Life-Cycle Pavement Cost Allocation

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Past highway cost-allocation studies have relied primarily on principles of highway construction in attributing cost responsibilities among vehicle classes. However, the changing character of state and federal highway programs, which emphasizes maintenance and rehabilitation in lieu of new construction, coupled with the need for increased highway revenues prompted Congress to mandate a new cost-allocation study in 1978. As part of that effort, this research considered one key element of highways—pavements—and investigated life-cycle (i.e., maintenance and rehabilitation) costs attributable to different vehicle classes. Central to this study was the use of a simulation model of highway performance and costs that could consider variations in the several parameters of the problem. Different economic criteria were applied, which included pure efficiency (short-run marginal cost pricing) and equity-based measures. The general engineering and economic concepts used in this approach and results of several case studies for flexible and rigid pavements in urban and rural regions within two different climatic zones are discussed. Cost responsibilities for pavement maintenance and rehabilitation are presented individually for six vehicle classes and on a cent-per-ESAL-mile basis. Although the values differ by pavement type, environmental region, and economic criterion used, in general they show that heavy combination trucks bear approximately 1000 times the cost responsibility of automobiles for pavement maintenance and rehabilitation. Differences between flexible and rigid pavements and between climatic zones are also highlighted.

The nationwide system of streets and highways, one of the most important public investments in the United States, is financed primarily by highway user charges. Of the $37.5 billion in receipts designated for highway purposes in 1979, about $22.8 billion, or 61 percent, was derived from imposts on highway users, primarily in the form of a full tax imposed at the federal, state, and (to a limited extent) county and municipal levels. Another $10 billion, or 27 percent, was received through other taxes and fees, mainly property assessments and general revenues earmarked for local roads at the county and municipal levels (1). Although there has been no opposition to the notion that users should pay for highway services, the amount that each class of user (or class of vehicles) should pay is open to controversy and involves a host of technical, economic, and political issues.

As a result, many studies under the generic title of highway cost allocation have been conducted by federal and state agencies. The first major federal cost-allocation study was mandated in 1956 by the Highway Revenues Act, which established the Highway Trust Fund. This study lasted until 1965, and its findings were updated twice, in 1969 and 1975. However, recognizing the unreliability of extrapolating earlier results and the potential need for new highway taxes, the Congressional Budget Office (CBO) in 1978 recommended a new highway cost-allocation study (2). In November 1978, Congress passed the Surface Transportation Assistance Act, which mandated a comprehensive cost-allocation study by the U.S. Department of Transportation (DOT) and a concurrent review of the existing and alternative tax structures. The cost-allocation studies conducted by states bear strong ties to the 1956 and 1978 federal studies, although some states have actively developed their own cost-allocation methods.

FOCUS OF OUR RESEARCH

The early federal and state studies were performed during a time of major highway construction; not unexpectedly, methods for allocating pavement maintenance costs were neglected (or were patterned after the method of construction cost allocation). By the time of the 1978 study, however, the highway system had aged, and both the CBO and the performing agency for DOT, the Federal Highway Administration (FHWA), recognized that allocation of maintenance and rehabilitation costs was an important issue.

Our research was undertaken as part of the 1978 study to investigate allocation of life-cycle highway pavement costs, which considered explicitly the maintenance and rehabilitation costs incurred as the result of wear and tear due to traffic and the environment. Thus, the costs of pavement construction and reconstruction are not considered in the results reported in this paper. Moreover, since our study has focused on the costs of structural pavement damage, other costs--such as those due to loss of skid resistance, to problems in materials characteristics (e.g., bleeding), to shoulder maintenance, or to opening of longitudinal construction joints (in flexible pavements)--have likewise not been included. As used in this paper, the term "pavement life-cycle costs" therefore refers to costs incurred through the life of the pavement for routine structural maintenance (patching, crack filling, mudjacking, joint sealing, etc.) and for overlays.

The prime objectives of this study were (a) to develop a sound framework for attributing pavement maintenance and rehabilitation costs to different vehicle classes based on the pavement deterioration attributable to each vehicle class and (b) to illustrate how this framework can be applied to develop highway user charge responsibilities. Other issues, such as the effects of using different cost-attribution methods on user charge responsibilities, the impact of environment and pavement type on maintenance and rehabilitation costs, and the implications of life-cycle cost analyses, were also studied.

Determining appropriate user charge responsibilities requires two analytical steps: (a) cost estimation and (b) cost allocation among vehicle classes. To estimate the pavement maintenance and rehabilitation costs arising from road deterioration, a computer simulation model was used to predict pavement performance and life-cycle costs. For cost allocation, theoretical concepts and practical approaches were reviewed to develop allocation methods that satisfied the objectives and constraints of the federal study.

Two broad classes of allocation objectives are generally recognized in the literature: equity and efficiency. Equitable charges attempt to reflect some notion of fairness. Although definitions of equity abound, in this paper we have followed the federal lead in focusing on the concept that users should pay for the highway costs they occasion, where costs here are defined as highway agency expenditures. By contrast, the concept of economic efficiency is well grounded in economic theory and entails computing short-run marginal costs attributable to each user or vehicle class. Costs here encompass not only agency expenditures for routine pavement maintenance and overlays, but also costs borne by the highway users for vehicle operation, travel time, and accidents. (Costs borne by nonusers, such as for air and noise pollution, were considered briefly in our study but are not discussed in this paper.) Costs computed under the efficiency objective are therefore sometimes referred to as total social costs, to differentiate them from agency expenditures.

The choice between equity and efficiency is a political decision, which then dictates appropriate analytical methods and procedures to be used in the allocation process. Accordingly, we have estimated user charge responsibilities for each vehicle class for both the equity and the efficiency criteria. Comparisons between the two results will be presented later in this paper.

The research conducted for DOT emphasizes the systematic development of a rational approach for highway cost estimation and allocation. The details of this methodology are presented elsewhere (3) and encompass the following issues:

1. A description of the process of determining highway user charges;
2. An examination of goals and constraints in user charge determination and associated issues (e.g., the definition of equity and compatibility between equity and efficiency);
3. An examination of goals and constraints in user charge determinations;
4. Estimation of maintenance and rehabilitation costs over the life of the pavement, which considers important technical and economic variables relating to pavement structural and material properties, environmental factors, maintenance policies and technologies, traffic characteristics, unit costs, and so forth; and
5. Allocation of costs under both equity and efficiency criteria.

