Highway Cost Allocation Methodology for Pavement Rehabilitation and Capacity-Related Costs Occasioned by an Increment in Heavy Truck Traffic

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ABSTRACT

A methodology is outlined for estimating incremental pavement rehabilitation and capacity-related costs that would be occasioned by loading an increment of bulk commodity traffic on a highway link. The cost estimates are referred to as "build-sooner costs" because they represent the financial impact of the increment of traffic on the future timing of pavement rehabilitation and capacity improvement projects. The analysis encompasses eight bulk commodity truck movement scenarios in the Province of New Brunswick, Canada. The build-sooner costs are compared with incremental user fee revenues that would be generated by these movements if they were to be captured by the truck mode.

The methodology described in this paper was developed as part of a much larger research project on incremental costs and revenues occasioned by the trucking of bulk commodities on selected highway links in the Province of New Brunswick, Canada (1). That study examined five broad categories of incremental cost and three categories of incremental revenues, with the objective of assessing whether trucking firms enjoy an inherent advantage in competing for the movement of bulk commodities in the province. Such an advantage would exist if the incremental public costs of these truck movements were not fully recovered through highway user fees.

The focus of this paper is on describing the methodology developed to estimate one of the five categories of incremental cost. The cost component in question shall hereafter be referred to as "build-sooner costs."

Build-sooner costs related to the hypothesis that loading a large increment of heavy traffic on a link will cause two conditions to evolve. First, pavement life cycles are likely to become shorter, and, second, future capacity improvements will be needed sooner. Because both kinds of improvements require substantial expenditures, the cost of investing the capital "x" years sooner because of the increment of heavy traffic can legitimately be assigned to that traffic.

Before outlining the methodology used to estimate these costs, a review of other highway cost allocation studies from the perspective of their treatment of pavement and capacity costs is instructive.

LITERATURE REVIEW

Growing interest in highway finance has given rise in recent years to a significant research effort to resolve the question of the cost responsibility of various classes of highway users.

In Canada the recent work of Bunting (2) examined highway expenditures and revenues at three different levels--all of Canada, the Province of Ontario, and Highway 401. At the national and provincial levels, expenditures were allocated on the basis of highway usage patterns, with 40 percent of construction and maintenance costs and 30 percent of other costs assigned to heavy trucks (2,p.23).

In the Highway 401 analysis, 45 percent of pavement-related costs was assigned to trucks. This estimation of pavement costs was based on the assumption that 40 percent of highway construction expenditures were pavement-related (2,p.29). The remaining 55 percent of construction costs was allocated according to the trucks' share of capacity use, estimated at 50 percent.

Many of the cost estimation and cost allocation formulas used in Bunting's work were drawn from the most recent U.S. Highway Cost Allocation Study completed in 1982 (3). This study was concerned with the allocation of U.S. federal program expenditures to users of federal-aid roads. This research attempted to correct often-cited deficiencies of two previous U.S. investigations of highway costs, the Section 210 study on highway cost allocation, conducted between 1956 and 1965, and the AASHO Road Test, conducted between 1958 and 1960.

The major criticism of the Section 210 study is that it focused on capital expenditures for new pavement. Although this may have been appropriate for that period when the Interstate system was being constructed, it had become anachronistic with the current emphasis on rehabilitation of the system.

The AASHO Road Test, conducted in Illinois, attempted to measure the relationship between pavement deterioration and repetition of axle loadings. Although the results of this test have been widely used as a basis for pavement design, it has been strongly criticized as a method for assigning cost responsibility to classes of vehicles. One of the major criticisms is that it does not account for the effect of environmental conditions on pavement deterioration.

The 1982 highway cost allocation study uses a so-called "modified incremental cost allocation approach." First, a distinction is made between new pavement and pavement rehabilitation. In the case of the former, costs are allocated as follows (3,p.IV-43).

