Thickness Incremental Method for Allocating Pavement Construction Costs in Highway Cost-Allocation Study

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ABSTRACT

A new incremental approach is proposed for allocation of pavement construction costs to highway users. A description of the concept and a working algorithm for computation of the cost responsibility of each vehicle class are presented. The proposed procedure considers pavement thickness increments rather than traffic volume increments or decrements commonly employed in past cost-allocation studies, thereby eliminating the need for an iterative process to compute the vehicle equivalent single-axle load (ESAL), which is required for cost responsibility calculations. The procedure also eliminates the economy-of-scale problem present in the classical incremental cost-allocation method. A hypothetical numerical example is given for illustration. Cost responsibility results of a full-scale analysis are also presented.

Highway cost-allocation studies seek to distribute highway cost equitably among all classes of users. The results of cost-allocation studies have been used to assist state legislatures as well as the U.S. Congress in making highway user tax decisions.

New pavement cost is one of the major cost items in a highway cost-allocation study. Historically, the most commonly used procedure for allocating pavement construction costs has been the traditional incremental method. In this method, the costs of pavement are allocated on the basis of the incremental costs needed to build a thickness capable of accommodating a particular category of traffic (1). The cost-allocation method employed by a 1965 FHWA study (2) is an example of the incremental technique in which trucks and cars share the costs of the basic pavement depth necessary for carrying cars, and the costs of the extra pavement depth required to carry heavy trucks are charged to heavy trucks (2).

In spite of its wide application in the area of cost-allocation, the traditional incremental approach has been found to be unsatisfactory as a procedure for allocating pavement construction cost. Pavement costs remain one of the most controversial aspects of highway cost allocation. Presented in this paper is a review of the traditional incremental method as well as other methods adopted in recently completed studies, and a proposal for revised incremental approach for allocating pavement construction costs.

REVIEW OF EXISTING COST-ALLOCATION METHODS

In general, the existing pavement cost-allocation methods may be classified into three broad categories: (a) methods that follow the traditional incremental approach, (b) methods that distribute cost directly in proportion to a cost allocator, and (c) decremental or avoidance methods based on a removal technique that hypothetically removes vehicle groups from the traffic stream. Listed in Table 1 are some recent studies classified according to their allocation methods (2-11).

The direct cost-allocator approach is easy to use. However, its theoretical basis is weak, and it is questionable whether an equitable and fair cost allocation is attainable with such an approach.

TABLE 1 Allocation Procedures for New Pavement Cost in Recent Studies

Procedure Type and Study	Description
Traditional incremental approach	
Oregon, 1980 *(4)*	Incrementally by observed axle weight
Wyoming, 1981 *(5)*	Traditional six-step incremental method
Maryland, 1983 *(6)*	Eleven axle load increments, cost allocated on the basis of axle miles
Direct cost-allocator approach	
Kentucky, 1982 *(7)*	Based on total 18-kip ESAL for a 20-year period
Georgia, 1979 *(8)*	First 5-in. concrete or equivalent asphalt concrete thickness distributed to all vehicles according to vehicle miles of travel (VMT); balance allocated on the basis of ESAL and VMT
Virginia, 1982 *(9)*	Minimum pavement method; minimum thickness costs distributed by average daily traffic (ADT); balance allocated by ESAL
Maine, 1982 *(10)*	Passenger car equivalent (PCE), 50 percent of minimum pavement cost; VMT, the other 50 percent; balance allocated by ESAL
Connecticut, 1982 *(11)*	Common costs allocated by VMT, attributable costs by ESAL
'Decremental removal' or avoidance approach	
FHWA, 1982 *(2)*	Uniform removal technique by hypothetically removing vehicle classes and calculating costs saved using AASHO Road Test equations
Wisconsin, 1982 *(3)*	Basic costs distributed in proportion to PCE miles; service costs allocated by avoidance technique; remaining unallocated service costs distributed to all vehicle groups in proportion to ESAL
Virginia, 1982 *(9)*	Similar to Wisconsin basic-avoidance-residual technique, except that the basic costs are allocated to all vehicles on the basis of ADT

The traditional incremental approach, which has enjoyed wide application in the past, has been much criticized for its unfairness in allocating pavement thickness costs by giving the benefits of economy of scale to heavy vehicle classes (2,3,12). Economies of scale in pavement cost allocation arise from the nonlinear relationship between pavement thickness and traffic loadings. A curve of pavement thickness plotted against traffic loading tends to level off as load increases. Figure 1 shows a typical pavement

