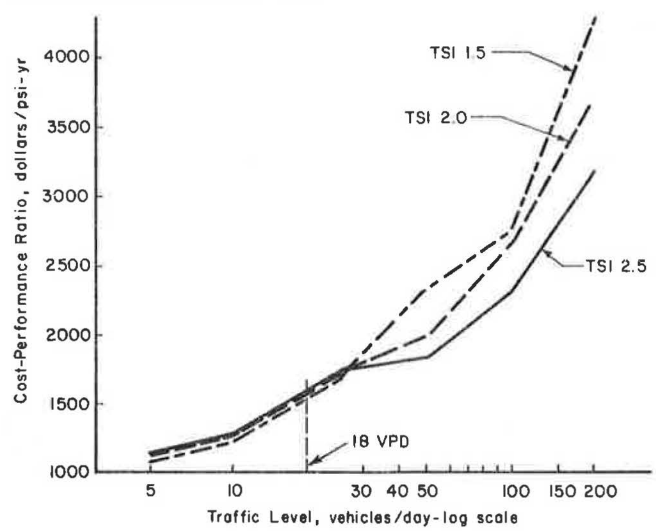


Figure 9 shows a larger effect of TSI on cost-performance ratio than was seen with total cost in Figure 8. This is a case where the cost-performance ratio can be useful in evaluating optimum pavement strategies. Figure 8 showed relatively little difference between TSI levels, but Figure 9 could be used to assist the designer in choosing the best rehabilitation strategy. As with Figure 8, the vertical line in Figure 9 indicates the optimum level of traffic for the asphalt pavement. Again, there is little effect of TSI when the pavement is less than optimum, but significant differences occur in the optimum range.

Marginal cost is shown as a function of TSI for vehicles 3 and 2 in Figures 10 and 11, respectively. In both figures, little effect of TSI is seen in the suboptimum region. However, Figure 10 illustrates the effect of TSI in the optimum region: The highest level of maintenance has the lowest marginal cost. Figure 11 is entirely in the suboptimal region, since asphalt surfacing for two vehicles did not become optimum for the traffic levels considered (Figure 3).

Length of Analysis Period

The analyses summarized in this paper were also per-

Figure 10. Marginal cost per mile for vehicle 3 traffic at three PSI levels (asphalt pavement).

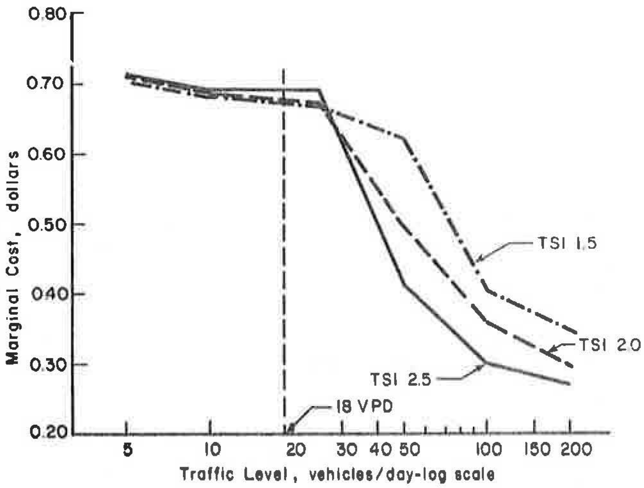
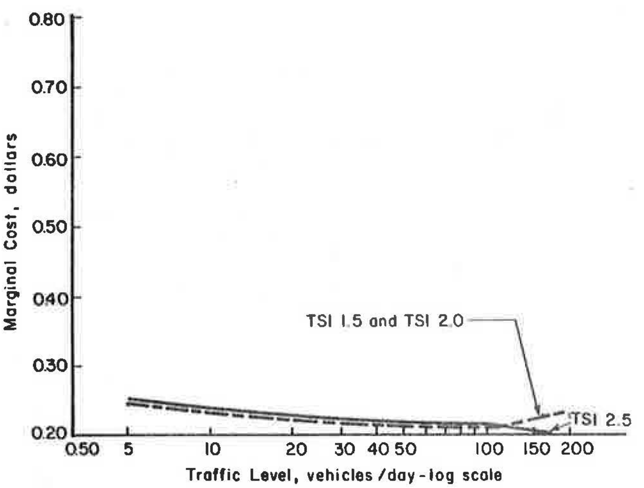


Figure 11. Marginal cost per mile for vehicle 2 traffic at three PSI levels (asphalt pavement).



formed for an analysis period of 10 years instead of 20. No appreciable difference in the results was found when a 10-year analysis period was used.

CONCLUSIONS

The main conclusion of this paper is that economic evaluations are extremely important for low-volume-road systems and that a pavement management system can be a valuable tool in conducting economic analyses of alternative pavement designs. Specifically, the following conclusions are made:

1. For the specific conditions examined in this study, the aggregate surface was the optimum surface type for up to 5 ESALs/day. The surface treatment was optimum for 5-20 ESALs/day, and the asphalt pavement was optimum for traffic levels greater than 20 ESALs/day.

2. The cost-performance ratio can be very helpful in evaluating pavement strategies that also satisfy total cost constraints.

3. Marginal cost, as calculated in this analysis, is much higher for weaker pavement structures than for strong ones. It is possible that marginal costs for stage construction pavements should be adjusted to compensate for the stage construction costs.

4. For the data analyzed in this study, marginal cost was nearly constant for the case of an overdesigned pavement structure, decreased for an optimum pavement structure, and increased for an underdesigned pavement structure.

5. TSI had little effect if the pavement structure was not optimum but was significant in the optimum range for the same pavement structure.

6. No appreciable difference was found in the results presented when an analysis period of 10 years instead of 20 years was used.

7. The designer can greatly reduce low-volume-road pavement costs by determining and implementing the optimum pavement design and rehabilitation strategy for a given set of conditions. A significant reduction of marginal cost and a significant effect of TSI are found in the optimum range for a given pavement structure.

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The contents of this paper reflect our views, and we are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the U.S. Forest Service. This paper does not constitute a standard, specification, or regulation.

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