A Performance-Based Approach for Determining Cost Responsibilities of Load-Related and Non-Load-Related Factors in Highway Pavement Rehabilitation and Maintenance Cost Allocation

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ABSTRACT

A methodology is presented that was developed for use in a 1983-1984 Indiana highway cost-allocation study to determine the responsibilities of load-related and non-load-related factors for pavement routine maintenance and rehabilitation costs. Proportions of the effects of the two types of factors are derived by comparing actual pavement performance curves with predicted pavement performance by using design equations. A technique is presented to estimate the amount of total pavement damage caused by load-related and non-load-related factors combined. The cost-responsibility proportions of the two types of factors are then computed. An example is given to illustrate the application of the procedure.

An old problem in highway cost-allocation studies, unresolved since the first such studies were undertaken several decades ago, involves the determination of respective proportions of traffic and environmental responsibilities in highway pavement rehabilitation and maintenance expenditures.

In cost-allocation studies, it is convenient to divide factors that affect pavement performance into those that are load related (or traffic related) and those that are not load related. Non-load-related factors include environmental variables such as temperature, moisture, soil and site conditions, material variables, soundness of engineering design, quality of construction work, and others not related to traffic loadings. Pavement deterioration may result from load-induced distress, non-load-associated distress, and interaction of the two.

It is recognized that design technology has not advanced to the stage where interaction of the distresses can be accurately predicted. Nor is there enough information to reliably separate load-related effects from non-load-related effects by physical measurement of pavement conditions. Established engineering principles therefore offer relatively little help to cost-allocation analysts in identifying the effects of such factors on pavement performance. As a result, the contribution of these two types of factors has been assigned judgmentally, if not arbitrarily, in almost all cost-allocation studies to date.

Listed in Table 1 are the proportions of allocations for pavement maintenance and rehabilitation based on load-related and non-load-related factors used by different cost-allocation studies. Also listed is the basis on which these assignments were made. The wide diversity of these allocation proportions, which vary practically from 0 to 100 percent for either of the two types of factors, indicates clearly that subjective judgment does not provide an acceptable solution to this problem.

In recent studies, there has been a tendency to employ the Delphi approach to obtain from a pool of selected experts their opinions regarding the shares of load-related and non-load-related factors responsible for pavement maintenance and rehabilitation costs. The Wisconsin (10) and Maine (8) studies are two examples of this approach. However, on a topic such as this where there is a wide disparity of views among highway pavement experts, it is doubtful that efforts to find averages from pooling would produce any meaningful results. This subjective approach provides at best only group-consensus values for cost-allocation purposes. It does not necessarily offer a more reliable answer than the judgmental decisions used in earlier studies.

In this paper a methodology is described in which estimates are obtained of total pavement damage or wear in terms of the present serviceability index (PSI) and equivalent single axle loads (ESALs) computed from a pavement performance curve. The total pavement damage is estimated by defining a zero-maintenance pavement performance curve. A technique is introduced to derive the zero-maintenance curve by considering the routine maintenance expenditures associated with the pavement sections under consideration. Last, a proportionality assumption is made to determine responsibility shares of the load-related and non-load-related factors for total pavement damage.

BASIS OF THE APPROACH

In practice, actual pavement performance rarely coincides with predicted performance based on pavement design equations. Although inaccurate design equations could lead to discrepancies between predicted and actual pavement performance, there are other factors that would contribute to these discrepancies. Four of these factors are (a) elements not considered in the design, such as inferior materials, substandard construction, and so forth; (b) incorrect assessment of the values of design parameters such as regional factors and material proper-

TABLE 1 Proportions of Allocations for Pavement Rehabilitation and Maintenance Based on Load-Related and Non-Load-Related Factors