This paper summarizes the results of this cost-allocation study. First we present below a brief description of the simulation model used to estimate pavement maintenance and rehabilitation costs. Then we develop an outline of the case studies investigated. Finally, we present some of the key results obtained.

OVERVIEW OF SIMULATION MODEL

Since the cost-allocation data were estimated by the EAROMAR-2 simulation model, it is desirable for the reader to have a general understanding of the nature and characteristics of this model. The following is a very abbreviated description; details of this model are provided elsewhere (4).

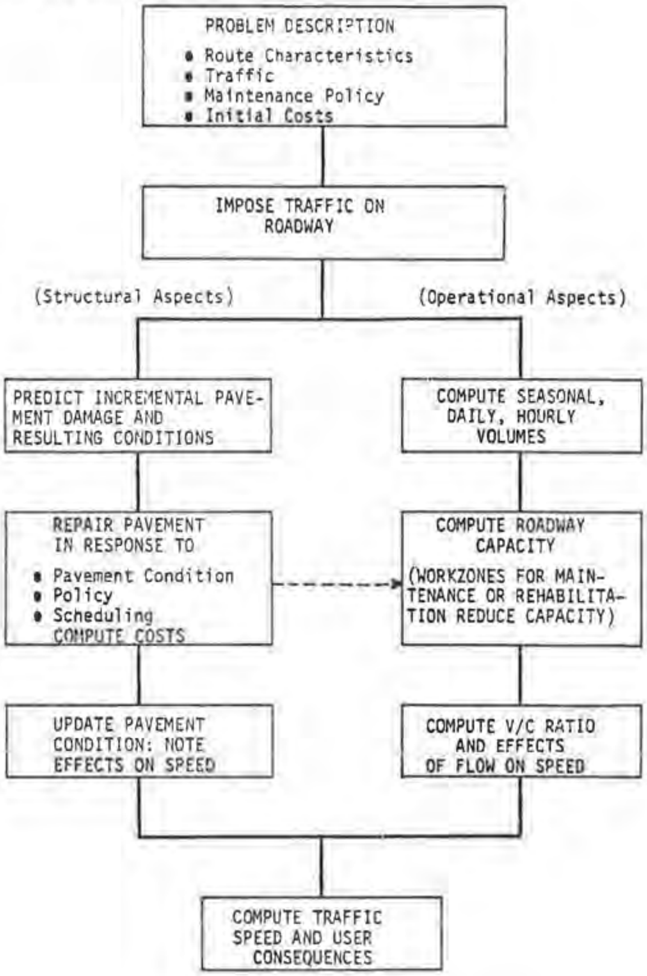
The economic analyses performed by EAROMAR-2 are based on simulations of highway performance and costs, which encompass both the structural (i.e., pavement related) and the operational (i.e., speed and flow related) aspects of road use, as shown in Figure 1. Costs predicted include highway agency expenditures for route or pavement reconstruction, pavement overlays, and pavement routine maintenance, and user costs of vehicle operation, travel time, and accidents, all discounted through an analysis period.

Costs are calculated through successive seasons within years; in each season the collective influences of pavement structural and materials properties; imposed traffic loadings; environmental factors; maintenance policies; local practices on work scheduling; and prevailing unit costs of maintenance labor, equipment, and materials on pavement damage and corresponding maintenance, rehabilitation, or reconstruction requirements are accounted for. The following sections describe briefly the operation of each model component in Figure 1. Additional technical information on each phase of the analysis may be obtained from the FHWA report (4).

Problem Definition

Before the EAROMAR-2 analysis can proceed, the problem itself must be defined to the system through sets of technical, economic, and administrative parameters. Problem definition is the task addressed at the top of Figure 1. These input data establish the characteristics of the route to be studied, the scope of the economic analysis, and the policy alternatives to be investigated.

Figure 1. Concept of EAROMAR simulation.



Economic analyses of highway investment or maintenance policies result from interactions among several geometric, operational, administrative, and economic variables that affect a road during its analysis life. For brevity and clarity, in Figure 1 route characteristics, traffic, and maintenance policy have been emphasized as important components of problem description. A more complete list of factors actually incorporated within EAROMAR-2 would encompass traffic volume, composition, and growth; roadway capacity in relation to demand volume; quality and thickness of pavement initially constructed; environmental factors affecting pavement performance; construction projects to upgrade route geometry, capacity, or pavement or to overlay pavement; standards of pavement serviceability and maintenance to be performed; maintenance technology, work-zone configurations, and scheduling; unit costs (and projected inflation in costs) of maintenance labor, equipment, and materials; budget or resource constraints on maintenance work; vehicle operating costs and values of travel time perceived by the user (with projected changes through the analysis period); and discount rates and length of road life used in the economic analysis.

Analysis Through One Season

The simulation in Figure 1 begins with the assignment of traffic of appropriate volume and composition to each roadway. Roadway geometry, capacity, and current pavement condition derive from the description of the route (whether new or existing) at the beginning of the analysis period, any modifications to the roadway accomplished under construction or overlay projects, the loadings to which the roadway pavement has been subjected, and past maintenance performed. Traffic volume and composition are determined from the initial annual average daily traffic (AADT), growth patterns, and composition of the traffic stream specified by the user.

We now track the flow of the simulation for one roadway through a given season of a year within the analysis period. Conceptually the simulation is divided into two branches, that dealing with structural deterioration and repair of the pavement surface and that treating roadway operational characteristics.

Structural Deterioration and Repair

Pavement Damage

The assignment of traffic to each roadway imposes axle loads that, in conjunction with moisture and temperature, damage the pavement. To estimate the type and magnitude of damage that occurs each season, the EAROMAR-2 system incorporates a set of damage models, as indicated at the top of the left-hand branch in Figure 1.

Models to predict pavement damage are included for two purposes. First, highway maintenance is often a demand-responsive activity in that work is done after damage has appeared. Therefore, to be able to estimate future maintenance requirements accurately, one must be able to predict the type and amount of damage expected to occur and when it will occur. Second, the condition of the highway surface affects user response and may have some bearing on speed, vehicle operating costs, and accident frequencies.

