Determination of Economically Balanced Highway Expenditure Programs under Budget Constraints: A Practical Approach

DETERMINATION OF ECONOMICALLY BALANCED HIGHWAY EXPENDITURE PROGRAMS UNDER BUDGET CONSTRAINTS: A PRACTICAL APPROACH

Thawat Watanatada and Clell G. Harral

World Bank, Transportation, Water and Telecommunications Department
1818 H Street, N.W., Washington, D.C. 20433, USA

THAILAND, USA

I. INTRODUCTION

In most highway expenditure programs in less developed countries we have seen in recent years there are considerably more economically worthwhile projects than can be implemented within the available funds. This situation is growing worse as the highway expenditure budgets in these nations have been steadily losing their purchasing power, especially with respect to the cost of fuel and bitumen. The problem that faces the highway authority more urgently than before is to find the best way to allocate limited resources in the face of growing needs. To this end we are seeking a method for selecting projects under budget constraints that fulfills the following requirements. The method must: (1) be relatively simple and practical; (2) have a reasonably sound theoretical basis; (3) not overlook any important economic trade-offs; and (4) be capable of handling the types of project interdependencies normally encountered among highway investment projects (particularly mutual exclusivity).

This paper describes public expenditure budgeting criteria which can be employed in assisting the highway authority in deciding economic priorities of proposed investments, involving engineering trade-offs with respect to competition for scarce financial resources. These criteria are useful in the determination of short and medium range highway expenditure programs entailing both recurrent and capital outlays on road maintenance new construction, rehabilitation and strengthening. The criteria have already been introduced in part in the preparation of World Bank loans in

1/ The views expressed in this paper are those of the authors and should not be attributed to the World Bank or any individual acting on its behalf.
developing countries.

Although the public expenditure budgeting criteria are described in the context of highway sector planning they can be applied, in principle at least, to the other transport subsectors and the transport sector as a whole.

II. MULTIPLE PERIOD EXPENDITURE BUDGETING: GENERAL METHODOLOGY

Various possible approaches for handling multiple period budgeting problems were reviewed, including heuristic and mathematical programming approaches. The review included some of the techniques described in more recent literature surveys (Beenhakker, 1976; Wilkes, 1977; and Moavenzadeh, et al., 1977; among others). Although the review was far from exhaustive, the basic finding is that with the exception of the dynamic programming approach, none of the methods examined appear to satisfy all the four requirements stipulated above. Although integer programming techniques yield a global optimum in a finite number of search steps the number of steps can be excessively large for practical purposes. For the nature of problems dealt with in this paper, an integer programming algorithm is not likely to be computationally more efficient than a dynamic programming counterpart. Furthermore, the solution produced contains little sensitivity information and is usually difficult to interpret in economic terms.

Heuristic methods usually do not produce a guaranteed global optimum, but they are simple to use. Therefore, they can be useful provided that the heuristic solution is not unreasonable in that the important economic trade-offs are properly accounted for. However, no heuristic methods have been found to yield a reasonable solution in general, except under rather restrictive assumptions. In one heuristic method, projects are selected sequentially from the first budget period to the last in the descending order of incremental benefit-cost ratios. This heuristic decision rule does not recognize the fact that, because of scale-economies such as in pavement construction, it can be more advantageous economically to implement relatively few physical projects each year to a high standard than vice versa. Thus, heuristic methods must generally be used with caution.

For these reasons, a dynamic programming technique has been developed and proposed in this paper as a general methodology for multiple period budgeting problems. However, because of its simplicity and ease of interpretation, a heuristic technique based on budget shadow prices is presented as a possible alternative solution technique for special cases.
Basic Definitions

Let \( k \) denote the subscript of an "investment unit" defined as a set of \( M_k \) mutually exclusive alternatives, \( m = 1, 2, \ldots, M_k \) in a given sector. Investment units are assumed to be mutually independent. For alternative \( m \) of investment unit \( k \), \( k = 1 \) to \( K \), where \( K \) is the total number of investment units available for possible implementation,

\[
\text{let } \text{NPV}_{km} = \text{the present value of net economic benefits, measured in terms of discounted future consumption stream at an exogenously determined social discount rate } S/; \]

and \( \text{Ekmt} = \text{the (undiscounted) expenditure incurred by the sectoral agency in a budget period } t, t = 1 \) to \( T \), where \( T \) = total number of budget periods; the duration of \( t \) may be one or more years and need not be equal for different budget periods.