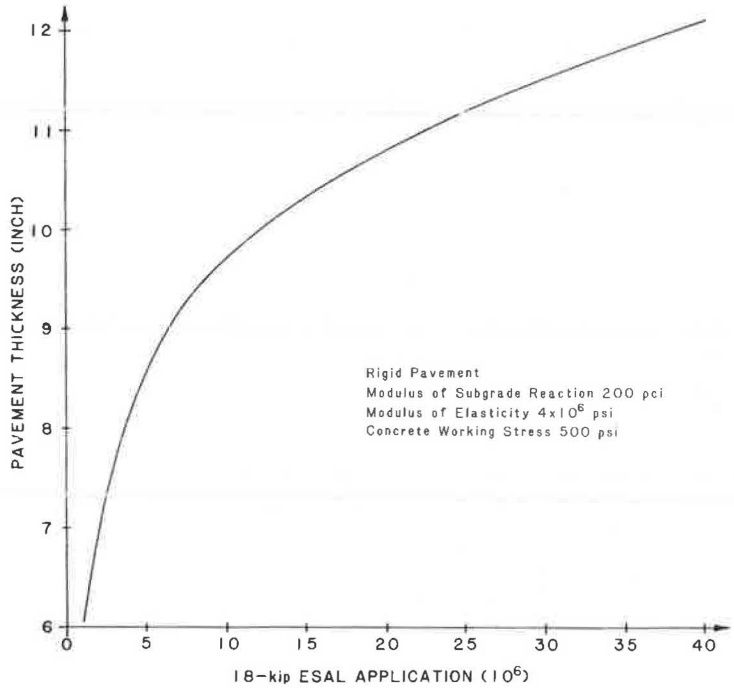

FIGURE 1 Relationship between ESAL application and pavement thickness.

thickness-load relationship for rigid pavements. A similar nonlinear relationship also holds for flexible pavements. This means that the last unit thickness at the top of a pavement could withstand much higher traffic loading than could the first unit thickness at the base of the pavement. Under the traditional incremental approach, vehicle classes are added sequentially to the traffic stream and those vehicle classes added later are assigned lower unit costs than those vehicle classes added earlier. An unfair allocation results as long as the sequential addition of vehicle classes, which is the central idea of the traditional incremental approach, is retained.

In reality, traffic loadings are applied randomly and not in the pattern assumed in the traditional incremental approach. Applying traffic loads sequentially in vehicle classes is also not consistent with most pavement design procedures. Practically all pavement design methods involve consideration of the entire traffic loadings as one entity and the pavement thickness is then designed for these mixed traffic loadings as a whole. No existing design procedure has indicated or implied that a certain thickness is designed explicitly for a particular class of vehicle. In other words, vehicle classes have never been considered individually for thickness design purposes.

The considerations discussed in the preceding paragraph can be used as a yardstick to judge the rationality of any cost-allocation procedure for pavement thickness cost. Several attempts have been made to improve the accuracy and rationality of the traditional incremental method. Studies have been made by using 15 or more increments (2), instead of the traditional six increments that were used to increase the accuracy of cost allocation. Unfortunately, the cost (pavement thickness) increment is not a linear function of the parameter (in this case, the vehicle class) increment. Increasing the number of increments alone does not eliminate the inherent weakness of the method. That is, the economy-of-scale problem remains no matter how many increments are used in the analysis.

In an attempt to overcome the economy-of-scale problem, the Wisconsin study (3) employed a technique called Basic-Avoidance-Residual (BAR) for allocating pavement costs. A vehicle group is randomly removed from the traffic stream and the reduction in pavement thickness is calculated. This vehicle group is then returned to the traffic stream and the procedure is repeated by removing a different vehicle group. The calculated cost reduction for the pavement saved each time is considered to be the responsibility of the vehicle group removed. The main drawback of this procedure is that thickness reduction is computed for each vehicle group at the top end of the thickness design curve shown in Figure 1. This is not consistent with the actual concept used with most pavement thickness design procedures. Another undesirable feature of this method is that the avoidance technique described in the preceding paragraphs cannot fully account for the entire attributable pavement thickness. A residual thickness is left unallocated after all vehicle groups have been considered. This leftover portion is distributed to each vehicle group in proportion to its contribution to the total equivalent single-axle load (ESAL).