The models included within EAROMAR-2 are based on empirical pavement research or on closed-form approximations to theoretical model predictions. Damage predictions by these models are sensitive to pavement layer thicknesses, seasonal variations in materials properties, applied traffic loadings, and pavement age. In several cases no models exist to predict damage modes of interest; for these, users may provide directly their own estimates of rates of deterioration.

Maintenance and Rehabilitation

Maintenance and rehabilitation are treated within EAROMAR-2 as demand-responsive actions. This means that maintenance requirements in a given season are not extrapolated from historical trends of past work performed but rather are based directly on the type and amount of pavement damage predicted. How much damage is to be repaired among the several maintenance and rehabilitation activities simulated is a management decision expressed through the maintenance and rehabilitation policies, or quality standards.

These demand-side considerations control the determination of seasonal work requirements within EAROMAR-2. However, the actual conduct of work is also governed by supply-side constraints on resource availability and scheduled time allotted to each activity. Maintenance costs depend to some extent on the time of day at which work is carried out. Application of maintenance quality standards to the total damage present in a particular season results in a total maintenance workload for each activity in that period. The maintenance workload is then used as the basis for estimating seasonal maintenance costs.

To cost maintenance requires knowing the production rate, unit resource requirements, and unit costs for labor, equipment, and materials for each activity. The production rate is in units of damage required per hour. Unit resource requirements are the number of workers and the quantity and type of equipment and materials to be used. Unit costs are the dollar-per-hour costs for labor and equipment and unit quantity costs for materials. To the direct costs will be added other costs associated with the activity, such as those for traffic management and inspection. These costs will be summed over all types of damage repaired to arrive at seasonal maintenance costs.

Resulting Pavement Condition

The benefits of pavement maintenance and rehabilitation are accounted for in two ways within the EAROMAR-2 simulation. First, there is an immediate improvement in surface condition due to the damage repaired; if the repairs are significant enough, the present serviceability index (PSI) may also be increased somewhat. (Overlays restore the surface to essentially new condition.) Second, by restoring at least some of the pavement structural capacity lost through use and aging, maintenance and rehabilitation affect the rate of damage accumulation in the future.

By superimposing the results of two calculations--the accumulation of damage simulated by the deterioration models and the repair of damage discussed above--the resulting pavement condition this season is obtained. This revised condition encompasses updated values of all damage components and a recomputed PSI. The updated pavement condition has implications for several remaining steps in the analysis. First, if the pavement surface has deteriorated sufficiently, it may limit the speed of the traffic flow; this possibility is indicated at the lower part of the left-hand branch in Figure 1. Second, pavement condition affects the rates of vehicle fuel, oil, and tire consumption and will thus influence vehicle operating costs. Third, the net cumulative damage predicted by the model becomes part of the roadway damage history and will be used as the starting point of pavement damage analysis in the following season.

Roadway Operations

Roadway operating characteristics describe the level of service afforded motorists in speed and smoothness of flow. These characteristics are quantified within EAROMAR-2 in terms of free-flow speed, speed-change cycles, and congestion or queuing. The procedures involved are shown in the right-hand branch in Figure 1.

Demand Flows

Travel demand is represented by the traffic stream assembled by using data specified by the user. Demand flows are computed in vehicles per lane per hour for each of the 24 h of a typical weekday and of a typical weekend day. Hourly demand may vary along the roadway length.

Roadway Capacity

The capacity of the roadway may also vary over its length with changes in the number of lanes, roadway geometry, side clearances, and so forth. Capacity is computed in both passenger-car equivalents per lane per hour and vehicles per lane per hour for each hour of typical weekdays and weekends, according to procedures recommended in the Highway Capacity Manual (5). The effects of the percentage of trucks and of the vertical grade (if any) are explicitly accounted for.

As indicated in Figure 1, roadway occupancy for maintenance or rehabilitation causes a temporary local decrease in capacity. The amount of disruption depends on when repair work is scheduled, the extent of the work zone, and the duration of work (a function of both the amount of pavement damage present and the maintenance policy specified). Scheduling and work-zone characteristics, as well as maintenance technology and production rates, are controlled by the user in his or her description of each maintenance activity.

Speed-Flow Relationship

EAROMAR-2 simulates traffic operations along the entire roadway length and simultaneously accounts for daily (weekday versus weekend) and hourly variations in demand flows and road occupancy determined by maintenance policies and scheduling requirements discussed above. This procedure is indicated at the bottom of the right-hand branch in Figure 1. Uncongested flows are estimated by using speed-flow relationships developed from the Highway Capacity Manual (5). Where hourly demand exceeds local capacity (whether due to normal rush-hour peaks or to occupancy for pavement repair), congested flows are simulated over both the roadway length and the time. A speed-change cycle is also introduced on entry of the flow into the congested zone.

User Consequences

The last block in Figure 1 represents the calculation of user consequences. In most cases the operational aspects (i.e., the speed-flow relationship on the right-hand branch in Figure 1) will dominate this calculation. In cases of a badly deteriorated pavement, roadway surface condition itself may limit the speed. In either situation, however, pavement condition will affect the rate of fuel, oil, and tire consumption by each vehicle.

Models are included to compute vehicle operating costs, travel time and costs, accident costs, and pollution levels as functions of speed, speed changes, congestion, the characteristics of the vehicular traffic, and the current condition of the pavement surface. These calculations are performed for each hour of each type of day and account for any interruptions due to maintenance or rehabilitation.

Variations in user costs among different components of the traffic stream are automatically taken into account. For example, costs attributable to fuel consumption and emissions will vary by vehicle type. Values of travel time, on the other hand, are a function of trip purpose. Data from which these distinctions can be made are provided in the descriptions of travel demand.

Annual and Total Summaries

At the completion of each season's simulation, the following costs are assembled for use in the economic analysis:

1. Initial investment costs (if any) provided by the user at the beginning of the analysis;
2. Roadway maintenance and rehabilitation costs to repair pavement damage; and
3. User costs associated with vehicle operation, travel time, and accidents.

Seasonal totals are summed for each year. If components of the cost stream are subject to differential inflation, appropriate adjustments to costs are made; the annual costs are discounted at specified rate(s) and the discounted totals accumulated. At the completion of the simulation, the discounted maintenance and user costs are displayed, together with initial construction costs, to yield a total cost stream.