Both \( \text{NPV}_{km} \) and \( \text{Ekmt} \) are assumed to be computed in social prices to account for market distortions. The expenditure in a given budget period \( t \), \( \text{Ekmt} \), may include capital costs (e.g., for construction) or recurrent costs (e.g., for maintenance) or both; \( \text{Ekmt} \) may also include direct revenues which are incorporated as negative components. Thus, all expenditure and revenue components that impinge on the budget are included in \( \text{Ekmt} \).

Problem Statement

The public expenditure budgeting problem for multiple periods can be stated as a general integer programming problem of maximizing the total net present value for the sector, \( \text{TNPV}_2 / \):

1/ Acceptance of an exogenously determined social discount rate (SDR) does not mean that the SDR is easy to determine with any precision. But the point is that the analyst must take the SDR as given although the analyst may have an idea about what the range of the SDR should be and can perform sensitivity analyses accordingly. At any rate, the SDR is basically a policy parameter which must be decided at the policy level. Discussions of the SDR and how it should be determined are given in Marglin (1967), Steiner (1969), UNIDO (1972), Squire and Van der Tak (1975), among others.

2/ Other social welfare objectives such as income distribution are not addressed in this paper. However, it is possible to incorporate other objectives in the form of relative weights and constraints in a mathematical programming formulation (Steiner, 1969; UNIDO, 1972; and Major, 1973).
Maximize

\[
\text{TNPV}\left[X_{km}\right] = \sum_{k=1}^{K} \sum_{m=1}^{M_k} \text{NPV}_k X_{km}
\]

(1)

over the "zero-one" decision variables \(X_{km}\), \(m = 1\) to \(M_k\) and \(k = 1\) to \(K\), where \(X_{km}\) equals 1 if alternative \(m\) of investment unit \(k\) is chosen for implementation, and equals zero otherwise; subject to budget constraints for different periods:

\[
\sum_{k=1}^{K} \sum_{m=1}^{M_k} E_{km} X_{km} \leq T_{B_t} \quad \text{for } t = 1 \text{ to } T
\]

(2)

where \(T_{B_t}\) is the maximum total budget available for period \(t\); and also subject to the constraints that for each investment unit \(k\) no more than one alternative can be implemented:

\[
\sum_{m=1}^{M_k} X_{km} \leq 1 \quad \text{for } k = 1 \text{ to } K
\]

(3)

**Interpretations of Investment Units**

Defined as a set of mutually exclusive alternatives, an investment unit can be interpreted in a variety of forms, as described in the examples below:

1. **Independent projects**: an investment unit may represent a single-alternative project independent of other projects.
2. **Scale of investment**: for example, a road construction project in which three different design standards represent alternative investment levels.
3. **Scale and timing of investment**: for example, the above road construction project of three alternative investment levels may have two alternative construction dates (e.g., immediately and five years from now); this gives a maximum of six mutually exclusive combinations.
4. **Staging strategies**: for example, two alternatives are considered in a road construction project: the first consists of 10 units of lump sum investment in the first

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Interpretations of mutually exclusive alternatives have been made in Hirshleifer, et al. (1960), Beenhakker (1976), and Juster and Pecknold (1976).
year; and the second consists of 6 units of lump sum investment in each of the first and seventh years, where the seventh year is for upgrading to a higher pavement standard.

5. **Compound projects:** for example, an investment unit may consist of the proposed modernization of a sugar refinery as one undertaking and the proposed upgrading of the access road to the plant site as another. The total benefits of both undertakings when taken together exceed the sum of the benefits of each if taken alone. In this example we have three combinations or compound projects: modernizing the refinery alone, upgrading the access road alone, and doing both.

6. **Recurrent expenditure:** an investment unit may involve recurrent expenditure on an existing facility such as alternative maintenance standards for a given road class.

The concept of the investment unit provides a convenient means for organizing project analysis work. Physical projects in different investment units are assumed to be independent whereas those within each investment unit are assumed to be interdependent. In principle any type of project interdependency (mutual exclusivity, joint effect on benefits and costs, etc.) can be handled. However, the number of feasible combinations of interdependent projects should not in practice become unmanageably large.