A notable contribution toward logical allocation of pavement thickness cost was made in the federal cost-allocation study completed in 1982 (2). A decremental approach was adopted in which traffic was systematically removed and the attendant hypothetical cost savings were assigned to the vehicles under consideration. Because order of removal can drastically affect the costs assigned to a given axle, it was proposed that each vehicle class be divided into an equal number of subgroups, and one subgroup from each vehicle class be removed before the second subgroup was removed from any class. The amount of thickness saved was distributed to vehicle classes on the basis of ESAL. On the basis of the argument that the ratios of thickness saved for one vehicle class relative to other vehicle classes were nearly constant at different points on the removal curve, only an average ESAL value for each vehicle class was computed. Each average ESAL value was obtained iteratively by first assuming a middle-range pavement thickness.

DESCRIPTION OF THE PROPOSED APPROACH--THE THICKNESS INCREMENTAL METHOD

A revised incremental procedure is developed in this paper to (a) overcome the problem of economy-of-scale in pavement thickness cost allocation and (b) be consistent with procedures commonly used in pavement design.

The proposed cost-allocation procedure begins by defining pavement thickness increments, in contrast to the common practice of starting with traffic increments or decrements. There are two advantages to this new approach: (a) by beginning with a known thickness, calculation of ESALs becomes a straightforward noniterative procedure, and (b) pavement thickness is more directly related to cost than is traffic loading.

In the definition of the number and magnitude of pavement thickness increments, a minimum practical pavement thickness must first be determined because it is impractical to construct surface, base, or subbase courses of less than some minimum thickness. This minimum thickness is the basic pavement thickness that is required regardless of the traffic level. For instance, the AASHTO Interim Guide (13) recommends the following minimum practical thicknesses:

Course	Thickness (in.)
Surface	2
Base	4
Subbase	4

Only those costs that correspond to the thickness in excess of the specified minimum will be allocated by the incremental approach described in this section. The costs corresponding to the minimum thicknesses cannot be allocated to any particular vehicle group and will be considered as nonattributable costs or basic costs. These costs are the collective responsibility of all the vehicles that use highways. They are commonly distributed to vehicle classes on the basis of a use-related travel function such as vehicle-miles of travel (VMT) (2) or passenger car equivalent (PCE) (3).

The total thickness in excess of a specified minimum is divided into equal increments, the number and thickness of which depend on the desired accuracy of the final results. Beginning with the specified minimum thickness, a thickness increment is first added. With this thickness, the ESAL of each vehicle type or a representative vehicle type of a vehicle class can be computed directly from equations developed from the AASHO Road Test (14).

The same procedure is repeated for each additional increment until the last increment is added and analyzed. The incremental pavement thickness cost calculated for each thickness increment is assigned to all vehicle classes based on their need for that thickness in accordance with pavement design procedure. When each increment is sufficiently small, the proportional amount of incremental pavement thickness cost attributable to a given vehicle class can be taken as being in direct proportion to its ESAL value at the thickness concerned.

An important feature of the foregoing procedure with respect to input data requirements is worth mentioning. With the exception of direct cost-allocator methods (i.e., the second procedure category in Table 1), virtually all analytical cost-allocation methods use the following general relationships:

$$c = f(T,C,m) \quad (1)$$

$$t = g(Vt,VPx,ESALx,r,s,k) \quad (2)$$

$$ESALx = h(t,Wx) \quad (3)$$

$$CRx = w(ESALx,\sum_{x} ESALx,t,c,VPx) \quad (4)$$

where

- c = unit pavement thickness cost;
- m = pavement material type;
- T = total thickness of pavement;
- C = total pavement cost;
- V = total traffic volume;
- Vt = traffic volume considered in an intermediate stage of cost-allocation analysis, $0 \leq Vt \leq V$;
- t = pavement thickness corresponding to traffic volume Vt, $0 \leq t \leq T$;
- VPx = volume proportion of vehicle class x, x = 1,2,...,n;
- n = total number in vehicle class;
- ESALx = equivalent 18-kip single axle load of vehicle class x, x = 1,2,...,n;
- r = regional factor to account for regional climatic and environmental effects;
- s = subgrade soil property parameter;
- k = pavement material properties;
- Wx = axle loads of vehicle class x, x = 1, 2,...,n; and
- CRx = cost responsibility of vehicle class x, x = 1,2,...,n.