> New pavement costs are assigned based on current pavement design practice. Ve-

hicles from each class are hypothetically removed in equal proportions until further removal would not reduce pavement thickness requirements.

A major research effort was launched to develop relationships to assign pavement deterioration cost responsibilities. Pavement distress models were developed for both flexible and rigid pavements to measure distresses such as loss of serviceability, alligator cracking, rutting, transverse cracking, loss of skid resistance, faulting, pumping, joint deterioration, depression, and swell (3,Appendix D-24). Some of the distresses were found to be a function of traffic, some a function of traffic and other variables, and some independent of traffic. Costs are assigned on the basis of the relative importance of each type of distress in the decision to rehabilitate a pavement.

Capacity-related costs such as steepness of grades and roadway width again are assigned on an incremental basis by hypothetically removing successive classes of vehicles (e.g., vehicles in various weight-to-power ratios in the case of grade costs). Within-group costs (i.e., different vehicle types within a specific group) and residual costs (i.e., costs that cannot be attributed to a particular class of vehicle) were arbitrarily allocated on the basis of vehicle-miles traveled.

One of the criticisms of the most recent U.S. highway cost allocation approach is that it is based on expenditures, not costs. Any expenditures that are incurred in a particular year are allocated to the traffic of that year, even though the benefits arising from the investments are realized over a long period. Such an approach neglects the indivisibilities that are necessarily involved in the provision of highway infrastructure and the resultant excess of capacity.

The major consequence of the existence of this excess capacity is a residual of cost in the cost allocation process, a residual that can only be allocated among components of traffic by some arbitrary means. This is really an issue of cost allocation versus cost assignment. The difference between the two is well presented by Wohl and Hendrickson (4,p.223). They suggest that cost attribution involves "the identification of valid cause-and-effect relationships between highway cost and highway use."

The focus of this research is on cost assignment rather than on cost allocation. The difference between the two is explained by the existence of a residual of costs that can only be allocated according to some accounting rules.

In the remainder of this paper, the methodology for assigning pavement rehabilitation and capacity-related costs to bulk commodity truck traffic will be described and the results of the analysis summarized.

METHODOLOGY

Eight bulk commodity movement scenarios were analyzed in this study; none of the commodities are currently moved by truck. The objective was to estimate the incremental public costs that would result if these movements were to be captured by the truck mode. The commodity movements, projected annual tonnages, and length of haul associated with each movement are given in Table 1.

TABLE 1 Commodity Movement Scenarios

Commodity Movement	Projected Annual Tonnage	Length of Haul (mi)
Potash 1	700,000	50
Potash 2	1,400,000	35
Potash 3	2,100,000	—[a]
Woodchips 1	100,000	—[a]
Woodchips 2	75,000	115
Coal	360,000	210
Concentrates	500,000	75
Petroleum	150,000	105

[a]Consists of two separate movements.

Build-Sooner Period: Pavement Rehabilitation

The objective of this analysis is to determine the cycle time for pavement resurfacing with the commodity traffic moving on the highway compared with the pavement life cycle that would occur under existing traffic mix conditions and normal growth. In other words, how much faster will the pavement condition deteriorate to the threshold that triggers a resurfacing requirement? This concept is illustrated graphically in Figure 1. It should be noted that Figure 1 shows only pavement life cycle after the addition of the new commodity traffic.

Subsequent pavement cycles are important not only because each cycle is set ahead by the build-sooner period (BSP) but also because it is reasonable to expect that successive pavement life cycles will get shorter. If the rate of pavement deterioration is due to the cumulative effect of truck traffic, the slope of the deterioration function will increase with each successive pavement life cycle until the slope reaches some theoretical maximum. This is shown in Figure 2.

After a review of the literature on pavement deterioration, it was decided that the Ontario flexible pavement design method would be used to develop a pavement deterioration function for the various highway links and commodity movements under study (5).