Source	Proportions	Basis
Oregon study 1980 *(1)*	Overlay: 100 percent load related; maintenance: 10 percent environmental, 90 percent load related	Recommendation of departmental maintenance research engineers and officials
Wyoming study 1981 *(2)*	Maintenance: 80 percent non load related	Based on judgment
Maryland study 1983 *(3)*	Modified federal primary method: 25 percent environmental, 75 percent load related	Based on FHWA input
Washington study 1977 *(4)*	48 to 68 percent non-load-related, varies among highway classes	Used values intermediate to 1976 Oregon study and 1965 federal study
Georgia study 1979 *(5)* and Florida study 1979 *(6)*	Resurfacing: 25 percent environmental and aging factors; maintenance: 80 percent environmental and aging factors	Georgia study: Georgia Department of Transportation assumption; Florida study based on 1965 federal study
Kentucky study 1982 *(7)*	Rehabilitation: 100 percent load-related; maintenance: 80 percent to all vehicles by axle miles	Based on other cost-allocation studies
Maine study 1982 *(8)*	44 percent allocated by PSI; 56 percent allocated by ESAL	Delphi approach
Connecticut study 1982 *(9)*	75 to 80 percent common costs; 25 to 20 percent attributable costs	Based solely on engineering judgment
Wisconsin study 1982 *(10)*	Rehabilitation: (rural) 40 percent environmental (urban), 50 percent environmental; maintenance: 15 to 21 percent environmental, varies among highway classes	Derived from judgments of Wisconsin Department of Transportation experts and 1981 Texas study
Federal study 1982 *(11)*	Responsibility of pure environmental effects in the decision to rehabilitate: 7 percent (flexible pavement), 1 percent (rigid pavement); pavement maintenance not within scope of study	Based on distress models

Note: PSI = present serviceability index; ESAL = equivalent standard axle load.

ties; (c) faulty design; and (d) level of maintenance performed.

The Indiana Department of Highways (IDOH) pavement design method (12) basically follows the procedure described in the AASHTO Interim Guide (13). The Indiana design equations estimate the traffic-loading effects under a set of selected design conditions. The responsibility for pavement damage caused by these design load-related factors can be attributed to vehicle classes by considering the parameters in the design equations (basically the ESALs). Other pavement damage costs are due to the effects of non-load-related factors and the interaction of load- and non-load-related factors.

In Figure 1, curve 1 represents a field pavement performance curve and curve 2 the corresponding performance predicted with Indiana design equations. Area A may be considered as a measure of the pavement wear or damage due to the design load-related factors defined earlier. Area B represents further pavement wear due to non-load-related factors and interaction of these factors with load-related factors. However, area (A + B) does not truly represent the amount of damage or wear caused jointly by load-

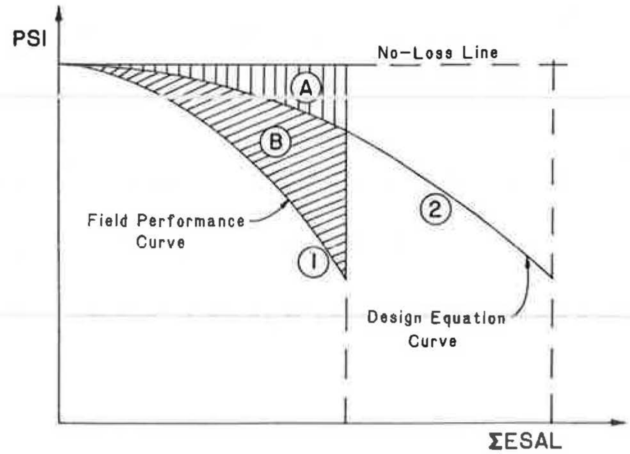

FIGURE 1 Field and predicted pavement performance.

related and non-load-related factors and their interaction. This is because a certain level of routine maintenance is always present in practice. Some of the damage caused by the various factors discussed is repaired or "recovered" by maintenance work. Therefore, the true total damage caused by these factors is greater than that represented by area (A + B) in Figure 1.

Theoretically, the true total damage may be represented by the shaded area $(A + B)_0$ between curves 3 and 4 in Figure 2. Curve 3 is a hypothetical no-loss line and curve 4 a hypothetical performance curve for the pavement concerned in a situation where no maintenance has been carried out. An actual pavement performance curve may lie anywhere between curves 3 and 4 depending on the level of maintenance performed. By considering actual performance of pavements and their associated maintenance expenditure, a technique was developed by which the zero-maintenance curve could be derived.