The FHWA study's Uniform Removal Technique, Wisconsin's BAR method, and the traditional incremental approach all involved consideration of increments or decrements of traffic volume and the resulting pavement thickness was computed iteratively by using the relationships in Equations 2 and 3. This process requires a complete range of input information, as is needed in a design problem. Cost-allocation analysis, though closely related to design, is not a design problem because the total pavement thickness is already known. For a pavement constructed or going to be constructed with a total thickness T and cost C, Equations 1, 3, and 4 indicate that with an appropriate procedure such as the method proposed in this paper, it is not necessary to resort to the iterative thickness design steps in order to calculate cost responsibilities. Consequently, information such as V, r, s, and k need not be known in a pavement cost-allocation problem.

COMPUTATIONAL ALGORITHM OF THICKNESS INCREMENTAL METHOD

The AASHO Road Test equations (13,14) for the ESAL calculation can be expressed as follows:

$$\log ESALx = G\,[(1/b_{18}) - (1/b_x)] + \log\{[(L_x + L)/19]^A \cdot (L)^B\} \quad (5)$$

$$G = \log[(I - P_t)/(I - 1.5)] \quad (6)$$

$$bx = C + [D(L_x + L)^E/(SN + 1)^F \cdot (L)^H] \quad (7)$$

$$SN = T \text{ for rigid pavement} \quad (8a)$$

$$SN = a1 \cdot D1 + a2 \cdot D2 + a3 \cdot d3 \text{ for flexible pavement} \quad (8b)$$

where

L_x = axle load (kips);
L = 1 for single axles, 2 for tandem axles;
P_t = terminal serviceability index;
SN = slab thickness (for rigid pavement), structure number (for flexible pavement);
A,B,C,D,E,F,H,I = constants with values specified in Table 2;
a1,a2,a3 = layer coefficients representative of surface, base, and subbase course, respectively; and
D1,D2,D3 = thickness (in.) of surface, base, and subbase course, respectively.

TABLE 2 Values of Constants in Equations 5-8

Constant	Flexible Pavement	Rigid Pavement
A	4.79	4.62
B	4.33	3.28
C	0.40	1.00
D	0.081	3.63
E	3.23	5.20
F	5.19	8.46
H	3.23	3.52
I	4.20	4.50

Inputs to the problem include (a) cost information, (b) pavement data, and (c) traffic composition, vehicle axle configuration, and axle-weight data. In practically all previous cost-allocation studies, pavement costs were assumed to be directly proportional to thickness. The Thickness Incremental Method presented herein does not have this restriction. The algorithm described in the following can accommodate any nonuniform linear or nonlinear thickness-cost relationship.

The computation algorithm for cost allocation involves the following steps:

1. Divide the pavement thickness in excess of a practical minimum into N equal increments. In the case of flexible pavement, each increment is composed of thickness of surface, base, and subbase materials in the same proportions as are in the total "excess" thickness to be allocated.
2. Calculate the cost for the minimum thickness and distribute to all vehicle classes on the basis of VMT.
3. Calculate the incremental thickness cost.
4. Add an increment to the minimum thickness, and compute ESAL for all vehicle classes (or vehicle types if desired) using Equations 5 through 8.
5. Compute the cost responsibility factor of each vehicle class (or vehicle type) as the following ratio:

$$F(i,j) = P(i) \cdot ESAL(i,j) / \sum_{r=1}^{M} [P(r) \cdot ESAL(r,j)] \quad (9)$$

where

F(i,j) = cost responsibility factor of vehicle class i for thickness increment j,
P(i) = proportion of vehicle class i in traffic stream,
ESAL(i,j) = ESAL of vehicle class i for thickness increment j, and
M = total number of vehicle classes.

6. Allocate incremental thickness cost to each vehicle class as follows:

$$c(i,j) = F(i,j) \cdot Cd(j) \quad (10)$$

where c(i,j) is the cost allocated to vehicle class i for thickness increment j, and Cd(j) is the incremental cost for thickness increment j.

