OPTIMAL HIGHWAY SAFETY IMPROVEMENT INVESTMENTS BY DYNAMIC PROGRAMMING

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Determining which projects to implement under a given budget and which to defer until later is central to the planning and management of highway systems. With a limited budget for construction, maintenance, and safety improvements, investments must produce optimal benefits. This paper discusses a dynamic programming procedure developed to select the optimal combination of safety improvement projects for a given budget. The type of dynamic programming considered is multistage, i.e., cost optimization of several projects, each with one or more alternatives. All safety improvement costs are dealt with in terms of present worth, and consideration is given to construction or installation cost, yearly maintenance cost, present interest rate, and expected life of the improvement. The option of staging safety improvements over a number of years was excluded from this analysis. All possible combinations of improvements were input as alternatives for each of the 61 projects involved in this study. The input consisted of the designated budget for the safety improvement program, the improvement cost, and the benefits derived from each improvement. The accuracy and reliability of dynamic programming depend on the accuracy of benefits and costs used as input. In a comparison with benefit-cost analyses, dynamic programming yielded a higher return for a given budget. An optimal allocation of funds will always be obtained if the individual project costs are multiples of the increment used in dynamic programming.

•THE PROCESS of determining which projects to implement under a given budget and which to defer until later is central to the planning and management of a highway system. Because the construction, maintenance, and safety improvement budget is limited, investments that will produce the optimal benefits must be chosen. This is often impossible to accomplish without the aid of a computer because of the complexity of the problem. Dynamic programming has been proved to be an efficient method for selecting priority projects to derive maximum benefits.

Dynamic programming is an optimization technique that transforms a multistage decision problem into a series of one-stage decision problems. The decision at each stage depends on the input to that stage, the feasible set of decisions at that stage, and the conditional set of decisions from the preceding stages.

There are three main reasons why dynamic programming is needed for transportation planning. First, dynamic programming is designed to provide the best plan over a period of time, inasmuch as the scheduling of a project is a critical variable. Second, dynamic programming makes it possible to obtain the best combination of projects where some approaches are inaccurate and trial-and-error methods can become an impossible task. Third, dynamic programming can determine the optimal investment plan when the usual benefit-cost, present worth, or maximum rate of return approaches are not practical. When the amount of money required for a single project is a large por-

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tion of the budget, the best projects are not necessarily those that would be chosen by the conventional means of priority selection. Benefit-cost and rate of return methods may not provide the best overall use of resources because an efficient implementation of results may not be possible. In addition, the benefit-cost method of selecting optimal alternatives does not always produce the best results because it focuses narrowly on immediate benefits and often precludes some future combinations of alternatives that are more desirable.

Many programs do not require detailed knowledge of the mechanics of dynamic programming. The input consists only of the costs and benefits anticipated for a project and the time required for completion. By taking all possible combinations into account, dynamic programming avoids the possibility of missing an optimal plan that will guarantee the best economic investment.

There are several approaches to priority programming as it relates to the capital allocation problem. Benefit-cost, present worth, and rate of return calculations have traditionally been used as an integral part of the transportation planning process. Performance bugeting has been proposed as a means of highway maintenance management (1). Construction and maintenance programs must continually be assigned priorities when funds are insufficient to complete all projects. Safety improvement programs, which were initially funded through the Highway Safety Act of 1966 and expanded through the Federal-Aid Highway Act of 1973, have become so large that they are unmanageable without a clear, concise means of priority allocation. Possibly the most comprehensive and accurate method of cost allocation for a constrained budget is dynamic programming. The term was coined by Bellman (2) in an attempt to simplify the phrase definition previously used: mathematical theory of multistage decision processes. He summarized dynamic programming applicability into three types of projects: single-stage, multistage, and multistage incorporating a time factor.

Single-stage dynamic programming is the evaluation of a single project with several alternatives as compared to multistage programming in which several projects with several alternatives are evaluated. Multistage with a time factor involves allocation of funds by dynamic programming in which several projects with several alternatives are subject to implementation over a period of time.