The mathematical relationship between the parameters included in the Ontario method are

$$RCI_f = RCI_i - (P_t + P_e) \qquad (1)$$

where

RCI_f = final road comfort index,
RCI_i = initial road comfort index,
P_t = loss of RCI due to traffic factors, and
P_e = loss of RCI due to environmental factors.

P is further defined as

$$P = 2.4455X + 8.805X^3 \qquad (2)$$

where

X = 100 WN,
W = Odemark subgrade deflection,
N = number of ESALs per year, and
ESAL = equivalent single 18,000-lb axle loads.

Note that the Odemark subgrade deflection is derived from Dynaflect pavement deflection readings using the following relationship:

$$D = 0.9W + 40W^2 \qquad (3)$$

where D is mean spring deflection and W is Odemark subgrade deflection.

P_e is further defined as

$$P_e = [RCI - (1 + BW)]\ (1 - e^{-0.06Y}) \qquad (4)$$

where Y is number of years of loading and B is 60.

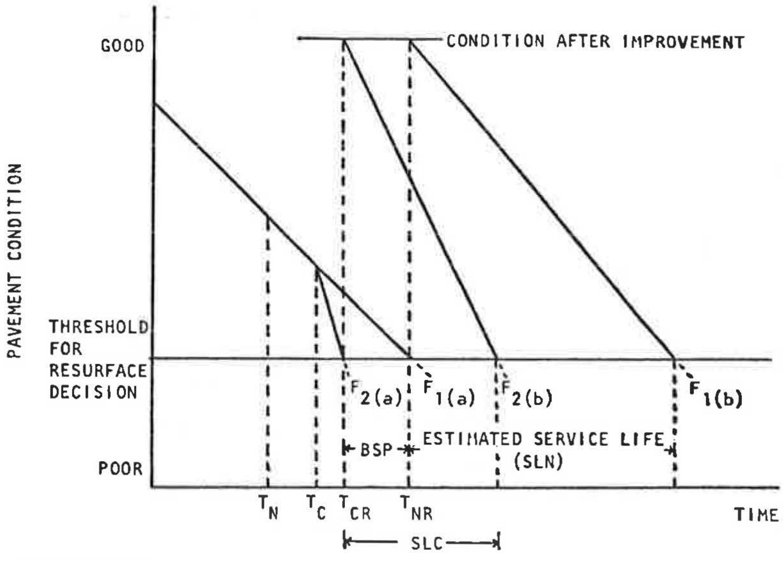


FIGURE 1 Build-sooner period for pavement rehabilitation. F_1 is a function that describes pavement deterioration under normal traffic conditions; F_2 is a function that describes pavement deterioration under the combined effect of normal plus commodity traffic; T_N is the present time; T_C is the time at which the commodity movement begins; T_{NR} is the time at which the pavement requires resurfacing under normal conditions; T_{CR} is the time at which the pavement requires resurfacing under the combined effect of normal plus commodity traffic; SLN is estimated pavement service life under normal conditions; SLC is estimated pavement service life with commodity traffic added; BSP is the build-sooner period (i.e., the life difference between SLN and SLC); (a) denotes the existing pavement cycle; and (b) denotes the second cycle. Note: function is shown as linear for simplicity of illustration.