DEVELOPMENT OF CASE STUDIES

To demonstrate the application of the EAROMAR-2 results to cost allocation, eight case studies were developed that considered combinations of two environmental regions, two pavement types, and two traffic levels. The environmental regions typified the Northeastern and the Southwestern United States; they represented cold-wet and hot-dry conditions, respectively. The two pavement types comprised flexible (asphalt-concrete) and rigid (portland cement concrete), in each case designed according to the AASHTO method (6). The traffic levels corresponded respectively to high and low volumes and were taken from FHWA projections for urban and rural Interstate systems, respectively. Designs typical of the Interstate highway system were chosen in constructing the case studies; however, the cost-allocation concepts developed under this research apply to other classes of roads as well.

The eight highway cases tested had identical geometric characteristics consistent with Interstate standards. Each road consisted of a four-lane level-tangent divided highway that had 12-ft lane widths and 10-ft shoulders. Since highways were divided with an assumed 50-50 directional traffic split, we needed to look at only two of the four lanes of each route considered in the analysis; we assumed that the remaining two lanes had identical conditions. Consequently, the results must be interpreted with care; costs per mile pertain to a two-lane mile (i.e., a roadway mile, if only one traffic direction is considered).

FHWA had identified 38 vehicle classes for consideration in the DOT study. In this particular research these classes have been consolidated within six classes according to registered weight. Again, the conceptual basis of the study was not affected; the redefinition was done simply to reduce the analysis effort.

Details on the several categories of information specified for the case studies (road engineering characteristics, traffic volume and composition, maintenance policy and technology, unit costs, and so forth) are explained elsewhere (3, Appendix A) and would be too lengthy to present here. However, there are some aspects of case study design that should be understood in assessing the results below:

1. The focus of this project was to demonstrate the applicability of simulation models such as EAROMAR-2 to the allocation of life-cycle pavement costs and not to estimate total user charge responsibilities for pavements. Thus, only routine structural maintenance and rehabilitation costs were considered; other pavement-related costs, such as those for initial construction, shoulder maintenance, skid resistance, and pavement reconstruction, were not included.
2. To avoid slanting the analyses toward a particular environmental region or pavement type, certain elements of the case studies were addressed as objectively as possible, e.g., by holding certain

Table 1. ESAL factors used in analysis.

Vehicle Class	Vehicle Type	Flexible Pavement		Rigid Pavement	
		Urban	Rural	Urban	Rural
Northeast Region					
1	Automobile	0.000 361 2	0.000 368 5	0.000 348 1	0.000 353 5
2	Light single-unit truck	0.090 41	0.082 50	0.074 97	0.071 19
3	Heavy single-unit truck	0.359 2	0.252 7	0.187 7	0.136 2
4	Combination <25 tons	0.276 6	0.285 0	0.154 4	0.152 4
5	Combination 25-35 tons	0.332 1	0.381 2	0.179 9	0.181 2
6	Combination >35 tons	0.458 4	0.446 0	0.172 2	0.153 8
Southwest Region					
1	Automobile	0.000 501 4	0.000 665 2	0.000 473 2	0.000 620 9
2	Light single-unit truck	0.066 72	0.078 29	0.056 37	0.066 59
3	Heavy single-unit truck	0.298 9	0.381 4	0.162 0	0.195 3
4	Combination <25 tons	0.495 6	0.751 4	0.172 4	0.192 4
5	Combination 25-35 tons	0.380 4	0.376 7	0.135 7	0.134 3
6	Combination >35 tons	0.549 0	0.556 5	0.270 5	0.255 5

parameters constant or by relying on data provided by FHWA as part of their own cost-allocation effort. These assumptions, however, themselves influenced comparisons between environmental regions and pavement types, and therefore should be taken into account:

a. Environmental parameters (regional factor, temperature, rainfall, and freezing index) and subgrade soil classifications represented very broad regional characteristics encompassing several states in the Northeast and Southwest, respectively. Therefore they may not coincide with the general characteristics of individual states, let alone those of specific areas within a state.

b. The AASHTO design procedures (6) were used to determine pavement thicknesses (in response to projected traffic) for both flexible and rigid pavements in each of the environmental regions. However, other than for variations in traffic, environmental parameters, and subgrade soil classification, no changes were made in the design procedures between the two regions. Specifically, the modulus of asphalt concrete was not adjusted between the two regions that had different temperature patterns. The relatively frequent overlays (and resulting higher costs) computed for flexible pavements in the Southwest are due in part to this fact.

c. Traffic streams simulated on the rigid pavements and the flexible pavements consisted of different numbers of vehicles:

Region	Flexible Pavement		Rigid Pavement	
	Urban	Rural	Urban	Rural
Northeast	29 054	9323	29 054	9323
Southwest	50 136	6392	50 136	8715

Also, the equivalent single axle-load (ESAL) factors of the respective vehicle classes differed among pavement type, region, and urban or rural designation, according to data provided by FHWA and summarized in Table 1. Thus, the costs among different pavements and regions were calculated by assuming different vehicle streams.

3. The costs of maintenance and rehabilitation computed in this study derive (as explained earlier) from predictions of pavement damage; the study results are therefore sensitive to the damage equations within EAROMAR-2. Although many of the equations incorporate environmental factors (e.g., temperature) or pavement characteristics that vary seasonally (e.g., layer moduli), most of the models simulate damage as occurring from a combination of environmental stresses and induced traffic loads. (The only "purely environmental" components of damage currently simulated within EAROMAR-2 are cold-weather cracking of asphalt pavements and spalling and blowups of portland-cement pavements.) Therefore, maintenance and rehabilitation costs are heavily dependent on traffic, measured in total number of vehicles or in cumulative ESALs.

RESULTS

Results were developed for the eight cases defined above. First, routine maintenance and rehabilitation costs (referred to below simply as maintenance costs) attributable to each vehicle class were simulated by using the EAROMAR-2 procedure. (Separate vehicle classes were in fact studied in our research. However, results by vehicle class agreed well with results expressed in terms of the number of 18-kip ESALs. The data reported below therefore may show either representative vehicle class or ESAL.) Then, costs were allocated by vehicle class (or ESAL) by using both the equity and the efficiency criteria. For brevity, only selected examples of the results are given below; the complete set of tables and figures is given elsewhere (3).