Johnson, Dare, and Skinner (3) presented dynamic programming as a means of selecting highway improvement projects to eliminate hazardous locations and therefore to maximize the annual cost reduction benefit. They suggested that use of dynamic programming ensures an optimal solution when several projects are being considered and construction funds are limited. de Neufville and Mori (4) dealt with a simplified procedure for determining the optimal construction schedule for additions to a highway or similar transportation network over time. They used only costs and benefits for each project as input to determine the optimum schedule. Funk and Tillman (5) used the systems approach to emphasize that the cost and benefits occurring to all parts of the system must be evaluated to establish the effect on a specific route under consideration. Dynamic programming was used to analyze the entire system such that construction was optimally staged.

Jorgensen (6) has done extensive work in identifying high-accident locations and developing methods for selecting improvements from among various projects. Jorgensen recommended use of benefit-cost, present worth, or rate of return calculations to determine which project yields the maximum difference between the annual investment cost and the annual expected safety benefit. Determining priorities with these methods is restrictive because they do not ensure the optimal combination of projects when the budget is limited. Lorrie and Savage (7) showed that, under a constrained budget, selecting a project with a large initial cost and a high ratio of present worth to cost may preclude the selection of several smaller projects that together yield a greater present worth. Another disadvantage is the inability of previously used methods to evaluate the relative merit of competing alternatives at varying investment levels.

Previous studies have dealt with highway budgeting in Kentucky (8, 9). Agent (10) evaluated the high accident location spot-improvement program in Kentucky and determined that the small investment in the program had returned significant dividends. It was felt that further study was warranted, and Zegeer (11) recently completed an investigation of the various methods for selecting high-accident locations. Favorable results from the studies by Agent and Zegeer, combined with an expansion of the spot-improvement program as a result of appropriations through the Federal-Aid Highway Act of 1973, have stimulated the development of an optimal method for allocating funds within the safety improvement program. Dynamic programming, as an optimal investment plan with a constrained budget, is presented here in a rather simplified but effective form for the particular problem.

The Alabama Highway Department has done considerable work in applying dynamic programming to the optimization of budget allocation for the spot safety improvement program (12). The Alabama program was modified significantly to evaluate the data available for the spot-improvement program in Kentucky.

PROCEDURE

In this study, multistage dynamic programming was evaluated as a means of assigning priorities and allocating expenditures for the spot safety improvement program in Kentucky. All safety improvement costs were dealt with in terms of present worth, and construction costs, maintenance cost, and the expected life of the improvement were all considered. The option of staging safety improvements over a number of years was excluded from this analysis. All possible combinations of alternatives were considered for each of the 61 projects involved in the analysis. For example, the safety of a curve where a large number of accidents occur may be improved in several ways, including realignment, resurfacing, signing, and delineation.

The problem of optimizing use of improvement funds can be divided into two distinct steps. First, the benefits associated with each proposed improvement are determined. Then, based on the costs and benefits for a set of improvements and a specific budget, the optimum combination of improvements to be implemented is chosen. A computer program[1] is used to calculate the costs and benefits in the subroutine COSBEN. These results are printed out and passed into the subroutine DYNAM along with the budget and output information. DYNAM then determines and prints out the optimum combination of improvements for the desired budgets. If no alternative emerges at a particular location, alternative O is printed. A range of budgets including the maximum budget available are considered. In this manner, an optimum budget is determined.

Calculation of Costs and Benefits Using the Present Worth Method

The following equations were used to calculate costs and benefits (13):

$$C = S + A[(1 - i)^L - 1]/i(1 - i)^L \quad (1)$$

where

C = present worth cost of improvement,
S = construction cost,
A = yearly maintenance cost,
i = present interest rate = 10 percent, and
L = life of improvement.