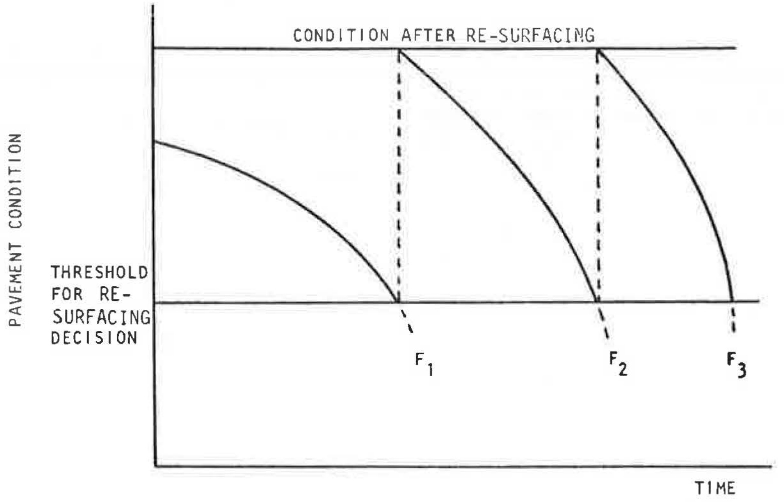


FIGURE 2 Pavement deterioration in successive life cycles. F_1, F_2, and F_3 are the pavement deterioration functions for successive cycles.

A key feature of these relationships is the road comfort index (RCI). The RCI is essentially a rating scale from 0 to 10 that describes on a subjective basis the comfort or rideability of a pavement surface. As the pavement surface deteriorates, so does the rideability. The mathematical relationship described is in essence an algorithm for forecasting future RCI values, which can be expected to decline because of both traffic and environmental factors. Before the relationship can be used, the values for each of the parameters must be either measured or calculated.

The initial RCI values were made available by the New Brunswick Department of Transportation (NBDOT). The NBDOT periodically conducts rideability assessments of its highways. Each rating section (a rating section is a section of highway that features relatively homogeneous physical characteristics) is assigned an RCI value following a field investigation.

The Odemark subgrade deflection factor is calculated using Dynaflect pavement deflection readings. NBDOT periodically collects this data for each rating section with a Dynaflect that uses a nondestructive testing method. The Dynaflect measurements are then converted to an equivalent Benkleman beam value using an appropriate regression equation.

A critical component of traffic impact on pavement deterioration is the repetition of axle loadings. In both the AASHO and the Ontario tests, the loading impact of a particular vehicle configuration is expressed in terms of an equivalent single 18,000-lb axle load (ESAL). The gross vehicle weight, the payload, the number of axles, and the axle spacing all affect the number of ESALs per vehicle. It is noteworthy that the ESAL conversion factors that have been developed assume that a passenger car is approximately equal to zero ESALs.

Because the purpose of this analysis was to determine the build-sooner period, it was necessary to first forecast future RCI values under normal traffic conditions. The analysis was then repeated with the commodity traffic added to the base load. The first step in the analysis was to convert the existing traffic stream into ESALs. This was done using average annual daily traffic (AADT) volumes and vehicle classification counts that permitted a disaggregation of the traffic stream as follows:

1. Automobiles,
2. Two-axle trucks,
3. Three-axle trucks,
4. Three-axle tractor-trailers,
5. Four-axle tractor-trailers,
6. Five-axle tractor-trailers, and
7. Tractor-trailers with more than 5 axles.

The AADT for each of these configurations was then converted into ESALs per day using the Asphalt Institute (_6_) conversion factors and axle weight data extracted from a 1981 truck vehicle weight, configuration, and dimension survey conducted by the NBDOT.

After the future RCI values were calculated under normal traffic conditions it was necessary to translate the commodity movement into ESALs. This required a forecast of the annual commodity tonnage and selection of an optimal truck configuration or handling the particular commodity. The ESALs produced by the commodity movement were then added to the existing base traffic load and a new set of future RCI values generated.

The next step in the analysis was to select a minimum desirable RCI value (i.e., a threshold that would theoretically trigger a decision to resurface the highway link being evaluated). The appropriate threshold for the New Brunswick situation was determined in consultation with NBDOT. For example, on arterial highways the minimum desirable RCI value was set at 5.5 whereas 4.5 was used on collector highways. With the threshold established, the build-sooner period would then be determined as shown in Figure 1 and Table 2.

It must be stressed that the methodology described presupposes that pavement resurfacing projects would be undertaken as soon as the minimum desirable RCI threshold is reached. In reality the actual timing of projects will depend on many factors other than pavement rideability, not the least of which is the economic justification of each project in comparison with other candidate projects competing for limited funds in a given year.