User Charge Responsibilities According to Equity

Pavement maintenance costs for both the base traffic and no traffic were determined so as to calculate the portion of maintenance costs that is attributable to traffic. The results indicate that the non-traffic-related pavement maintenance costs of flexible pavements are very small--less than 1 percent of the maintenance costs of the base traffic. The major cause of these purely environmentally induced maintenance activities is cold-weather lineal cracking. The non-traffic-related pavement maintenance costs for rigid pavements are higher; they range between 5 to 7 percent of the base maintenance and are primarily due to spalling of concrete and blowups between pavement slabs.

Table 2 determines the unit costs of the traffic-related pavement maintenance costs. The annual traffic-related maintenance costs are obtained by subtracting the annual non-traffic-related pavement maintenance costs from the annual base-traffic maintenance costs; they are then divided by the number of ESAL applications per year to arrive at the maintenance cost per ESAL mile.

Table 3 illustrates the computation of equitable pavement maintenance cost responsibilities for each vehicle class in terms of average cost per vehicle mile. In order to compute the cost responsibility of a vehicle class, the unit cost (from Table 2) is multiplied by the corresponding ESAL factor (from Table 1). Similar calculations were made for the

Table 2. Traffic-related life-cycle pavement maintenance cost for Interstate highways.

Roadway Type	Annual Cost ($/mile) Under Base Traffic	Under No Traffic	Traffic-Related	ESAL per Year	Unit Cost (¢/ESAL mile)
Northeast Region					
Urban flexible	6 754	29	6 716	669 904	1.0025
Urban rigid	2 886	147	2 739	316 506	0.8654
Rural flexible	5 174	46	5 128	281 732	1.8202
Rural rigid	2 666	151	2 515	120 140	2.0934
Southwest Region					
Urban flexible	11 044	21	11 022	252 932	4.3577
Urban rigid	2 376	146	2 230	117 183	1.9030
Rural flexible	7 024	15	7 009	144 084	4.8645
Rural rigid	2 247	141	2 106	75 000	2.8080

Table 3. Equitable life-cycle pavement maintenance cost for Interstate highways in Northeast.

	Flexible Pavement			Rigid Pavement		
Vehicle Class	Cents per ESAL Mile	ESAL Factor	Cents per Vehicle Mile	Cents per ESAL Mile	ESAL Factor	Cents per Vehicle Mile
Urban						
Automobile	1.0025	0.0004	0.0004	0.8654	0.0003	0.0003
Light single-unit truck	1.0025	0.0904	0.0906	0.8654	0.0750	0.0649
Heavy single-unit truck	1.0025	0.3592	0.3601	0.8654	0.1877	0.1624
Light combination	1.0025	0.2766	0.2773	0.8654	0.1544	0.1336
Medium combination	1.0025	0.3321	0.3329	0.8654	0.1799	0.1557
Heavy combination	1.0025	0.4584	0.4595	0.8654	0.1722	0.1490
Rural						
Automobile	1.8202	0.0004	0.0007	2.0934	0.0004	0.0008
Light single-unit truck	1.8202	0.0825	0.1502	2.0934	0.0712	0.1491
Heavy single-unit truck	1.8202	0.2527	0.4600	2.0934	0.1362	0.2851
Light combination	1.8202	0.2850	0.5188	2.0934	0.1524	0.3190
Medium combination	1.8202	0.3812	0.6939	2.0934	0.1812	0.3793
Heavy combination	1.8202	0.4460	0.8118	2.0934	0.1538	0.3199

Table 4. Equitable user charge responsibilities for life-cycle pavement maintenance on Interstate highways.

	Flexible Pavement		Rigid Pavement	
Vehicle Class	Urban	Rural	Urban	Rural
Northeast Region				
Automobile	0.0004	0.0007	0.0003	0.0008
Light single-unit truck	0.0906	0.1502	0.0649	0.1491
Heavy single-unit truck	0.3601	0.4600	0.1624	0.2851
Light combination	0.2773	0.5188	0.1366	0.3190
Medium combination	0.3329	0.6939	0.1557	0.3793
Heavy combination	0.4595	0.8118	0.1490	0.3199
Southwest Region				
Automobile	0.0022	0.0034	0.0010	0.0017
Light single-unit truck	0.2907	0.3809	0.1073	0.1870
Heavy single-unit truck	1.3205	1.8553	0.3083	0.5484
Light combination	2.1597	3.6552	0.3281	0.5403
Medium combination	1.6577	1.8325	0.2582	0.3771
Heavy combination	2.3924	2.7071	0.5148	0.7174

cases tested in the Southwest environmental zone.

The resulting equitable user charge responsibilities (in cents per vehicle mile) for life-cycle pavement maintenance cost on the Interstate highways are compared in Table 4. The equitable cost responsibilities for the flexible pavements, rural roadways, and the roadways in the Southwest are higher than those of the rigid pavements, urban roadways, and the roadways in the Northeast, respectively. Automobiles pay a very little share of the pavement maintenance cost; however, they and all other vehicles are responsible for other types of maintenance costs (such as those for maintaining traffic signals and signs), for pavement construction costs, and for common costs that have not been included in this analysis. Until all such cost responsibilities are computed, it is unclear which class of vehicle will benefit more under this equity-based scheme.

In general, the rigid pavements benefit from the longer interval simulated between overlays (effectively reducing the per-mile cost responsibility). This longer life depends on the respective pavement design procedures used. Furthermore, a fair comparison between flexible and rigid pavements must also include the pavement construction costs as well as other pavement maintenance and rehabilitation costs (e.g., for skid resistance), comparisons that were not included as part of this study. The relatively high flexible pavement costs observed in the Southwest are due in part to the effects of high temperature. (Simulation of a stiffer asphalt mix would reduce some of the damage predicted and maintenance costs observed.) Higher costs for the rigid pavements in the Southwest are also due to environmental effects, in particular the greater incidence of fatigue cracking induced by thermal stresses.

User Charge Responsibilities According to Efficiency

Efficient user charge responsibilities are determined according to the first-best short-run marginal cost pricing rule. Since the relevant cost for efficiency-based pricing is marginal total social cost, we need to consider not only pavement maintenance expenditures but also road user costs.