[1]The original manuscript contained several appendixes giving the computer program, the subroutines, variables, and flow charts. These are available in Xerox form at the cost of reproduction and handling. When ordering, please refer to XS-67, Transportation Research Record 585.

$$B = \left\{ \frac{[(1 + t)^{L+1}/1 + i] - 1}{(1 + t/1 + i) - 1} - 1 \right\} \beta \tag{2}$$

where

B = present worth benefit,
t = exponential growth rate factor for traffic volume = 4 percent, and

$$\beta = \left(\sum_{m=1}^{J} \sum_{n=1}^{3} a_m N_{mn} \gamma_n \right) \Big/ T \tag{3}$$

where

β = benefit per year associated with the improvement,
T = time (years) of accident history,
J = number of accident causes associated with the location,
a_m = percentage of reduction of m th cause affected by the improvement,
N_{mn} = number of accidents associated with m th cause, and
γ_n = average cost of an accident (n = 1-fatality, n = 2-nonfatal injury, and n = 3-property damage only).

Dynamic Programming Algorithm

1. Step 1. Divide budget into N equal intervals.
2. Step 2. (Stage 1) Determine the best alternative at location 1 to maximize the return by using j increments, j = 1, 2, . . . , N; i.e.,

$$O_1(j) = R_1(j) \tag{4}$$

where

$O_1(j)$ = total optimum return after stage 1 for an investment of j increments,
$R_1(j)$ = return from location 1 for an investment of j increments, and
$D_1(j)$ = chosen alternative at location 1 for an investment of j increments.

3. Step 3. (Stages 2 through M) Repeat step 2 for each stage.

$$O_i(j) = \mathrm{Max}\,[(R_i(k) + O_{i-1}(j - k)] \tag{5}$$

for j = 1, 2, . . . , N and k = 1, 2, . . . , j, where

M = number of locations considered,
$O_i(j)$ = total optimum return after stage i for an investment of j increments,
$R_i(k)$ = return from location i for an investment of k increments ($k \leq j$),
$O_{i-1}(j - k)$ = total optimum return after stage (i - 1) for an investment of (j - k) increments, and
$D_i(j)$ = chosen alternative at location i for an investment of j increments.

4. Step 4. The optimum alternative at each location can now be obtained by determining the best alternative for location M at stage M with N increments. The remaining increments can now be used at stage (M-1). Therefore,

$A_M = D_M(N)$, leaving N_M increments,
$A_{M-1} = D_{M-1}(N_M)$, leaving N_{M-1} increments,
$A_{M-2} = D_{M-2}(N_{M-1})$, leaving N_{M-2} increments, and

$$A_i = D_i(N_{i+1}) \quad (6)$$

where A_i = alternative chosen at the i th location.

Development of Benefit and Cost Values

Some of the major inputs to the dynamic programming model are the benefits assigned to each improvement at a location. For example, the effect on accident patterns of upgrading a traffic signal at an intersection will be different from that of installing channelization. To quantify the effect of various improvements on accidents, 447 improvement projects in Kentucky since 1968 were studied to determine the accident reduction (or increase) associated with each at various location types.

Various improvements on curves, intersections, and other (general) locations are given in Table 1. The total accident reduction value (in percentage of reduction) at each location under consideration was used to calculate an approximate benefit. Accidents unrelated to the location caused by brake failures, drunk driving, tire blowouts, and the like were disregarded. Associated with the high accident locations were 447 improvement projects. Many of the improvement projects included a combination of the various improvements listed in Table 1. Therefore, an alternative that was input for the dynamic programming model may be a combination of several types of improvements with respective adjustments in the percentage of accident reduction. To make the data manageable for this evaluation, 61 improvement projects were selected as input.

The subroutine COSBEN was used to compute monetary benefits from expected accident reductions. Accident costs used were recent National Safety Council values (14):

Accident Type	Cost (dollars)
Fatality	45,000
Injury	2,700
Property damage only	400

The accident occurrence at each location is multiplied by the expected percentage of reduction for the improvement alternative. The cost of accidents is then multiplied by the expected accident reduction to give annual benefits. These annual benefits are then multiplied by an exponential growth, present-worth factor (equation 2) to obtain the benefits for the entire service life of the improvement.