If the zero-maintenance curve is known, area $(A + B)_0$ can be calculated. Proportion of the damage responsibility that can be attributed entirely to design load-related factors may be computed as $A/(A + B)_0$ and the joint responsibility of non-load-related factors and interaction factors as $[(A + B)_0 - A]/(A + B)_0$. On the assumption that the share representing non-load-related plus interaction factors is the arithmetic sum of the two components and that the interaction portion is composed of two parts, namely, load-related and non-load-related parts, the total respective proportions of load-related and non-load-related factors may be computed by means of a proportionality assumption discussed later in this paper.

DERIVATION OF ZERO-MAINTENANCE CURVE AND AREA $(A + B)_0$

As mentioned earlier, the role of routine maintenance is to move the actual pavement performance curve away from the zero-maintenance curve, shown as curve 4 in Figure 2. The higher the level of routine maintenance performed, the closer the field performance curve would be to the no-loss line. Performance curves for three sections of a given stretch of pavement, each with a different level of routine maintenance, are shown schematically in Figure 3 in which maintenance level L_3 is higher than L_2 and L_2 is higher than L_1.

Each of the three performance curves in Figure 3 is also labeled with a value S_i, which is the

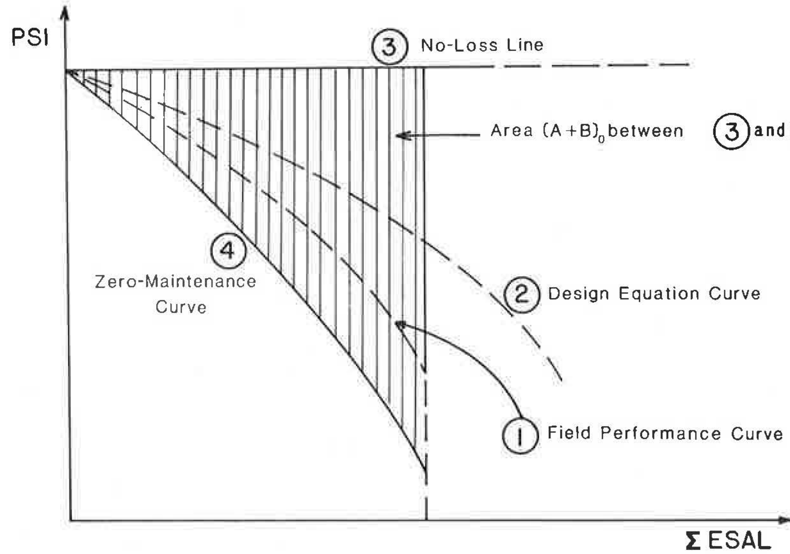

FIGURE 2 Total pavement damage as defined by zero-maintenance pavement performance curve.

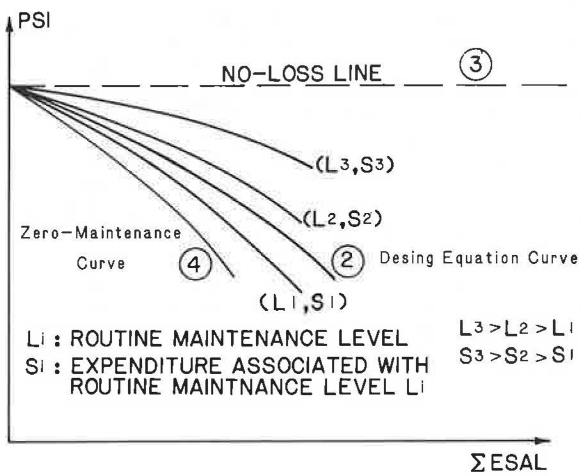

FIGURE 3 Pavement performance curves with their associated routine expenditures.

maintenance expenditure associated with maintenance level L_i. A convenient measure of maintenance expenditure would be the annual maintenance expenditure per lane mile of the pavement section under consideration. On the assumption that all three maintenance levels are performed with the same technology, it is reasonable to consider that the maintenance expenditure would be positively related to the level of maintenance performed. In Figure 3, one would expect S_3 to be greater than S_2 and S_2 greater than S_1.

The steps involved in deriving the zero-maintenance curve for a stretch of pavement are discussed in the following paragraphs.