7. Repeat steps 5 and 6 for each new thickness increment until the full pavement thickness is reached.
8. Calculate the total allocated cost for vehicle class j by summing up its cost responsibility for all increments:

$$C(i) = CM(i) + \sum_{j=1}^{N} c(i,j) \quad (11)$$

where

C(i) = total cost responsibility of vehicle class i,
Cm(i) = cost responsibility of vehicle class i for the minimum thickness, and
N = total number of thickness increments.

AN ILLUSTRATIVE EXAMPLE AND FINDINGS

A hypothetical problem, described in Figure 2, is developed herein for illustration purposes. Only two vehicle types are chosen for ease and clarity in presentation. Also, minimum practical thickness is set to 0 to highlight the salient features of the incremental allocation procedure. Cost is assumed to be directly proportional to pavement thickness. From the results shown in Figure 2, the following observations can be made:

1. Incremental cost responsibility varies with pavement thickness. A fair allocation of cost cannot be attained by using a direct cost allocator. Using an ESAL evaluated at full thickness as the cost allocator overestimates cost responsibility of the heavier vehicle whereas using an ESAL at intermediate range tends to underestimate its responsibility.
2. The cost responsibility curve fluctuates because it depends on the relative magnitude of ESALs of different vehicle classes that are themselves nonlinear functions of thickness. It may not be appropriate to use an average ESAL value for each vehicle class to allocate costs.
3. The overall cost responsibility distribution will change when a minimum practical thickness is introduced. The direction of this change depends on the magnitude of the minimum thickness introduced and the vehicle-mile proportion of each vehicle class.
4. For structural numbers greater than 6, further analyses show a small but steady increase of heavy vehicle responsibility.
5. Results from a similar analysis performed on concrete pavement (see Figure 3) show the same pattern of cost responsibility distribution, but the amplitudes of fluctuations of the cost responsibility curves are much smaller.

Figure 4 presents a plot of cumulative cost responsibility versus pavement thickness for the problem described in Figure 2. The total cost responsibility of each vehicle class is given by the responsibility value at T, the total pavement thickness.

In Table 3, cost responsibility factors for the hypothetical problem in Figure 2 are computed by using five different methods. The traditional incremental method always underestimates the cost respon-

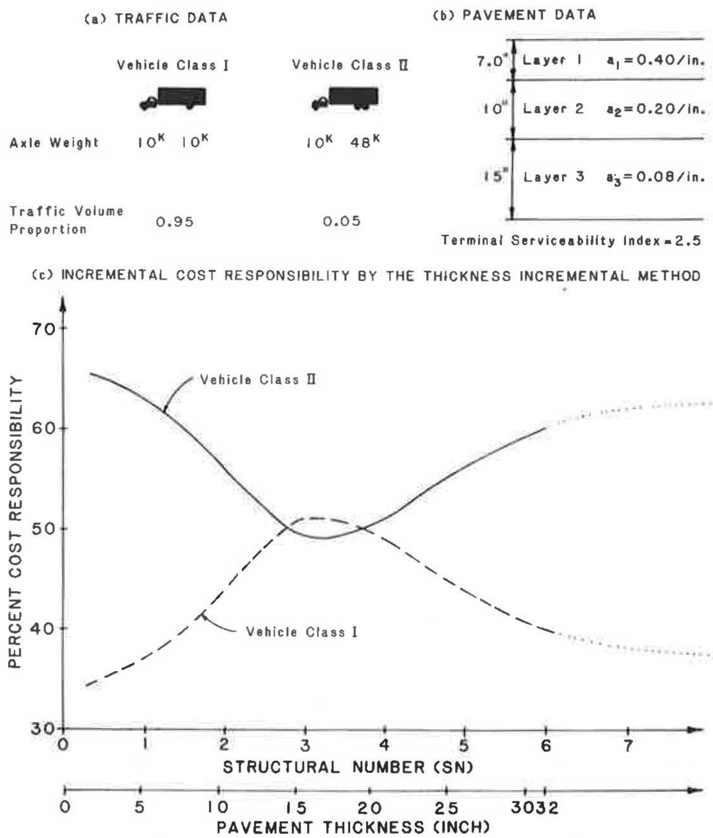

FIGURE 2 A hypothetical cost-allocation problem for flexible pavement.