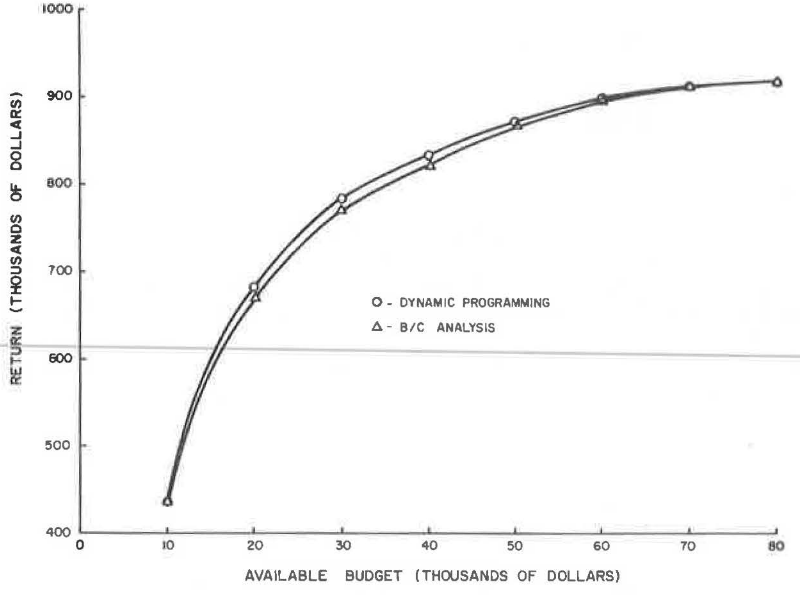
The costs used in the calculations are the sum of the improvement cost for each project and the maintenance cost. A present-worth factor (equation 1) was used to adjust the maintenance cost from a future date to the present.

Accurately estimating benefits and costs can be very difficult. Even with a large sample of before-and-after data for locations that have been improved, accident reduction estimates may be inaccurate. This is partially attributable to the varying characteristics of specific highway locations. Randomness in accident occurrence makes it impossible to accurately predict future accidents. Predictions of expected accidents after a particular improvement should be based on large samples combined with care-

Table 1. Summary of improvement costs and benefits.

Location	Type of Improvement	Number of Projects	Total Accident Reduction (percent)	Service Life (years)	Annual Maintenance Cost (dollars)
General	Signs and markings	9	36	3	25
	Warning signs	23	35	5	25
	Regulatory signs	16	22	5	25
	Guidance signs	10	14	5	25
	Sign combinations	16	20	5	25
	Markings	8	16	2	0
	Sight distance improvements	9	28	2	50
	Post delineators	3	25	5	20
	Combination delineators, markings, signs, and maintenance	11	22	5	25
	Shoulder improvements	7	23	10	100
	Combination resurfacing, patching, drainage, deslicking, culvert	22	16	10	100
	Rumble strips	8	29	5	0
	Removal of median crossovers	2	29	20	0
	Lighting	1	-58	10	500
	Lighting and rumble strips	1	17	7	300
	Rumble strips and beacon	2	32	7	50
	Side road sign only	31	19	5	25
	Prepare for sudden stop sign only	19	25	5	25
	Side road sign and warning sign	15	27	5	25
Curves	Signing	34	30	5	25
	Post delineators	4	32	5	25
	Signs and delineators	16	28	5	25
	Signs and maintenance	6	47	3	25
	Combination delineators, markings, signs, and maintenance	16	24	5	25
	Resurfacing, patching, drainage, deslicking, culvert, guardrail	22	33	10	100
	Realignment (relocation)	3	32	20	100
Intersections	Signs and markings	21	24	3	25
	Warning signs	11	27	5	25
	Regulatory signs	5	48	5	25
	Regulatory and warning signs	20	16	5	25
	Markings	17	16	2	0
	Marking, maintenance, and signing	9	35	5	25
	Channelization, storage lane	13	15	10	100
	Channelization and signs	2	37	7	75
	Install beacons	13	2	10	100
	Upgrade beacons	10	5	10	100
	Installation of signals	10	23	10	300
	Upgrade signals	2	18	10	250
Total		447	24		

Figure 1. Expected return versus available budget for dynamic programming and benefit-cost analyses.



ful engineering judgment. Dynamic programming can give near-perfect results if all input is correct. However, if benefit and cost input is carelessly or incorrectly estimated, results of dynamic programming will be equally in error.