While one may argue that all projects are interdependent at least to some extent and that no project should in general principle be considered in isolation, many projects can be assumed to be independent for approximation purposes without seriously affecting project selection results. The analyst must exercise judgment to decide whether the projects should be analyzed as independent or interdependent. Also it is assumed that the analyst has sufficient understanding of the basic engineering-economic trade-offs of investment strategies in the sector so that only a few but meaningful alternatives are carefully formulated.

**Solution Method: A Dynamic Programming Technique**

One solution method that satisfies the criteria stated earlier employs a dynamic programming formulation. This method is described as follows.

For the sequence of investment units, \( k = 1, 2, \ldots, K \), let \( f_k (B_{kt}, t = 1 \text{ to } T) \) denote the maximum net present value obtainable from
the period budgets, $B_{kt}$, made available for the first $k$ investment units in the sequence. According to dynamic programming literature (Bellman, 1957), the period budgets $B_{kt}$ (where $B_{kt} \leq TB_t$) are treated as "state" variables, and the subscript $k$ as one of $K$ "stages." The function $f_k$ is related to the function $f_{k-1}$ by the following recursive relationship:

$$f_k(B_{kt}, t = 1 \text{ to } T) = \text{Maximum of } \left\{ \sum_{m=1}^{M_k} \text{NPV}_{km} X_{km} + f_{k-1}(B_{kt} - \sum_{m=1}^{M_k} E_{km} X_{km}), t = 1 \text{ to } T \right\}$$

over the zero-one variables $X_{km}$, $m = 1 \text{ to } M_k$; subject to the budget constraints:

$$\sum_{m=1}^{M_k} E_{km} X_{km} \leq B_{kt} \text{ for } t = 1 \text{ to } T$$

and to the constraint that no more than one alternative may be chosen:

$$\sum_{m=1}^{M_k} X_{km} \leq 1$$

The recursive function for the zero stage $k = 0$, $f_0$, is defined as zero:

$$f_0 = 0$$

In this dynamic programming formulation the original complex integer programming problem is reduced to $K$ much smaller subproblems each having $T$ state variables ($B_{kt}$, $t = 1 \text{ to } T$) and $M_k$ "decision" variables ($X_{km}$, $m = 1 \text{ to } M_k$).

Solution to this dynamic programming problem can be obtained using the following procedure which can be coded into a relatively small computer program:

1. Divide each total period budget $TB_t$ into INT equal intervals. This gives $L = \text{INT} + 1$ discrete budget levels (or grid points) for each state variable, $B_{kt}$. This in turn gives $LT$ combinations of period budget levels for each stage $k$.

2. For each stage $k$, $k = 1 \text{ to } K$, determine the value of $f_k$ for each of the $LT$ combinations of budget levels.
B_{kt}. This is accomplished by optimization over the zero-one decision variables \( X_{km} \), \( m = 1 \) to \( M_k \). The optimization is computationally rather trivial since it involves linear search over \( M_k + 1 \) mutually exclusive alternatives (including the zero-expenditure alternative). Store each value of \( f_k \).

**Step 3:** The maximum total net present value for all investment units, \( \text{TNPV}^* \), corresponding to the total period budgets, \( TB_t \), are obtained from the recursive function at the last stage, \( k = K \):

\[
\text{TNPV}^* = f_{k=K} (B_{Kt}, TB_t, t = 1 \text{ to } T)
\]

The set of projects selected corresponding to \( \text{TNPV}^* \) is determined by optimization over the zero-one decision variables \( X_{km} \) for each stage in the backward order, \( k = K, K - 1, \ldots, 1 \).

Provided that the number of grid points per budget period, \( L \), is sufficiently large, according to Bellman (1957) the above algorithm yields the global optimum to the original multiple period budgeting problem (Eq.1) The global optimality requires no restrictive assumptions on the relationship of \( \text{NPV}_{km} \) to \( E_{kmt} \).

The amount of computational effort or "problem size" can be approximated by the following relationship:

\[
\text{CE} = C_e M K L^T
\]

where \( CE \) = computational effort (e.g., in seconds of computer CPU time); \( C_e \) = a constant; \( M \) = average number of alternatives per investment unit; and \( L, K \) and \( T \) are as defined earlier.