Marginal Life-Cycle Pavement Maintenance Cost

There are two basic steps in determining the marginal pavement maintenance cost. The first step is to determine the marginal pavement maintenance cost with respect to the ESAL level. The second step is to multiply this cost per ESAL by the ESAL factor of vehicle class i to obtain the marginal pavement maintenance cost responsibility of each class-i vehicle trip.

Table 5 summarizes the efficient user charge responsibilities (in cents per vehicle mile) for life-cycle pavement maintenance for Interstate highways. The efficient user charges for rigid pavements, rural roadways, and the roadways in the Southwest are higher than those on flexible pavements, urban roadways, and the roadways in the Northeast, respectively, for the same reasons as those discussed earlier for the equity-based results.

Rural roadways exhibit higher marginal costs than urban roadways because of long-run economies of scale with respect to ESAL, as shown in Figure 2 for the Northeast region. The results in Figure 2 actually capture two competing trends:

1. Increasing numbers of ESALs per year cause increased damage to a given pavement and correspondingly higher maintenance costs. This short-run relationship is indicated by the solid-line segments for each pavement classification in Figure 2.
2. Incremental increases in pavement thickness substantially increase the design capacity of pavement (in terms of cumulative ESALs). In other words, adding 1 in to a 4-in pavement increases its design capacity by much more than 25 percent. The fact that this trend dominates the first trend can be inferred by the long-run comparisons between urban and rural flexible pavements in Figure 2. Each urban pavement carries more traffic than its rural counterpart, but it is also designed to higher standards.

The net result is the concave relationship between life-cycle pavement maintenance costs and annual ESAL applications in Figure 2, which implies long-run economies of scale. Whether these results are general and would be achieved for different maintenance policies or for different pavement damage equations is difficult to say; the issue requires more research. Within our own study, however, the same results were in fact also observed in the results for the Southwest region.

Efficient User Charge Responsibilities for User Costs

Highway users experience average user costs. In the computation of efficient user charge responsibilities, these out-of-pocket costs must be subtracted from the marginal user costs. The major components of user costs are travel-time cost and vehicle operating cost.

Our analyses showed that the differences between marginal and average travel-time costs were small because the simulated 55-mph speed limit caps the traffic speeds. Even when the volume/capacity ratio is small, the traffic stream could not (theoretically) go beyond the speed limit. Therefore, changes in traffic volume have little effect on travel time and travel-time costs. Since trucks have greater impact on the travel time of a traffic stream than automobiles, their congestion tolls on travel time are higher.

The two major types of vehicle operating costs that are affected by other vehicle trips are fuel

Table 5. Efficient user charge responsibilities for life-cycle pavement maintenance on Interstate highways.

	Flexible Pavement		Rigid Pavement	
Vehicle Class	Urban	Rural	Urban	Rural
Northeast Region				
Automobile	0.0002	0.0004	0.0003	0.0010
Light single-unit truck	0.0591	0.0953	0.0935	0.2080
Heavy single-unit truck	0.2350	0.2920	0.2341	0.3980
Light combination	0.1810	0.3294	0.1925	0.4453
Medium combination	0.2173	0.4400	0.2243	0.5294
Heavy combination	0.2999	0.5154	0.2147	0.4494
Southwest Region				
Automobile	0.0010	0.0019	0.0010	0.0016
Light single-unit truck	0.1287	0.2223	0.1169	0.1784
Heavy single-unit truck	0.5767	1.083	0.3360	0.5231
Light combination	0.9562	2.133	0.3576	0.5154
Medium combination	0.7339	1.069	0.2814	0.3597
Heavy combination	1.0590	1.580	0.5610	0.6844

Figure 2. Life-cycle pavement maintenance cost versus ESAL level, Northeast region.

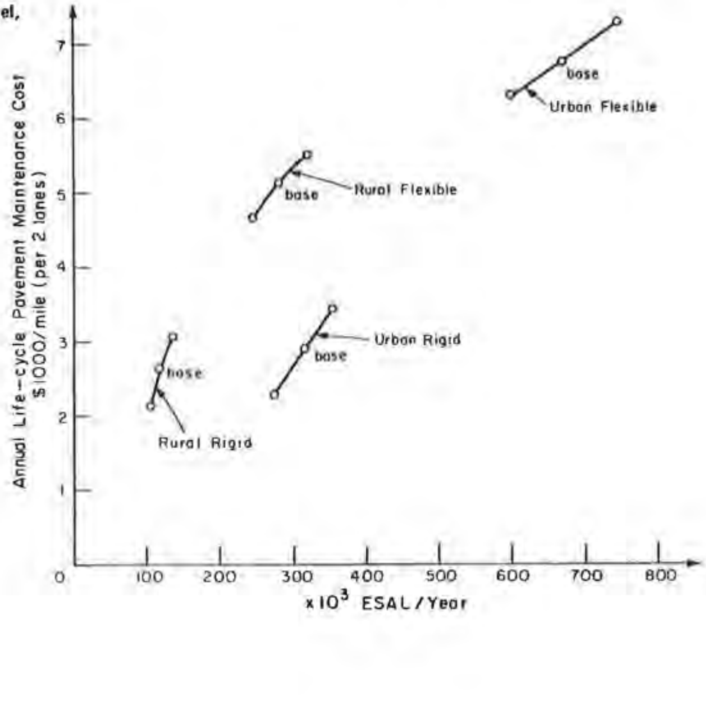


Table 6. Efficient user charge responsibilities for Interstate highways in Northeast.

		Component			
Roadway Type	Vehicle Class	Pavement Maintenance	Travel Time	Vehicle Operating	Total[a]
Urban flexible	Automobile	0.0002	0.3782	-0.2718	0.1066
	Medium combination	0.2173	0.6560	0.3834	1.2567
	Heavy combination	0.2999	0.9401	0.1212	1.3612
Urban rigid	Automobile	0.0003	0.6564	-0.2412	0.4155
	Medium combination	0.2243	2.9070	2.6536	5.7849
	Heavy combination	0.2147	2.9070	2.3218	5.4435
Rural flexible	Automobile	0.0004	0.1531	0.0112	0.1647
	Medium combination	0.4406	0.6020	1.1398	2.1824
	Heavy combination	0.5154	0.5959	0.8701	1.9814
Rural rigid	Automobile	0.0010	0.1429	-0.0399	0.1040
	Medium combination	0.5294	0.8582	1.9074	3.2950
	Heavy combination	0.4494	0.7410	1.9682	3.1586

[a] Total efficient user charge responsibilities here do not include pollution costs.