RESULTS

A group of 61 high accident locations previously improved under the Kentucky spot-improvement program was selected as test data for the dynamic programming model. Accident reports at each location were reviewed, and improvement alternatives were actual improvements made at the locations. Input to the computer program for each alternative at each location consisted of accident data, expected accident reduction, project costs, service life of improvement, maintenance costs, and interest rate.

The dynamic programming model computed benefits for each alternative. Then, as the available budget was varied from $10,000 to $80,000, an optimal scheme of alternatives was generated for each budget. For an available budget of $50,000, the computer processing time was 38 sec on an IBM 360 computer at a cost of $5.86. The computer storage required for the 61 improvement projects and increments of $250 was 268 K.

A similar calculation of return and benefit-cost ratio was made by using a benefit-cost analysis. There was very little difference between the benefit-cost analysis and the dynamic programming analysis for the test locations. This is shown in Figure 1 where expected return versus available budget is plotted for both dynamic programming and benefit-cost analyses. Details of the data used to plot Figure 1 are given in Table 2. The insignificant difference between benefit-cost analysis and dynamic programming can be attributed to the fact that the priority allocation of funds by benefit-cost is a very efficient method in many cases. However, there is no guarantee that benefit-cost will always assign priorities that will yield the greatest return for a specified budget. Comparison of dynamic programming and benefit-cost, presented below, shows the weakness of the benefit-cost method for certain situations.

Comparison of Dynamic Programming and Benefit-Cost Ratio

Theoretically, dynamic programming computer techniques will produce a scheme for allocating funds under a fixed budget that will provide the optimal return. Testing the computer model showed that this is true as long as each project cost is an exact multiple of the budget increment. For example, if computer storage constraints permit increments of $250 for a budget of $100,000, then the cost of each improvement should be a multiple of $250 if the optimal improvement scheme is to be obtained. An increment was defined as some fraction of the budget used in the computer analysis for weighing benefits against costs. In general, the smaller the increment is, the better the solution obtained will be. The number of increments into which the maximum budget may be divided, however, is largely governed by the computer storage capacity and computer time required. Practically, then, the increment cannot be made as small as desired.

A simplified example (Table 3) was developed to demonstrate how the monetary return using dynamic programming techniques will exceed the return from a benefit-cost analysis if project costs are multiples of the increment. As shown in Figure 2, the dynamic programming return is the best at nearly every budget level from $5,000 to $34,000. Although the two are fairly close at some points, the return from the benefit-cost curve is inferior to that of the dynamic programming curve by about $50,000 at a budget of $20,000 and by $40,000 at a budget of $30,000. The two curves are equal at budgets of $25,000 and $34,000. In this example, the $34,000 budget was divided into 34 increments of $1,000 each. Each project cost is a multiple of $1,000.

A more detailed explanation of the logic used in the comparative example of benefit-cost versus dynamic programming may be enlightening at this point. With reference to Table 3 and Figure 2, a budget of $15,000 will produce a greater return by using dy-

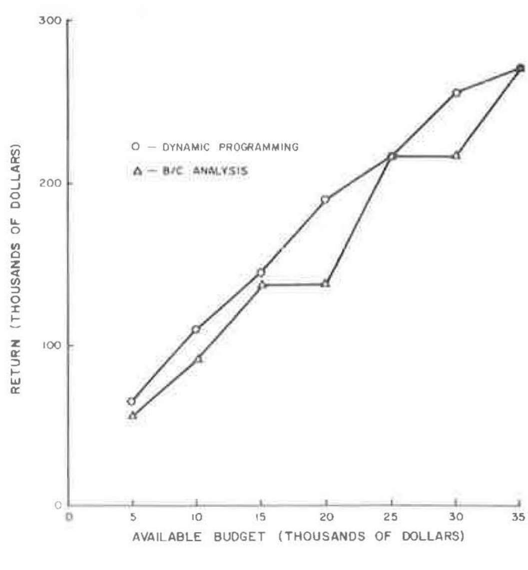
Table 2. Input data for comparison of dynamic programming and benefit-cost analysis.