In actual applications, because of its exponential form the term \( L^T \) is expected to be the factor that determines the problem size. The value of \( L \) on the order of 10 should suffice for accuracy; but experience with applications will indicate whether a smaller value, say \( L = 6 \), will suffice or a larger value than 10 will be required to provide sufficiently accurate results. With \( L \) equal to 10 or smaller, the algorithm should be able to handle 4 and possibly 5 budget periods without excessive computational requirements. As it is possible to group 2 – 3 years into one budget period, 4 – 5 budget periods or fewer should be satisfactory for expenditure programming purposes in general.
Sensitivity Analyses

Execution of the above algorithm automatically provides information on the sensitivity of the total net present value, TNPV*, to variations in the allocated budgets TBt. The sensitivity information can be expressed in terms of budget shadow prices and cut-off economic rate of return (see Section III), and also in terms of the marginal project increments. The marginal project increments may be added to or subtracted from the expenditure program if the allocated budgets, TBt, themselves are modified. The sensitivity information provides answers to questions of the following type: What would be the percentage loss (or gain) in the total net present value if the budgets were decreased (or increased) by, say, 20 percent? Are the existing budgets for road construction and maintenance economically optimal? If not, how much additional funding allocation will be required? How sensitive are the road design and maintenance standards to the projected highway department budgets over the next 5 or 10 years? And so on.

Possible Solution Method: A Shadow Price Technique

A possible method for solving the multiple period budgeting problem (Eq.1) is to use budget shadow prices. Let λt be the shadow price of budget TBt. Define the "adjusted" net present value for alternative m of investment unit k as:

\[ NPV_{km}^t = NPV_{km} - \sum_{t=1}^{T} \lambda_t E_{km} \]  

The budget shadow price rule is to choose for each investment unit the alternative with the largest positive adjusted NPV. If none of adjusted net present values are greater than zero, no alternative is chosen for the investment unit. The budget shadow prices, λt, are unknowns and generally must be found by trial-and-error.

As a possible procedure for 4 - 5 and fewer budget periods, an exhaustive search can be carried out over all possible combinations of discrete values of λt over a reasonable range. This can be done in two stages as follows. The first is the screening stage which covers a coarser grid over a relatively wide range of λt (say, 0 to 3 or greater). The combination of λt, t = 1 to T, which yields the greatest total net present value while still not causing the budgets to be exceeded is taken as the interim solution. The second stage covers a finer grid over a narrower range of λt around the interim solution. The selection criterion is the same as in the first stage. A third stage may be added for further refinements.
The budget shadow price technique is simple to use and can be interpreted readily in economic terms (see interpretations in Section III). However, the technique does not guarantee global optimality of the solution in general. In a special case where there is only one budget period and the relationship of the net present value to the expenditure is convex, then the technique yields a global or near-global optimum (see Section III). Further work is required to establish broader conditions under which the budget shadow price technique yields a global optimum.

### III. SINGLE PERIOD EXPENDITURE BUDGETING: ALTERNATIVE METHODS AND ECONOMIC INTERPRETATIONS

The dynamic programming technique described above is useful for general expenditure budgeting problems where the proposed projects can be postponed for a few or several years, such as the paving of gravel roads or, more generally, road construction projects. For these projects expenditures can be incurred in different time periods. However, there are two main types of projects for which expenditures fall into one budget period.

The first type covers projects that for one reason or another (e.g., engineering feasibility) will either be implemented immediately or not at all. The question of investment timing and staged-construction does not arise for these projects. The second type involves recurrent expenditure (e.g., for road maintenance) which must be provided on a continuing basis without substantial year-to-year fluctuations. For these projects it is generally much easier to estimate benefits for an entire recurrent expenditure program (4 - 5 years in duration) than to isolate benefits due to spending in any individual year. For such recurrent expenditure projects the average annual cost can be used for budgeting against an average annual budget ceiling.

Suppose, for example, that the sector has only one investment unit of three alternatives. The alternatives 1, 2 and 3 have NPV's of 20, 30 and 40 and expenditures of 20, 50 and 60 (in the first period only). According to the budget shadow price rule the alternative is selected as follows.

<table>
<thead>
<tr>
<th>Range of Budget</th>
<th>Range of Shadow Price</th>
<th>Selected Alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 &lt; TB_1 &lt; 20$</td>
<td>$1.0 &lt; \lambda_1$</td>
<td>None</td>
</tr>
<tr>
<td>$20 &lt; TB_1 &lt; 60$</td>
<td>$0.5 &lt; \lambda_1 &lt; 1.0$</td>
<td>Alt.1</td>
</tr>
<tr>
<td>$60 &lt; TB_1$</td>
<td>$0 &lt; \lambda_1 &lt; 0.5$</td>
<td>Alt.3</td>
</tr>
</tbody>
</table>

For a budget of 50 units, alternative 2 is obviously the optimum, but the budget shadow price rule chooses alternative 1 instead.
Therefore, these two types of projects can be handled as a single period budgeting problem. This is a special case of the dynamic programming technique where $T = 1$.