The first step is to establish the no-loss line, defined by the design initial PSI value specified in the design requirements. In accordance with the AASHTO Interim Guide, values of 4.2 and 4.5 are commonly used for flexible and rigid pavement, respectively.

Second, the actual performance curve is determined. Many state highway agencies maintain certain forms of pavement performance records as part of their pavement management or pavement evaluation system. In Indiana, IDOH began to systematically record yearly roadmeter roughness measurements on all Interstate and state highways in the late 1970s. The use of the roadmeter permits the evaluation of extensive pavement mileage in a relatively short period of time. These pavement roughness measurements have been found to be an efficient means for screening highway pavements relative to their present serviceability (14). PSI models have been developed for Indiana to correlate measured roughness and pavement serviceability (14,15). These models and their R^2-values are as follows for different pavement types:

Asphalt:

$$PSI = 3.94 - 0.00072C \qquad R^2 = 0.79 \qquad (1)$$

Overlay:

$$PSI = 4.37 - 0.00174C \qquad R^2 = 0.77 \qquad (2)$$

Jointed reinforced concrete (JCR):

$$PSI = 4.69 - 0.00141C \qquad R^2 = 0.88 \qquad (3)$$

Continuously reinforced concrete (CRC):

$$PSI = 4.40 - 0.00070C \qquad R^2 = 0.59 \qquad (4)$$

where C is roadmeter counts per kilometer.

For a given pavement section, if a PSI value and the corresponding cumulative ESAL are known, a point on the field performance curve of the pavement can be obtained. This procedure may be repeated for other points for which data are available. The field performance curve of the pavement may then be plotted. The area between this field performance curve and the no-loss line established in step 1 is the area (A + B) in Figure 1 for this pavement section. This area (A + B) is computed by considering the cumulative ESAL over the age of the pavement section measured at the analysis year. Similarly, field performance curves for other pavement sections may be plotted and their corresponding areas (A + B) calculated.

In the third step, the routine maintenance expenditure is computed. IDOH keeps a detailed annual record of highway routine maintenance activities. An earlier study (16) developed a procedure to compute an aggregated annual routine maintenance cost for each highway section from these records. A highway section is defined as that portion of the highway that lies within the boundaries of a county. The annual routine maintenance cost per lane mile of a given highway section is obtained by dividing its annual routine maintenance costs by its total lane miles. The annual routine maintenance expenditures over the analysis period are considered to compute the average maintenance cost for the highway section under consideration. Because routine maintenance information is documented by highway section, this same section has been chosen as the basic unit of analysis in this study. When a pavement section contains more than one roughness measurement, a weighted average of area (A + B) is calculated by using the lane miles of each roughness measurement as the weighting factor.

The last step is to derive area $(A + B)_0$ of the zero-maintenance curve. Area (A + B) calculated in step 2 may be plotted against its respective average annual routine maintenance expenditure per lane mile computed in step 3. A least-squares line may be fitted to the data points. The intercept of this line with the (A + B) axis gives area $(A + B)_0$ of the zero-maintenance curve of the pavement under consideration.

Because design criteria are different for different climatic regions, highway functional classes, and types of pavement, it is necessary to group pavements by region, highway class, and pavement type. In addition, different pavement thicknesses also give rise to different design performance curves. This means that the procedure just outlined has to be carried out separately for each combination of region, highway class, pavement type, and pavement thickness. In the Indiana highway cost-allocation study, two regions, five highway classes, and four pavement types were considered. The two regions are northern and southern Indiana (17). The five highway classes include Interstates, state primary routes, state secondary routes, city streets, and county roads. The four pavement types are flexible, rigid with bituminous overlay, JRC, and CRC.

DETERMINATION OF PROPORTIONALITY RULES FOR LOAD-RELATED AND NON-LOAD-RELATED EFFECTS

A schematic diagram representing the proportion of responsibility for pavement damage of load-related and non-load-related effects is shown in Figure 4(a). The proportion of these four types of effects in pavement damage are represented by a, b, c, and d in Figure 4(b). These four values add up to 1.

$$a + b + c + d = 1 \quad (5)$$

Proportion a represents the load-related effects according to design equations. It is given by

$$a = A/(A + B)_0 \quad (6)$$

Determination of $(A + B)_0$ has been described in the preceding section. Area A is computed from design equations for the same cumulative ESAL used in deriving area (A + B) discussed earlier.