Location Number	Location Name	Alternative Number	Cost (dollars)	Return (dollars)	Benefit-Cost Ratio	Location Number	Location Name	Alternative Number	Cost (dollars)	Return (dollars)	Benefit-Cost Ratio
1	63-25-10.9	1	1,500	7,620	5.08	31	72-641-8.5	2	1,500	13,357	8.90
2	30-60-15.1	1	4,250	158,707	37.34	31	72-641-8.5	3	2,000	56,100	28.05
3	30-60-15.2	1	2,000	11,385	5.69	32	56-I65KTP-130.1	1	1,500	11,711	7.81
4	54-41A-12.0	1	500	9,792	19.58	33	63-25-10.9	1	750	746	0.99
5	73-45-6.5	1	500	973	1.95	33	63-25-10.9	2	1,250	0	0.0
6	73-45-7.2	1	500	0	0.0	34	41-I75-155.6	1	4,000	152,094	38.02
6	73-45-7.2	2	500	0	0.0	35	51-41-20.0	1	2,000	1,678	0.84
6	73-45-7.2	3	750	6,726	8.97	36	051-41-20.0	1	500	4,699	9.40
7	48-421-14.4	1	500	0	0.0	37	82-31W-1.1	1	500	17,168	34.34
7	48-421-14.4	2	500	588	1.18	38	84-68-18.5	1	1,000	34,486	34.49
7	48-421-14.4	3	750	0	0.0	39	120-60-12.6	1	500	9,008	18.02
8	20-51-1.1	1	750	2,987	3.98	40	82-60-12.3	1	500	11,078	22.16
9	102-25-9.2	1	1,000	3,365	3.37	41	10-60-8.3	1	500	593	1.19
10	102-25-54	1	500	226	0.45	42	79-641-13.0	1	500	1,064	2.13
11	30-60-15.2	1	500	16,145	32.29	43	51-60-20.3	1	750	86,411	115.21
11	30-60-15.2	2	4,750	3,524	0.74	44	70-60-11.4	1	750	412	0.55
11	30-60-15.2	3	5,000	31,866	6.37	45	82-US60-12.7	1	750	9,097	12.13
12	72-641-8.5	1	750	40,588	54.12	46	82-US60-12.7	1	1,750	4,488	2.56
13	30-60-4.1	1	1,250	814	0.65	47	82-31W-1.0	1	500	922	1.84
14	39-I71-63.7	1	4,500	26,029	5.78	48	30-60-15.0	1	4,250	2,792	0.66
15	79-641-18.9	1	750	3,548	4.73	49	10-60-9.2	1	500	2,664	5.33
16	54-41A-12.4	1	500	14,598	29.20	49	10-60-9.2	2	750	3,196	4.26
16	54-41A-12.4	2	500	3,442	6.88	49	10-60-9.2	3	750	5,860	7.81
16	54-41A-12.4	3	750	18,040	24.05	50	79-641-12.5	1	500	8,710	17.42
17	24-68-9.1	1	500	814	1.63	50	79-641-12.5	2	750	5,784	7.71
17	24-68-9.1	2	500	916	1.83	50	79-641-12.5	3	1,000	17,152	17.15
17	24-68-9.1	3	1,000	1,729	1.73	51	79-641-12.5	1	1,000	26,532	26.53
18	114-31W-16.2	1	500	2,649	5.30	52	70-US60-11.3	1	500	626	1.25
18	114-31W-16.2	2	500	1,422	2.84	52	70-US60-11.3	2	750	1,649	2.20
18	114-31W-16.2	3	750	4,071	5.43	52	70-US60-11.3	3	1,000	366	0.37
19	63-25-16.0	1	500	966	1.93	52	70-US60-11.3	4	2,000	1,465	0.73
19	63-25-16.0	2	500	1,272	2.54	52	70-US60-11.3	5	1,750	8,021	4.58
19	63-25-16.0	3	750	2,238	2.98	52	70-US60-11.3	6	4,000	13,348	3.34
20	106-6-3.2	1	500	373	0.75	52	70-US60-11.3	7	4,250	14,447	3.40
21	37-127-8.7	1	750	2,348	3.13	53	47-31W-23.3	1	2,000	4,894	2.45
22	47-31W-26.0	1	2,250	24,654	10.96	54	63-25-10.4	1	500	4,735	9.47
23	30-54-12.6	1	750	4,290	5.72	54	63-25-10.4	2	500	5,380	10.76
24	114-31W-16.1	1	1,750	256	0.15	54	63-25-10.4	3	1,000	10,115	10.11
25	41-22-11.3	1	500	5,765	11.53	54	63-25-10.4	4	1,500	1,889	1.26
25	41-22-11.3	2	500	5,765	11.53	54	63-25-10.4	5	1,750	10,200	5.83
25	41-22-11.3	3	500	39	0.08	54	63-25-10.4	6	2,000	11,334	5.67
25	41-22-11.3	4	1,000	11,530	11.53	54	63-25-10.4	7	2,250	19,645	8.73
25	41-22-11.3	5	750	5,855	7.81	55	102-25-11.9	1	500	3,934	7.87
25	41-22-11.3	6	750	5,855	7.81	56	82-31W-2.2	1	2,500	6,780	2.71
25	41-22-11.3	7	1,250	11,620	9.30	57	51-41-20.0	1	500	10,792	21.58
26	73-62-17.8	1	500	424	0.85	58	82-31W-1.2	1	500	1,921	3.84
26	73-62-17.8	2	500	0	0.0	59	30-60-16.4	1	500	1,731	3.46
27	73-45-6.5	1	750	824	1.10	59	30-60-16.4	2	500	3,338	6.68
28	73-62-16.9	1	2,000	7,039	3.52	60	22-60-26.2	1	750	221	0.29
28	73-62-16.9	2	1,250	5,246	4.20	61	63-25-10.0	1	500	287	0.57
28	73-62-16.9	3	3,000	12,286	4.10	61	63-25-10.0	2	500	326	0.65
29	63-25-10.8	1	750	746	0.99	61	63-25-10.0	3	1,000	613	0.61
30	54-41A-12.2	1	500	4,528	9.06	61	63-25-10.0	4	1,500	114	0.08
30	54-41A-12.2	2	500	3,985	7.97	61	63-25-10.0	5	1,750	618	0.35
30	54-41A-12.2	3	750	8,513	11.35	61	63-25-10.0	6	2,000	687	0.34
31	72-641-8.5	1	500	10,565	21.13	61	63-25-10.0	7	2,250	1,191	0.53