**Incremental Benefit-Cost Ratio Method**

For the single period budgeting problem the dynamic programming algorithm provides a general solution method that requires no restrictive assumptions on the relationship between the net present value $NPV_{km}$ and the expenditure $E_{km}$. (Note that the subscript $t$ has been removed from the mathematical notation to indicate single period expenditure budgeting.) However, if $NPV_{km}$ is a "convex" function of $E_{km}$, it is possible to use a simpler technique, called the "incremental benefit-cost ratio" method.

For each investment unit $k$, let the alternatives be so arranged that $E_{km}$ increases monotonically with $m$, $m = 1$ to $M_k$. Then, the function $NPV_{km}$ is convex if

$$\frac{\Delta NPV_{k,m-1}}{\Delta E_{k,m-1}} > \frac{\Delta NPV_{km}}{\Delta E_{km}}$$

for $m = 1$ to $M_k$ (9)

where $\Delta NPV_{km} = NPV_{km} - NPV_{k,m-1}$

and $1/

$$\Delta E_{km} = E_{km} - E_{k,m-1}$$

and where $NPV_{ko}$ and $E_{ko}$ are defined as zero. A typical shape of the relationship of $NPV_{km}$ and $E_{km}$ is illustrated in Figure 12. In this figure if each straight line segment of the curve is taken as a "project increment" $m$, then the assumption of convexity ensures that for a given investment unit the selection of a project increment $m$ automatically implies selection of the earlier increments ($m-1$, $m-2$, etc.) in the unit. Because of this "inclusive" property of the function $NPV_{km}$, the expenditure increments $\Delta E_{km}$ can be treated as if they were independent projects. For notational simplicity, a single subscript $j$ will be made equivalent to the subscripts $k$ and $m$. Thus, we have $\Delta NPV_{km}$ and $\Delta E_{km}$ equivalent to $\Delta NPV_j$ and $\Delta E_j$, respectively. For a project increment $j$ we define the "incremental benefit-cost ratio," $R_j$, as:

1/ The possibility that $\Delta E_{km}$ equals zero is ignored for simplicity since it has no practical implications.

2/ The convexity assumption is not applicable to projects with joint positive benefits such as in the sugar rengistry example, nor with projects with increasing returns to scale.
Let $N$ be the total number of available project increments. We now rank these project increments in the descending order of the ratio $R_j$, yielding a new sequence of project increments, $i = 1, 2, \ldots, N$, where $R_j = \frac{\Delta NPV_j}{\Delta E_j}$.

$$R_j = \frac{\Delta NPV_j}{\Delta E_j}$$  \hspace{1cm} (10)

The new subscript $i$ is used instead of $j$ to indicate randomness of the old sequence of project increments indexed by $j$. In the incremental B/C ratio method as many project increments are selected as the budget $TB$ will allow by running down the sequence $i, i = 1$ to $N$. All project increments $i, i = 1$ to $n_b$ are chosen where $n_b$ is such that

$$\sum_{i=1}^{n_b} \Delta E_i < TB < \sum_{i=1}^{n_b+1} \Delta E_i$$  \hspace{1cm} (12)

Although optimality is not guaranteed the incremental B/C ratio method should be satisfactory in most cases where convexity of the net present value function applies.

**Economic Interpretations of Incremental B/C Ratio at Budget Margin**

The following interpretations are made in the context of single period expenditure budgeting but can be extended to multiple period budgeting.

Define the shadow price of a budget, $\lambda$, as the incremental B/C ratio of the best rejected project of the budget period. In the incremental B/C method, we have

1/ The possibility of a tie has been ignored for simplicity, as it has no practical implications.