If proportion a is known, it is possible to calculate proportions b, c, and d by making a proportionality assumption as follows:

$$b/(b + c + d) = a/(a + b + c + d) \quad (7)$$

$$c/(a + b + c) = d/(a + b + c + d) \quad (8)$$

Equation 7 assumes that for a given case of purely load-related effects (proportion a), the share of the load-related effects in the remaining non-load-related and interaction effects is directly proportional to the share of the purely load-related effects in the total (a + b + c + d). Similarly, Equation 8 assumes that for a given case of purely non-load-related effects (proportion d), the share of non-load-related effects in the remaining load-related and interaction effects is directly proportional to the share of the purely non-load-related effects in the total (a + b + c + d).

In a physical sense, the proportionality assumption implies that for a given pavement and a known set of environmental conditions and time period, the higher the traffic loading, the higher share it is going to have in the interaction effects. It also implies that for the same pavement with a given amount of traffic loading, the more severe the weather and other environmental conditions, the big-

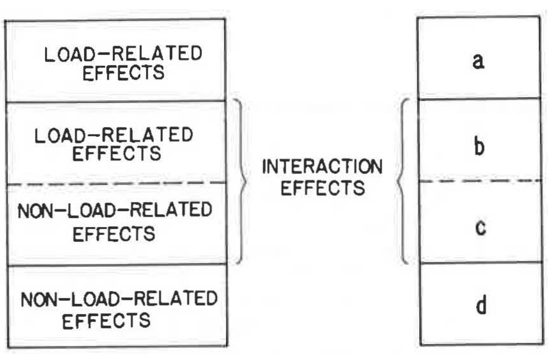

FIGURE 4 Responsibility for pavement damage by load-related and non-load-related effects.

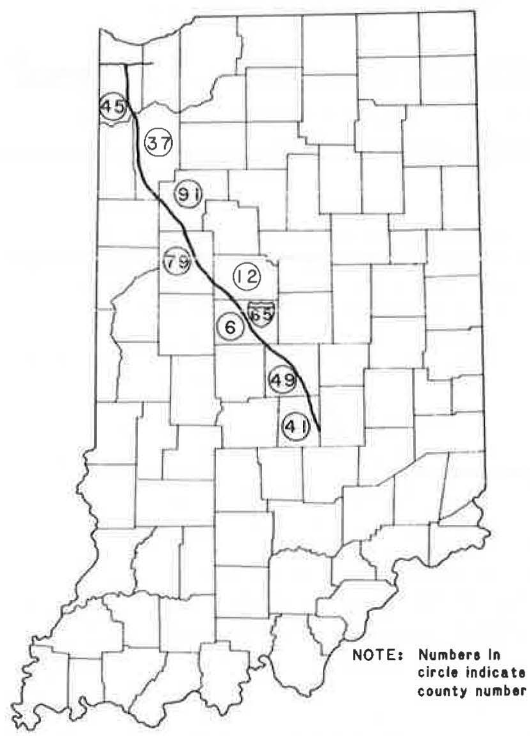

FIGURE 5 Location of the sections of I-65 analyzed.

ger share those conditions will represent in the interaction effects. This phenomenon has been confirmed by the recent research of Sharaf (17).

Equations 7 and 8 may be reduced to

$$b = a(b + c + d) \quad (9)$$

$$c = d(a + b + c) \quad (10)$$

Solving for d by using Equations 9 and 10 gives

$$d = 1 - [1 - (1 - a)]^{1/2} \quad (11)$$

Proportions b and c may then be determined by solving Equations 9 and 10. The total proportion of responsibility for load-related effects is given by (a + b) and that for non-load-related effects by (c + d).

APPLICATION OF THE METHODOLOGY

The methodology presented in this paper was applied to determine the proportions of load-related and non-load-related effects responsible for the damage to different pavement types in different highway classes in Indiana. The results of an analysis on an Interstate highway in northern Indiana are presented for illustration.