Table 3. Example input data for comparison of dynamic programming and benefit-cost analysis.

Location Number	Alternate Number	Cost (dollars)	Benefit (dollars)	Benefit-Cost Ratio
1	1	1,000	20,000	20
2	1	1,000	15,000	15
3	1	1,000	12,000	12
4	1	3,000	30,000	10
5	1	5,000	45,000	9
6	1	10,000	80,000	8
7	1	1,000	7,000	7
8	1	9,000	54,000	6
9	1	2,000	6,000	3
10	1	1,000	2,000	2
Total		34,000	271,000	

Figure 2. Example problem of expected return versus available budget for dynamic programming and benefit-cost analyses.



namic programming than by using benefit-cost. The benefit-cost procedure permitted a sequential selection of projects in the order of decreasing benefit-cost ratios and a corresponding total of accumulative costs and benefits. Those projects whose costs would make the total exceed $15,000 were omitted, and the procedure was continued until the available budget was reached or the projects were exhausted. From Table 3 and based on this logic, locations 1, 2, 3, 4, 5, 7, 9, and 10 with an available budget of $15,000 would be selected. Therefore, by using benefit-cost analysis and a $15,000 budget, the improvement costs would be $15,000 and the return would be $137,000 in benefits.

The dynamic programming procedure is not constrained by the benefit-cost ratios and may search throughout the list of projects for those projects that provide the greatest return for an available budget. In this case with the $15,000 budget, dynamic programming would select locations 1, 2, 4, and 6. These selections would provide a return of $145,000 for improvement costs of $15,000.