2/ There are cases where the solution is not optimal. For example, the total expenditure may be substantially smaller than $TB$ so that a project increment $i'$ where $i' > n_b + 1$ can be squeezed within the budget. But problems of indivisibility should not be serious if the investment increments are small relative to the budget.
Then, an equivalent project selection criterion based on the "budget shadow price" can be applied, so that each project increment \( j \) is selected if \( S \neq 0 \):

\[
\Delta \text{NPV}_j - \lambda \Delta E_j > 0
\]

Let \( Q \) denote the marginal economic rate of return obtainable in the private sector. If \( Q \) is used for the social discount rate \( S (S = Q) \) and no budget is imposed, we have \( \lambda = 0 \) and the project selection criterion reduces to the usual net present value criterion. If \( S = Q \) and the budget constraint is binding, we have \( \lambda > 0 \), meaning that the net present value must be "penalized" by imposing a premium on the investment cost \( \Delta E_j \). Because of restricted public investment opportunities caused by the budget constraint the cost of investment in the sector is valued at 100 \( \lambda \) percent higher than the cost of investment in the economy at large.

The shadow price of public expenditure budget, \( \lambda \), can be interpreted as the net present value of future consumption (for social discount rate \( S \)) that must be sacrificed for one unit of funding shortage minus unity. The future consumption can be made equivalent to a hypothetical annual consumption stream of \( \beta \) per year to perpetuity. Discounting the future consumption at social discount rate \( S \) yields

\[
\lambda = \sum_{r=1}^{\infty} \frac{\beta}{(1+S)^r} - 1
\]

\[
\beta = (1+\lambda)S
\]

The term \( \beta \) may be called the "marginal (or cut-off) imputed economic rate of return" for the budget. Similarly, the "imputed economic rate of return" or "imputed ERR" for a given project increment \( j \), \( IERR_j \), is defined as

1/ The criterion of Eq.14 is equivalent to Eq. 8 for the special case of single period budgeting with convex NPV functions.

2/ The unity is the unit funding shortage measured in terms of present consumption.
By virtue of Eqs. 16 and 17, another equivalent criterion to the incremental B/C ratio rule can be stated on the basis of the cut-off imputed ERR. That is, we select each project increment \( j \) for which

\[
IERR_j = \left( \frac{\Delta NPV_j}{\delta j} + 1 \right) S \]  

(17)

For \( S = Q \) and where no funding constraint applies, we have \( S = Q \), i.e., the cut-off imputed ERR equals the economic rate of return in the private sector. Thus the cut-off imputed ERR criterion is very similar to the more familiar internal rate of return criterion. For projects with a relatively large initial lump sum cost, uniform future consumption stream and long life, the imputed ERR is expected to be similar to the internal rate of return (IRR) computed in the regular way. For short-lived projects with a relatively small initial lump sum cost (e.g., road maintenance) the imputed ERR is expected to be considerably smaller than the regular IRR. By definition (in Eq.17) the imputed ERR is mathematically tied to the net present value which is taken as the correct measure of a project's worth. Therefore, the imputed ERR is always consistent with the net present value for project ranking purposes and does not discriminate in favor of short-lived projects as does the regular ERR.

IV. APPLICATION EXAMPLE

The public expenditure criteria under budget constraints described above have been applied in part in the design of a five-year road maintenance program in Costa Rica, one of the World Bank's borrowing countries. In this application the total average annual maintenance budget was taken as given. The extent and characteristics of the classified national road network were projected for the 5-year period on the basis of the construction program already planned (including road strengthening, rehabilitation, upgrading and new construction)\(^1\). On the basis of surface type and traffic volume the road network of 7,000 kilometers was divided into 10 major categories, 6 paved and 4 unpaved, each treated as an investment unit\(^2\).

\(^1\) The network projection is important in that a construction program of high pavement standards result in low maintenance expenditures and vice versa.

\(^2\) The figures presented have been changed slightly.
In addition to the null maintenance policy, several alternative improved maintenance policies were specified for each of the road categories. Each of the maintenance policies in each road category was simulated by the Highway Design and Maintenance Standards (HDM) model to predict the corresponding vehicle operating and road maintenance costs. Then, for each road category the net present value (discounted at 12 percent) of each improved maintenance policy was computed in terms of total transport cost savings over the null policy. For each road category (i.e., investment unit) the relationship of the net present value to the annual economic maintenance cost is determined, as illustrated in an example in Figure 2-A. Because these benefit-cost relationships were found to be convex, the incremental B/C ratio method was employed for project ranking in the context of a single period expenditure budgeting problem (see Section III).