TABLE 2 Build-Sooner Period Hypothetical Results

Year	RCI Values with Normal Traffic	RCI Values with Commodity Traffic Added
1983	7.0	7.0
1984	6.7	6.7
1985	6.4	6.1
1986	6.0	5.4[a]
1987	5.7	4.4
1988	5.3[a]	3.1

[a]Threshold is RCI 5.5; therefore BSP = 2 years.

To summarize, the build-sooner period for pavement resurfacing was estimated using the Ontario flexible pavement design method. This method essentially produces a pavement deterioration function that is affected by both traffic and environmental factors. The procedure for converting build-sooner periods to build-sooner costs will be described later in this paper. The following section summarizes the methodology used to determine the build-sooner period for capacity improvements.

Build-Sooner Period: Capacity Improvements

The capacity analysis is similar in many respects to the build-sooner analysis for pavement resurfacing. In this case the build-sooner period is determined by a traffic growth function (under normal conditions and with the commodity traffic added). The threshold that triggers a decision for a capacity improvement is the capacity of the highway section under study at a given level of service. The capacity analysis methodology is shown graphically in Figure 3.

The capacity analysis was completed using techniques contained in the Highway Capacity Manual (HCM) developed by the U.S. Highway Research Board (_1_). The HCM techniques are widely accepted by traffic engineers in performing capacity analysis on elements of a highway system.

The HCM methodology is based on the following relationship:

$$C = CT \times (V/C) \times (W_L) \times (T_L)$$

where

C = practical capacity of a highway section at a given level of service;
LOS = level of service A, B, C, D, or E as described in the HCM;
CT = theoretical capacity;
V/C = volume-to-capacity ratio;
W_L = capacity adjustment factor for lane width and lateral obstructions; and
T_L = capacity adjustment factor for trucks.

The objective of this analysis is to determine the relative timing of capacity improvements under normal traffic conditions with the commodity traffic added to the existing traffic. The critical threshold that triggers the need for an improvement is the capacity of the section of highway under study. This capacity threshold varies with the selected minimum level of service desired. After consultations with NBDOT planners it was decided that the boundary between level of service C and D as defined in the Highway Capacity Manual would be used as the threshold for capacity improvements. The rationale for this choice is that when NBDOT plans and designs a highway capacity improvement, the decision is made that the highway should have sufficient capacity to operate at level of service C or better through its design life, given certain traffic growth assumptions. Again it must be recognized that no attempt was made to examine the justification for or priority of each of the capacity projects. A simplifying

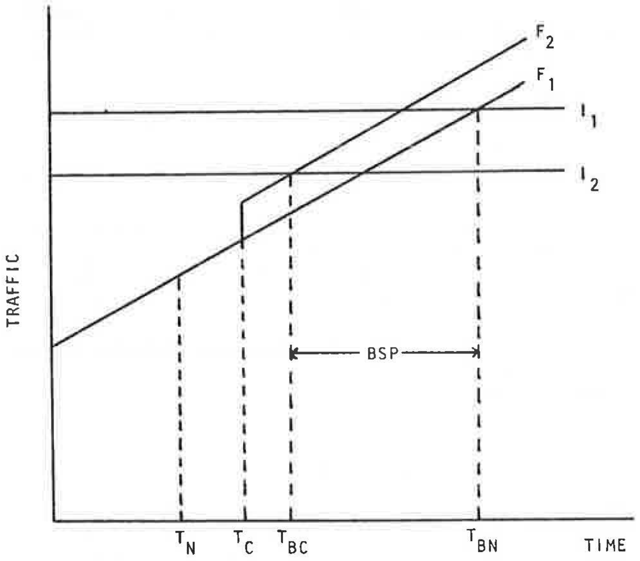


FIGURE 3 Build-sooner period: capacity improvements. F_1 is the traffic-versus-time function for normal growth (shown as linear for simplicity of illustration); F_2 is the traffic-versus-time function following an increment of commodity traffic; I_1 is the level of traffic at which a capacity improvement is required; I_2 is the level of traffic at which a capacity improvement is required following an increment of commodity traffic; T_N is the present time; T_C is the time when the commodity traffic is added; T_{BC} is the time when a capacity improvement would be required under normal traffic conditions; T_{BN} is the time when a capacity improvement would be required when commodity traffic is added; and BSP is the build-sooner period (i.e., the difference between T_{BN} and T_{BC}).