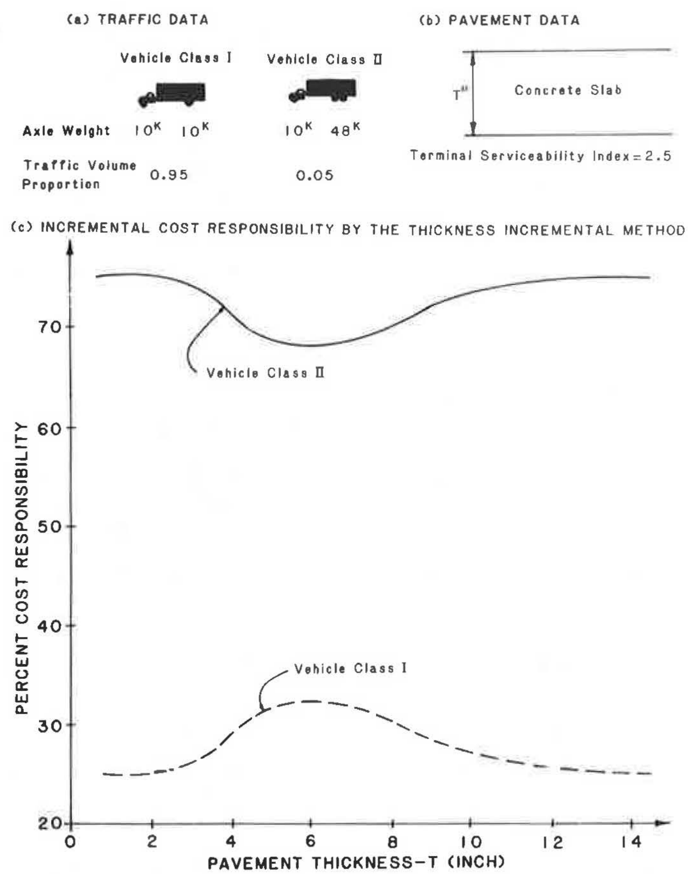

FIGURE 3 A hypothetical cost-allocation problem for rigid pavement.

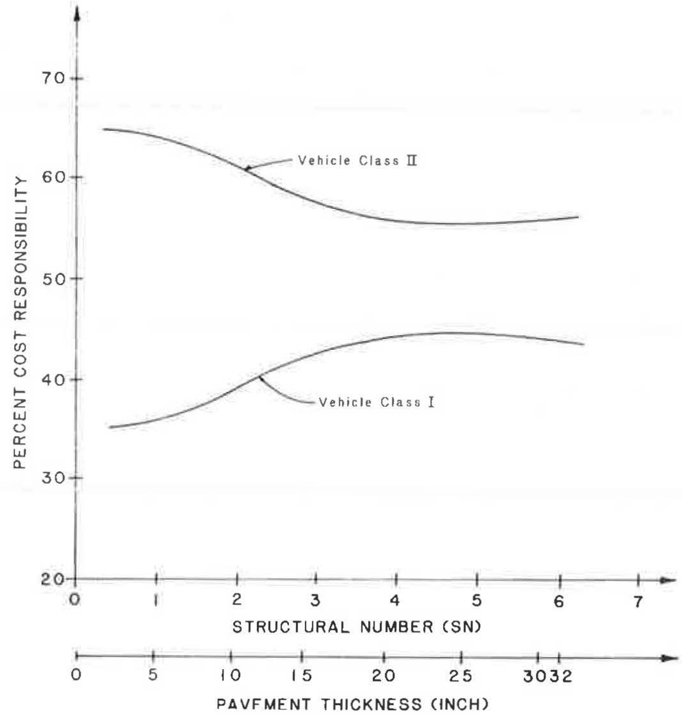

FIGURE 4 Variation of cumulative cost responsibility with pavement thickness—by thickness incremental method for problem in Figure 2.