Table 7. Comparison of equitable and efficient user charge responsibilities in life-cycle pavement maintenance.

	Flexible Pavement				Rigid Pavement			
	Urban		Rural		Urban		Rural	
Vehicle Class	Equitable	Efficient	Equitable	Efficient	Equitable	Efficient	Equitable	Efficient
Northeast Region								
Automobile	0.0004	0.0002	0.0007	0.0004	0.0003	0.0003	0.0008	0.0010
Light single-unit truck	0.0906	0.0591	0.1502	0.0953	0.0649	0.0935	0.1491	0.2080
Heavy single-unit truck	0.3601	0.2350	0.4600	0.2920	0.1624	0.2431	0.2851	0.3980
Light combination	0.2773	0.1810	0.5188	0.3294	0.1336	0.1925	0.3190	0.4453
Medium combination	0.3329	0.2173	0.6939	0.4400	0.1557	0.2243	0.3793	0.5294
Heavy combination	0.4595	0.2999	0.8118	0.5154	0.1490	0.2147	0.3199	0.4494
Southwest Region								
Automobile	0.0022	0.0010	0.0034	0.0019	0.0010	0.0010	0.0017	0.0016
Light single-unit truck	0.2907	0.1287	0.3809	0.2223	0.1073	0.1169	0.1870	0.1784
Heavy single-unit truck	1.3025	0.5767	1.8553	1.0830	0.3083	0.3360	0.5484	0.5231
Light combination	2.1597	0.9562	3.6552	2.133	0.3281	0.3576	0.5403	0.5154
Medium combination	1.6577	0.7339	1.8325	1.069	0.2582	0.2814	0.3771	0.3597
Heavy combination	2.3924	1.0590	2.7071	1.580	0.5148	0.5610	0.7174	0.6844

and tire cost. For a given roadway, the fuel cost is usually affected positively by the traffic speed, which is in turn influenced negatively by traffic volume and affected secondarily and positively by pavement condition. The tire cost is affected primarily and negatively by the pavement condition and secondarily and positively by traffic speed. In general, fuel cost and tire cost tend to act in opposite directions when traffic volume changes. With this information in mind, having negative efficient cost responsibilities for operating costs is not surprising. Since having more automobiles in the traffic stream has almost no effect on pavement condition but can reduce the traffic speed and fuel cost, it is reasonable that the efficient cost responsibilities for vehicle operation of the automobiles on the urban roadways are negative and close to zero on the rural roadways. The efficient cost responsibilities of trucks are higher than those of the automobiles because their influence on the tire costs of other vehicles is due to their large impacts on the pavement condition.

Table 6 is a summary of all the components of efficient user charge responsibility (in cents per vehicle mile) discussed previously. The efficient cost responsibility of each vehicle trip should be the sum of all the listed components. The ranking of the roadways in terms of highest efficient cost in descending order is as follows: urban rigid, rural rigid, rural flexible, and urban flexible. As indicated by the ranking, it is not necessarily true that the efficient cost responsibilities are higher on urban Interstate highways than on rural Interstate highways. When the congestion toll on travel time is small, other efficient cost components become important. In fact, the efficient cost responsibilities on rigid pavements are higher than those on flexible pavements because their vehicle operating-cost components are larger. Because the urban rigid roadway also has a large component of efficient cost responsibility for travel-time cost, it ranks the highest in efficient cost responsibility. Marginal pavement maintenance cost is not a large component in efficient cost responsibility; it is less than 25 percent of the total for the combination trucks and even less for automobiles.

Comparison of Equitable and Efficient User Charge Responsibilities

Table 7 summarizes the results of the equitable and efficient user charge responsibilities (in cents per vehicle mile) for life-cycle pavement maintenance costs. The efficient charge corresponds to short-run marginal costs, whereas the equitable charge corresponds to short-run average variable costs. The non-traffic-related (fixed) costs have been removed from the equitable charge. On the whole, the results show that the equitable and efficient user charges are significantly different (except for the Southwest rigid roadways). The equitable charges are greater than the efficient charges on all of the flexible pavements, which implies that collecting charges based on efficiency cannot cover the pavement maintenance budget of flexible pavements.

CONCLUSIONS

The objective of this study has been to demonstrate how user charge responsibilities for life-cycle pavement maintenance costs can be developed by using detailed simulations of roadway performance and costs. Two different economic objectives were investigated: one based on equity (to allocate highway maintenance expenditures) and the second based on efficiency (considering total social costs). The detailed procedures for estimating life-cycle pavement cost data and processing these data into relevant cost-allocation information have been developed elsewhere (3).

Several assumptions have been made in this study that affect the results and their interpretation. For example, the case studies are predicated on the design standards of Interstate highways, and the findings may not apply to other types of roadways. (For instance, non-traffic-related damage may be higher on other classes of roads.) Also, the technical and economic findings, particularly comparisons between cases (flexible versus rigid pavement, urban versus rural highways), are strongly influenced by the pavement models included in the EAROMAR-2 simulation model as described by Markow and Brademeyer (4). Furthermore, pavements were simulated with traffic streams of different volumes and compositions. Finally, costs discussed in this paper encompass routine structural maintenance and overlays but no other pavement-related costs or shoulder-related costs associated with construction or maintenance.