The ranking of the project increments by the incremental B/C ratio produced the relationship of the net present value to the total annual economic cost of the entire road maintenance program, as shown in Figure 2-B. If there was no budget limit, Figure 2-B suggests an (unconstrained) optimal program of £3.85 million per annum. But because of the budget limit of £3.45 million, a smaller program was obtained. At this constrained optimal solution, on the basis of the "best rejected" project increment (No. 5 in Figure 2-B), the ratio of the incremental average annual net economic benefit to cost equals 2.2. This is the shadow price of the road maintenance budget. Substituting this ratio in Eq.16 gives the cut-off imputed ERR equal to 38 percent.

The constrained optimal solution yielded the estimated amounts of expenditure and quantities of maintenance work to be performed in different activities. These quantities were then used as the basis for estimating the requirements for road maintenance vehicles and equipment and other detailed specifications of the road maintenance program.

Experience showed that the analysis process was relatively quick and simple. Excluding the collection of road inventory and traffic data, the total amount of time required to perform the analysis to arrive at the specifications of the road maintenance program and reporting was

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1/ The HDM model is an engineering-economic model for highway project evaluation supported and maintained by the World Bank. The model basically predicts the total transport costs of different highway design and maintenance options, including principally the costs of vehicle operation and road construction and maintenance. A full description of the HDM model is provided in Watanatada, et al. (1979). Various forms of applications of the model are reported in Harral, et al., (1977).
V. CONCLUSIONS

Criteria for determining economically optimal highway expenditure programs under budget constraints have been described. These criteria are intended to produce construction and maintenance programs which are economically balanced in the sense that the additional economic benefits for an extra pound spent on each program are approximately equal. Within each of the construction and maintenance programs, expenditure decisions at the level of individual projects will also be economically optimal, and the trade-offs among the principal engineering design variables such as pavement and geometric standards will have been adequately explored.

The public expenditure budgeting criteria presented include a general methodology of dynamic programming which can be used to select projects under single or multiple period budget constraints. The methodology can handle time-staging strategies, mutually exclusive projects and other types of project interdependencies normally encountered among highway investment projects. For the special case of single period budgeting in which the net present value functions are convex, the method of the "incremental B/C ratio" is proposed as a simpler alternative. Also for this special case, the "incremental B/C ratio" method is shown to be mathematically equivalent to the "budget shadow price" method and the "cut-off imputed economic rate of return" method. The latter methods can be readily interpreted in economic terms.

The public expenditure criteria have been applied in part in the design of a road maintenance program under a budget constraint in Costa Rica, and the practical application has proved to be quick and simple. A full scale application is contemplated in the future in the development of overall highway sector expenditure programs which include both construction and maintenance expenditures.

ACKNOWLEDGMENTS

We have benefited substantially from the discussions on public expenditure budgeting theories with several of our colleagues, including in particular Anandarup Ray, Alan Walters and Bernard Chatelin. The application example is a product of the efforts of a number of individuals. Without prejudicing the numerous individuals who cannot be named due to limited space, we wish to thank our colleagues, Sergio Miquel and Jose Veniard, World Bank Project Officers for Costa Rica, for their technical and moral support. Also we wish to express our appreciation for the valuable cooperation of the officials of the Ministry of Public Works and Transport of Costa Rica (MOPT), in particular, Ing. Rodolfo Mendez Mata, Minister, and Ing. Mario Fernandez Ortiz, Director of Highways. The analysis work which led to the application.
example would not have been accomplished without the generous contributions from the staff of the MOPT Computing Center, particularly Enrique Quiroz. We are, of course, solely responsible for any errors and omissions that remain in this manuscript.
REFERENCES


FIGURE 1

NET PRESENT VALUE VS. EXPENDITURE

Net Present Value of Investment Unit $k$
(at social discount rate $S$)

\[ \text{Expenditure of Investment Unit } k \]

\[ \Delta E_{k1} \quad \Delta E_{k2} \quad \Delta E_{k3} \]

\[ \Delta \text{NPV}_{k1} \quad \Delta \text{NPV}_{k2} \quad \Delta \text{NPV}_{k3} \]

Expenditure of Investment Unit $k$
A. Net present value vs. annual economic cost for an individual road category (investment unit)

Net present value over null policy, in $ million (at 12% discount)

B. Net present value vs. annual economic cost for entire road network

Net present value over null policy, in $ million (12% discount)