assumption was made that each of the capacity projects identified will be implemented when the critical capacity threshold is reached. In reality some of the projects will either not be undertaken or will perhaps be delayed at the expense of level of service. However, this approach was adopted because it appeared to be the most rational and consistent way to measure the impact of additional heavy truck traffic on the timing of improvements.

The practical capacity of a roadway section was calculated at the selected level of service using the previously outlined relationship. This was done by reducing the theoretical maximum capacity under ideal conditions (2,000 vehicles per hour) through the application of adjustment factors. These factors attempt to quantify the impact of certain conditions that tend to reduce the capacity of a roadway section. The factors are taken from the Highway Capacity Manual.

The T_L factor (truck adjustment factor) was a critical component of the capacity analysis in this study. The truck adjustment factors in the HCM are assumed to be valid for trucks within a certain operating performance range (i.e., power-to-mass ratio). A number of parameters affect the truck adjustment factor. Length of grade, magnitude of grade, type of terrain (level, rolling, mountainous), and percentage of trucks in the traffic flow all affect the number of passenger car equivalents (PCE) of trucks on any given section of highway. The PCE is simply the equivalent number of passenger cars of one truck under the existing physical and traffic flow conditions.

Clearly, as the length and magnitude of a grade increase, the number of PCEs per truck will also increase. It is also important to note that as the PCEs or percentage of trucks, or both, increase, the truck adjustment factor decreases. In other words, the increment of truck traffic due to the commodity movement not only increases the traffic, it also reduces the capacity due to a lower T_L factor. This is shown in Figure 3 in which the capacity threshold for F_1 is lower than the threshold F_2.

With the capacity of each section of highway established at a selected level of service, it was possible to project the number of years required to reach capacity under both traffic scenarios (normal traffic growth and with commodity traffic added). The growth rate assumptions applied to obtain forecasts of future traffic volumes were provided by NBDOT planners. In accordance with instructions from the client, the commodity tonnage projections assume zero year-to-year growth and a uniform distribution of truck traffic throughout each day.

When the build-sooner period had been estimated, it was necessary to identify the type of capacity improvement required. The range of alternatives include improvement of vertical and horizontal alignment, increased lane and shoulder width, provision of climbing lanes, and twinning of the highway. Again it must be recognized that, as in the case of the build-sooner analysis for pavement resurfacing, no attempt was made to examine the justification for each capacity project. The methodology is based on an assumption that each of the capacity projects identified will be implemented when the critical capacity threshold has been reached. It is conceivable that some of the projects identified would either not be undertaken or would perhaps be delayed at the expense of level of service.

To summarize, the build-sooner period for capacity improvements was determined using capacity analysis techniques documented in the Highway Capacity Manual. The effect of an increase in the presence of trucks due to the addition of an increment of commodity traffic is a lowering of the capacity of the highway at a given level of service. This in turn gives rise to the need for capacity improvements sooner than would be the case under normal traffic conditions. When the cost of these improvements is known, a build-sooner cost can be calculated. The methodology for estimating build-sooner cost is outlined in the next section.