From Figure 2, it is obvious that there is a great difference between the respective returns at an available budget of $20,000. This is because, for the benefit-cost procedure, no additional projects were added to the preceding $15,000 budget inasmuch as the remaining projects had costs of $9,000 and $10,000. An addition of either would have exceeded the available budget of $20,000. In contrast, dynamic programming was able to use all of the available budget because it was not constrained by limits similar to benefit-cost analysis. The respective benefits at an available budget of $20,000 were $137,000 with benefit-cost methods and $190,000 with dynamic programming.

Benefits from benefit-cost techniques may sometimes equal benefits from dynamic programming. In addition, when it is impossible to arrange the project costs such that they are an exact multiple of the budget increment, the benefits from benefit-cost may exceed those from dynamic programming because of rounding errors. However, dynamic programming will always produce the optimal scheme if project costs are expressed as multiples of the increment. For these reasons, it is suggested that both benefit-cost and dynamic programming be tested when it is not feasible to express project costs as multiples of the budget increment.

Use of Dynamic Programming

Application of dynamic programming techniques to the highway safety improvement program in Kentucky involves several steps. First, a list of potentially hazardous locations, based on accident data, is identified. A recommended location-identification procedure for Kentucky identifies hazardous 0.3-mile (0.5-km) spots and 3-mile (5-km) sections based on fatal accidents, total number of accidents, accident severity rating (the equivalent-property-damage-only number), and accident rate (applying quality control techniques). Locations should be identified based on 1- and 2-year time intervals. Also, locations identified by citizens, engineering personnel, and state police should be considered. All locations identified as possibly hazardous should then be reviewed. Locations considered worthy of a field inspection should be investigated for possible corrective measures.

The proposed program requires that all warranted minor improvements such as signs, paint striping, flashing beacons, and delineators be implemented without dynamic programming considerations. Major improvements such as resurfacing, bridge widening, realignment, and intersection channelization should be selected by dynamic programming techniques.

Project costs, expected benefits, maintenance costs, and expected service life of the improvement should be determined for each alternative at every location to be considered under dynamic programming. After the warranted minor improvements are considered, the remaining money should be budgeted for use in other projects where the dynamic programming may apply. An optimal set of improvement alternatives would then be generated.

SUMMARY AND CONCLUSIONS

The objective of this study was to develop or adopt appropriate dynamic programming methods that would assist in establishing optimal budgeting procedures for various highway programs. Dynamic programming is a multistage operation that involves evaluating several projects with several alternatives. The option of staging safety improvements over a number of years was excluded from this analysis. A dynamic programming procedure was developed to select the optimal combination of safety improvement projects for a given budget. Findings and procedures are summarized below.

1. Use of dynamic programming is relatively simple. Input consists of the budget, costs, and benefits. Estimating the benefits derived from a particular improvement presents the most difficulty.
2. Table 1, which gives accident reduction by type of improvement for past safety improvements, was developed from past accident experience for use in estimating savings.
3. The accuracy and reliability of dynamic programming depend on the accuracy of benefits and costs used as input.
4. Requisite to using dynamic programming for the safety improvement program is an efficient method of systematically identifying locations based on accident data. In-depth field investigations are also needed so that only necessary improvements are recommended as input for the dynamic programming model.
5. All possible combinations of improvements were included as alternatives in the model for each of the 61 projects.
6. Safety improvement costs were dealt with in terms of present worth, and construction or installation cost, yearly maintenance cost, present interest rate, and expected life of improvement were all considered.
7. Improvements selected by dynamic programming can yield a higher return for a given budget than those chosen entirely on the basis of benefit-cost ratios (Figure 2).
8. If individual project costs are multiples of the increment used in the dynamic programming, the optimum allocation of funds will always be obtained. In general, the smaller the increment is, the better the solution obtained will be. However, use of a smaller increment is restricted by available computer storage.
9. Both benefit-cost and dynamic programming should be tested when it is not possible to express project costs as multiples of the budget increment.
10. Applicability of dynamic programming to budget allocation in transportation planning is practically unlimited. In addition to highway safety improvement investments, optimal investments in maintenance and construction programs and eventually the entire transportation field can be determined through dynamic programming.

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