TABLE 3 Solution to Figure 2 Problem with Different Cost-Allocation Methods

	Cost Responsibility (%)	
Method	Vehicle Class I	Vehicle Class II
Thickness incremental method	43.81	56.19
ESAL cost-allocator method	40.00	60.00
FHWA study's *(2)* Uniform Removal Technique[a]		
Evaluated at SN = 2.5	48.38	51.62
Evaluated at SN = 3.0	50.54	49.46
Evaluated at SN = 3.5	50.45	49.55
Wisconsin study's BAR method[a]	38.79	61.21
Traditional incremental method[a]	81.54	18.46

[a]Additional data: total 18-kip ESAL applications = 10,000,000; region factor = 1.0; soil support value = 2.5.

sibility of heavy vehicles because of the economy-of-scale problem described earlier. The second and third methods may underestimate or overestimate heavy vehicle responsibility. In the former case, this depends on the total thickness of pavement as can be seen from Figure 2 and in the latter, on the thickness at which ESALs are computed. For most practical situations where total heavy truck ESAL is higher than total light vehicle ESAL, Wisconsin's BAR method leads to an overestimation of heavy vehicle responsibility.

RESULTS OF A FULL-SCALE STUDY

The thickness incremental method was used in the 1983-1984 Indiana cost-allocation study to allocate pavement construction costs. Presented in Tables 4 and 5 are data and cost responsibility results for rural Interstate highways in Indiana. Sixteen contracts completed between 1980 and 1983 were included in the analysis.

Table 4 shows the average traffic volume composition of 14 vehicle classes on Indiana rural Interstates. Each of these 14 classes was further subdivided into weight categories in increments of 2,500 lb. Table 4 presents the aggregate cost responsibilities for the 14 vehicle classes. For illustration, the breakdown of class 12 vehicle cost responsibility into weight category responsibilities is shown in Table 5.

CONCLUSIONS

There are two unique features that distinguish the proposed procedure from other existing cost-allocation methods: (a) a more direct approach using the cost-related pavement thickness as the controlling parameter is followed; and (b) the amount of input data required is considerably less. For example, only the proportional distribution of each vehicle class in the traffic stream is needed.

TABLE 4 Average Traffic Volume Composition on Indiana Rural Interstates

	Vehicle Class[a]													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Volume (%)	15.64	48.84	2.36	0.31	1.12	0.42	0.36	0.06	0.17	0.07	2.52	27.20	0.76	0.16
Cost responsibility (%)	8.54	26.85	1.98	0.48	0.65	0.42	0.47	0.03	0.23	0.06	3.73	54.19	2.13	0.24

[a]Definition of vehicle classes: Class 1, small passenger cars; Class 2, standard and compact passenger cars, panels, and pickups; Class 3, two-axle truck (2S and 2D); Class 4, bus; Class 5, car with one-axle trailer; Class 6, three-axle single-unit truck; Class 7, 2S1 tractor-trailer; Class 8, car with two-axle trailer; Class 9, four-axle single-unit truck; Class 10, 3S1 tractor-trailer; Class 11, 2S2 tractor-trailer; Class 12, 3S2 tractor-trailer; Class 13, other five-axle; Class 14, six or more axles.

TABLE 5 Pavement Construction Cost Responsibility Factors for Weight Categories of Class 12 Vehicle on Rural Interstate

Subdivision No.	Weight Category	Cost Responsibility (%)
1	Less than 22,500	0.040
2	22,500-24,999	0.205
3	25,000-27,499	0.736
4	27,500-29,999	2.170
5	30,000-32,499	1.847
6	32,500-34,999	1.192
7	35,000-37,499	1.043
8	37,500-39,999	0.971
9	40,000-42,499	0.938
10	42,500-44,999	0.934
11	45,000-47,499	0.964
12	47,500-49,999	1.009
13	50,000-52,499	0.971
14	52,500-54,999	1.252
15	55,000-57,499	1.490
16	57,500-59,999	2.075
17	60,000-62,499	2.047
18	62,500-64,999	2.159
19	65,000-67,499	2.708
20	67,500-69,999	4.418
21	70,000-72,499	7.609
22	72,500-74,999	9.015
23	75,000-77,499	4.923
24	77,500-79,999	2.296
25	80,000-82,499	0.254
26	82,500 and above	0.624
Total		54.190

By having each vehicle class proportionally represented each time an incremental cost is allocated, the proposed cost-allocation procedure effectively eliminates the economy-of-scale problem associated with the traditional incremental method. Iterative procedure is avoided by taking the thickness increment as the starting parameter. The algorithm is applicable to any nonuniform linear or nonlinear thickness-cost relationship. The procedure is easy to understand because it follows traditional thought in increasing thickness to account for increasing traffic.

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Publication of this paper sponsored by Committee on Taxation, Finance and Pricing.