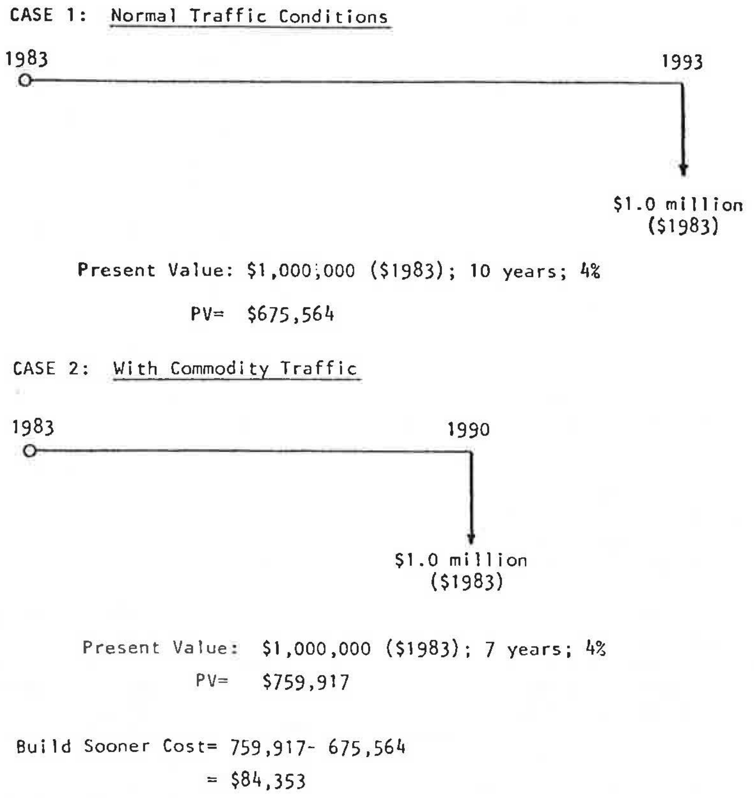
Build-Sooner Cost

The purpose of the build-sooner cost analysis is to determine the financial impact of having to invest in highway resurfacing and highway capacity improvements sooner than would be the case if the commodity were not transported by truck on public highways. In other words, what is the cost of tying up the capital required for the improvement over the build-sooner period? Figure 4 shows a hypothetical example.

The example assumes that a hypothetical improvement costing $1.0 million (1983 dollars) will be required in 1993 under normal traffic conditions. The same $1.0 million improvements will be required in 1990 if the commodity traffic is added. The commodity traffic thus causes a build-sooner period of 3 years.

Because costs are in constant dollars, a real discount rate (in this case 4 percent) is used to determine the present value of each investment. Clearly for Case 2 the present value is higher because the investment is of the same magnitude but occurs 3 years sooner. The build-sooner cost in this example is $84,353 representing the difference between the present values of the two investments.

This example calculated the build-sooner cost for only one improvement cycle (e.g., one pavement life



Present Value: $1,000,000 ($1983); 10 years; 4%
PV= $675,564

Present Value: $1,000,000 ($1983); 7 years; 4%
PV= $759,917

Build Sooner Cost= 759,917- 675,564
= $84,353

FIGURE 4 Build-sooner costs.

cycle). It is necessary to calculate build-sooner costs for each subsequent cycle within the study period or until the effects of discounting render the build-sooner cost insignificant.

The final step in the analysis involves converting the build-sooner cost into an equivalent annual cost over the life cycle of the improvements using the appropriate capital recovery factor. For each link, sensitivity analysis was done using real discount rates of 3, 4, and 5 percent. The assumption underlying the choice of real discount rates of this magnitude was that a spread of 3 to 5 percent between the yield on long-term government bonds and the inflation rate would be representative of the long-run cost of capital throughout the time horizon of this study.

Summary

Two categories of build-sooner costs were hypothesized in this study. A large increment of commodity traffic will theoretically cause pavement condition to deteriorate faster and will cause a section of highway to reach capacity earlier. To the extent that these phenomena occur, investments in pavement resurfacing and capacity improvements will also be required earlier. The cost of having to commit capital expenditures at an earlier date is the build-sooner cost.