With these caveats in mind, the following are some general conclusions of our study:

1. The life-cycle costs attributable to heavy trucks are, in order of magnitude, about 1000 times those estimated for automobiles. This finding is due almost entirely to the particular assumption of vehicle ESAL factors used in this study as shown in Table 1. It is apparent that the factors, computed from data provided by FHWA, reflect some average truck weight rather than maximum gross weight. Nevertheless, there was some concern raised during the study that the ESAL factors in Table 1 might not be accurate.
2. For both flexible and rigid pavements, purely environmental pavement damage (i.e., damage that has no dependence whatsoever on traffic loads) amounts to less than 10 percent of total life-cycle costs. This is to be expected from the types of pavement damage models included within EAROMAR-2; although these models do include the effects of temperature, rainfall, and freezing index, the environmental factors are applied in conjunction with traffic loadings (whether ESALs or other vehicle parameters) in most of the damage equations (4).
3. Generally speaking, the life-cycle costs of rigid pavement are less than those of flexible pavement, due to the longer intervals between overlays simulated for portland cement concrete. Bear in mind, however, that the life-cycle costs computed in this paper represent only a portion of total pavement costs. Construction costs and other maintenance costs (e.g., shoulder maintenance, skid-resistance maintenance, correction of construction or materials deficiencies) would have to be included to make a fair cost comparison between pavement types.
4. The study has shown the feasibility of applying the life-cycle cost-allocation approach to different environmental zones. However, a direct comparison between results for the Northeast and the Southwest obtained in this study is complicated by the different traffic characteristics assigned in each region (Table 1) and the fact that asphalt layer moduli were not adjusted in the pavement design for the higher temperatures in the Southwest. Additional analyses would clarify the role of regional environment in affecting life-cycle costs.

Recently, we have been attempting to compare our maintenance costs results with those produced under the federal Highway Cost-Allocation Study (HCAS) (7). In general, the results obtained in our study, under both the equity and the efficiency criteria, appear to impose less cost responsibility on vehicles than do the federal computations. A direct comparison is somewhat difficult because the two studies report their results in different ways. However, the following components are pertinent:

1. Our study has computed user pavement responsibilities based on an estimation of life-cycle costs and a distribution of uniform charges (over time) to users throughout an analysis period. The federal study has proceeded from a somewhat different premise--to allocate current estimated program expenditures based on pavement damage accumulated in the past, as well as additional damage predicted in the future. The two philosophies may in fact yield markedly different results. In addition, our analyses indicate that the pay-as-you-go principle currently underlying federal highway funding may at least have to be reviewed in financing maintenance and rehabilitation.
2. Estimation of pavement rehabilitation costs in our study and in the federal HCAS relied on different models of pavement damage and resulting costs. Therefore, some differences in the absolute values of the predicted costs, in allocation among vehicle classes, and in the ratio of traffic-related to non-traffic-related costs should be expected.
3. User charge responsibilities by vehicle class reported in the federal HCAS (7) apply generally to the highway system as a whole. Results reported in this paper apply only to Interstate highways in two regions of the country.
4. The federal study considered only pavement rehabilitation and excluded routine maintenance. In this study we have considered routine structural maintenance and rehabilitation but have excluded certain other types of pavement maintenance (identified earlier in the paper).
5. In demonstrating use of the simulation model and subsequent calculations, we have focused on those variable costs (under the equity objective) or marginal costs (under the efficiency objective) that are attributable to traffic. Common costs (for equity) or residual costs (for efficiency) are not included in Tables 1-7. Since the federal HCAS has implicitly considered all user charge responsibilities, the results given earlier in this paper may show a lesser burden for all vehicle classes than do those of the federal HCAS.

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The contents of this report reflect our views and we are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policy of DOT. This document does not constitute a specification or a standard.

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Methodology for Evaluating Increase in Pavement Maintenance Costs That Result From Increased Truck Weights on Statewide Basis

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When this study was made, Indiana's weight limits for trucks were 18 000 lb on a single axle, 32 000 lb on a tandem axle, and 73 280 lb gross vehicle weight (GVW). The federal limits for the Interstate system and other primary roads were 20 000 lb on a single axle, 34 000 lb on a tandem axle, and 80 000 lb GVW. The objective of this study was to evaluate what the effects would be on pavement maintenance costs if Indiana's weight limits were increased to those of the federal limits. The methodology that was developed to evaluate the increase in load limits from 73 280 to 80 000 GVW is described. The road-life records of the Indiana Department of Highways were searched and pavement sections were evaluated by using these data coupled with truck weight information from the weight stations and soil and performance data available from previous studies. A total of 301 pavement sections were selected for evaluation. The types of pavements evaluated included continuously reinforced concrete, jointed reinforced concrete, asphalt, and concrete pavements overlaid with asphalt. The pavement sections were evaluated according to functional classification. The pavements were further divided on a regional basis so that climatic effects would be evaluated as well. Cost estimates were presented in dollars per lane mile per year and dollars per year for Interstates, primary roads (U.S. and state routes carrying more than 4000 vehicles/day), and secondary roads (U.S. and state routes carrying less than 4000 vehicles/day).

The Federal-Aid Highway Act of 1956 established the maximum weight limits for the Interstate system, which at that time were 18 000 lb on a single axle, 32 000 lb on a tandem axle, and 73 280 lb gross vehicle weight (GVW) (1). Since some states already permitted loads in excess of those specified by the Act, a grandfather clause was included to protect them from this Act (2).

After the 1973 energy crisis, the Federal-Aid Highway Act of 1974 raised the federal weight limits to 20 000 lb on single axles, 34 000 lb on tandem axles, and 80 000 lb GVW. At the time of this study, in 1978, nine states in addition to Indiana still maintained the 1956 weight limits. These states, known as "barrier states," lie in the midwestern part of the United States.

This paper presents the methodology used in this study to estimate the effect of increased truck weights on the service life of pavements, specifically on pavement maintenance costs.

The study was limited to evaluation of added load-related costs on the state system of Indiana highways, including Interstates and U.S. and state routes. This report deals with maintenance costs alone and does not consider changes in economic benefits that might result if weight laws were changed.

GENERAL BACKGROUND

Although pavement maintenance may be required for many reasons, including material breakdown and climatic effects, the number of heavy-load applications in terms of 18 000-lb equivalent single axle loads (ESALs) is a primary factor that causes pavement deterioration for a given set of conditions. Figure 1 shows the conceptual relationship between present serviceability index (PSI) and pavement life for a typical road that is exposed to an increase in load limits. It is to be noted that a change in load has an effect on pavement serviceability. If loads heavier than originally anticipated in the design are applied, the pavement will deteriorate more rapidly with two net effects. First, routine maintenance costs will increase and, second, the life of the pavement may decrease. On the other hand, if the pavement is designed for the newer and heavier loads, the change in serviceability will be essentially the same as that of the original pavement.

METHODOLOGY DESCRIPTION

The methodology adopted in this study to evaluate