The northern half of I-65 is a CRC pavement constructed in the late 1960s. The concrete slab thickness is 10 in. Figure 5 shows the location of this highway and the numbers of the counties through which it passes. Of the eight counties concerned, maintenance and roughness records for the sections in counties 91 and 12 were incomplete. The computed areas (A + B) and average annual routine maintenance expenditures per lane mile over the analysis period for the remaining six pavement sections are presented in Table 2 and plotted in Figure 6. By using AASHTO design equations for rigid pavement, area A for the pavement was computed to be 0.2163×10^7 PSI-ESAL. This gives a value of 0.4189 for proportion a, as shown in Figure 6. Solving Equations 9, 10, and 11 gives 0.1862 for proportion d, 0.2434 for proportion b, and 0.1515 for proportion c.

The total proportion of load-related effects (a + b) is 0.6623, and the total proportion of non-load-related effects (c + d) is 0.3377. If the total pavement rehabilitation or maintenance expenditure for this stretch of pavement is known for a cost-allocation study period, the appropriate cost responsibilities for load-related and non-load-related effects can then be obtained.

Continuing research is being conducted to apply the methodology presented in this paper to investigate (a) the regional effects of non-load-related factors; (b) the effects of non-load-related factors on different pavement types, (c) the effects of load-related factors on pavements of different highway classes, (d) the variation, if any, of the proportions of load-related and non-load-related effects with traffic volume levels, (e) the effects of pavement age on the relative proportions of load-related and non-load-related factors, and (f) the effects of pavement thickness on the relative proportions of load-related and non-load-related factors.

TABLE 2 Area (A + B) and Maintenance Expenditure for I-65, North Indiana

Highway Section	County No.	Annual Routine Maintenance Expenditure per Lane-Mile ($)	Area (A + B) (PSI-ESAL)
1	6	138.75	0.3172×10^7
2	37	80.05	0.3833×10^7
3	41	173.20	0.2734×10^7
4	45	47.33	0.4570×10^7
5	49	166.80	0.2656×10^7
6	79	129.38	0.3470×10^7

CONCLUSIONS

A relatively simple procedure for the analysis and determination of the responsibility proportions of load-related and non-load-related factors has been presented in this paper. The procedure does not require an extensive amount of data collection effort. It relies entirely on measured pavement performance data, which are generally available in the records of a state highway agency. It provides a means to compute from field measurements the cost-responsibility proportions of load-related and non-load-related factors for use in highway cost-allocation analyses, thereby eliminating the undesired element of subjective judgment commonly involved in such studies.

ACKNOWLEDGMENT

This paper was prepared as part of an investigation conducted by the Joint Highway Research Project, En-

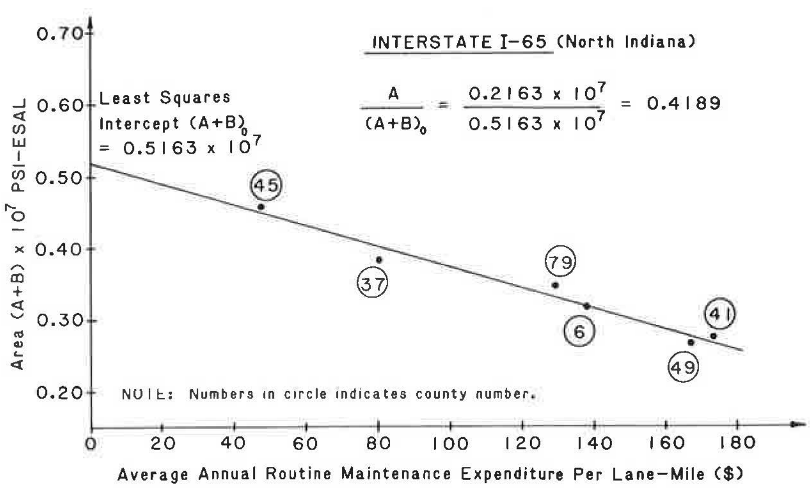

FIGURE 6 Sample plot of (A + B) versus routine maintenance expenditure.

gineering Experiment Station, Purdue University, in cooperation with the Indiana Department of Highways and FHWA, U.S. Department of Transportation.

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Publication of this paper sponsored by Committee on Transportation Programming, Planning and Systems Evaluation.