SUMMARY OF RESULTS

Table 3 gives a summary of the results of the build-sooner cost analysis and compares annualized costs to estimated incremental annual user fee revenue that might be expected from each movement. The user fee revenue consists of fuel taxes, registration fees, and license fees, of which fuel taxes represent the largest contribution.

TABLE 3 Annualized Build-Sooner Costs on Incremental Revenues (1983 dollars)

Commodity Movement	Build-Sooner Costs[a] Pavement	Capacity	Incremental Revenues
Potash 1	110,000	39,000	201,250
Potash 2	195,000	7,000	307,800
Potash 3	292,000	42,000	509,100
Woodchips 1	24,000	91,000	55,000
Woodchips 2	40,000	5,000	92,100
Coal	225,000	46,000	494,500
Concentrates	81,000	6,000	247,100
Petroleum	6,000	74,000	90,400

[a] Discount rate is 4 percent.

Table 4 gives build-sooner costs as a percentage of incremental revenue. It must be emphasized that Tables 3 and 4 present only the build-sooner costs that would result from the commodity movements. Other cost categories were addressed in the overall study but are not presented here.

Two major observations can be made from these data. First, build-sooner costs exceeded incremental revenues in only one case (Woodchips 1), (attributable primarily to capacity-related costs). This can be explained by the fact that the highway link in question has numerous steep grades, many in excess of 10 percent. Accordingly, the passenger car equivalent of each woodchip truck is high, with the result that capacity improvements that would not normally be required for many years on this relatively low-volume highway are advanced several years, creating a high build-sooner cost.

The other noteworthy feature of the data is that in all but two cases, pavement rehabilitation costs

TABLE 4 Build-Sooner Costs as Percentage of Incremental Revenues

Commodity Movement	Pavement Rehabilitation (%)	Capacity (%)	Total Build-Sooner Costs (%)
Potash 1	54.6	19.4	74.0
Potash 2	63.4	2.3	65.7
Potash 3	57.4	8.2	65.6
Woodchips 1	43.6	165.5	209.1
Woodchips 2	43.4	5.4	48.9
Coal	48.5	9.3	54.8
Concentrates	32.8	2.4	35.2
Petroleum	6.6	81.9	88.5

exceed capacity-related costs by a substantial margin. This appears somewhat surprising given the large expenditures normally associated with capacity enhancements. The explanation lies in the fact that the volume of commodity traffic (expressed in terms of passenger car equivalents) is generally low in comparison with existing passenger car and truck traffic. Hence the impact of the commodity trucks on capacity utilization is such that build-sooner periods were consistently shorter (0 to 3 years).

The sensitivity of results to changes in the discount rate was analyzed using real discount rates of 3, 4, and 5 percent. The higher discount rates do produce higher build-sooner costs. Although this may appear to be counterintuitive, it must be remembered that all build-sooner costs are estimates from the difference in present values of an investment made at two different points in future time. The difference increases even though the absolute magnitudes of the present values fall as the discount rate is increased. Furthermore, the capital recovery factor increases as does the discount rate resulting in higher costs.

The build-sooner costs analysis indicates that the bulk commodity movements studied would have a significant impact on future pavement rehabilitation and capacity-related costs, ranging from a low of 35.2 to a high of 209 percent of incremental revenues that would result from each movement. These costs arise from the need to advance the timing of these kinds of highway improvements because of the presence of the commodity traffic.

CONCLUSION

Previous highway cost allocation studies could, in general, be characterized as attempts to allocate highway expenditures to various classes of vehicles. The allocations are based in part on cause and effect relationships and in part on arbitrary accounting rules.

This study differs somewhat in that it assigns costs, not expenditures, attributable to a hypothetical increment of heavy truck traffic and then compares these costs to the incremental revenues that this same traffic would generate. The costs examined in this paper are those related to the impact of the incremental traffic on the timing of future pavement rehabilitation and capacity enhancement projects.

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