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**Mr. Cohen was with the Tri-State Regional Planning Commission, New York, when this research was performed.*

Significance of Benefit/Cost and Cost/Effectiveness Ratios in Analyses of Traffic Safety Programs and Projects

G. A. Fleischer, Traffic Safety Center, University of Southern California, Los Angeles

This paper is a critique of NCHRP Report 162, Methods for Evaluating Highway Safety Improvements. Several important conceptual errors in that publication concerning the use of benefit/cost and cost/effectiveness ratios in evaluating traffic safety programs and projects are identified and discussed. Qualitative and quantitative arguments, as well as supporting numerical examples, are provided.

In the fall of 1971 the National Cooperative Highway Research Program (NCHRP) of the Transportation Research Board initiated a major research effort primarily funded by the American Association of State Highway Officials (AASHO). The principal objective of the study was to develop a set of guidelines detailing the methodology and techniques for evaluating the effectiveness of highway safety improvements in terms of reduced accidents. It was also expected that a methodology would be incorporated for evaluating these safety improvements by cost-benefit analysis.

The final report, NCHRP Report 162, is for the most part a well-written, useful document. But, in my view, its usefulness is markedly diminished by several serious conceptual errors concerning the proper application of benefit/cost and cost/effectiveness ratios.

FISCAL OBJECTIVES

The authors of NCHRP Report 162 point out that "the method of analysis chosen to select from among mutually exclusive improvements at a location depends upon the fiscal objective of the agency making the selection" (1, p. 8). They further assert that there are two fiscal objectives:

1. Optimum improvement, in which the goal is to obtain the most net benefit from each investment opportunity; and
2. Benefit maximization, in which the goal is to obtain the most net benefit from the funds budgeted.

After reference to an example listing of candidate projects (which will be discussed later in this paper), the authors conclude: "The theoretically correct fiscal objective is the optimum improvement objective" (1, p. 9). This statement is not only puzzling; it is misleading. A false distinction is created that has no meaningful operational significance. For a given budget constraint, the agency's proper fiscal objective should be the maximization of net benefits from all investment opportunities. The optimum budget is that combination of investments—among sites, roadway designs, equipment, and so on—that maximizes net benefits. All subproblems at the design level can be accommodated under this rule.

BENEFIT/COST RATIOS

The NCHRP report discusses three methods for evaluating independent alternatives: (a) benefit/cost (B/C) ratio, (b) rate of return, and (c) payback period. Here, alternatives are independent if the selection of one alternative does not preclude the selection of any of the others.

The B/C ratio for a given project is defined in the usual way, as equal to either (a) the ratio of equivalent uniform annual benefits (EUAB) to equivalent uniform annual costs (EUAC), or (b) the ratio of the equivalent present worth of benefits (PWOB) to equivalent present worth of costs (PWOC). That is,

$$B/C = EUAB/EUAC = PWOB/PWOC \tag{1}$$

The authors then assert that the B/C ratios should be used to rank independent alternatives: "Order the improvements by magnitude of the B/C Ratios, largest to smallest" (1, p. 42). An example of the basic data for this procedure, as well as calculations of the B/C ratios, is given in Table 1.

The authors conclude that "the order by magnitude for these independent alternatives is B, D, A, C" (1, p. 42). That conclusion is strictly correct, but the inference is unjustified. It is true that

$$B/C(B) > B/C(D) > B/C(A) > B/C(C) \tag{2}$$

But it is not true that the economic preferences for these

Table 1. Economic data for four independent alternatives.

Improvement	Cost ($) Initial	Cost ($) Annual	Terminal Value ($)	Service Life (years)	Annual Benefits (constant)	EUAC at 10% ($)	EUAB at 10% ($)	B/C Ratio
A	200 000	4000	20 000	20	80 000	27 143	80 000	2.95
B	100 000	2000	10 000	15	55 000	14 833	55 000	3.71
C	50 000	1000	0	10	25 000	9 137	25 000	2.74
D	75 000	0	0	10	40 000	12 206	40 000	3.28

Table 2. Capital budgeting problem.

Location	Alter-native	Initial Cost ($)	EUAC ($)	EUAB ($)	Net Annual Benefits ($)	B/C Ratio
A	1	1000	228	800	572	3.51
A	2	2000	456	700	244	1.54
A	3	2500	570	1170	600	2.05
B	1	2000	456	750	294	1.64
B	2	4000	912	1750	838	1.92
C	1	1000	228	700	472	3.07
C	2	2000	456	900	444	1.97
C	3	3000	684	1000	316	1.46
D	1	1000	228	800	572	3.51
D	2	5000	1040	2000	960	1.54
E	1	500	114	500	386	4.39
E	2	4000	912	1600	688	1.75
F	1	1500	342	1200	858	3.51
F	2	3000	682	1100	418	1.61

alternatives are necessarily reflected by this ordering.

It should be observed at this point that ranking the four improvement projects is unnecessary if they are truly independent. The only relevant test is whether the resulting B/C ratios exceed unity. In this case they do. Each of the projects is therefore preferred to the do-nothing alternative. All of these independent projects should be accepted.

Suppose that, contrary to the original assumption of independence, ranking the four projects is desirable because (a) funds are not available for all improvements or (b) the projects are, technologically or physically, mutually exclusive. Then the correct ranking can be inferred by examining the net equivalent uniform annual benefits (or, alternatively, the net present worths):

1. Net EUAB (A) = $80 000 - $27 143 = $52 857;
2. Net EUAB (B) = $55 000 - $14 833 = $40 167;
3. Net EUAB (C) = $25 000 - $9137 = $15 863; and
4. Net EUAB (D) = $40 000 - $12 206 = $27 794.

It is also true that the incremental analysis of B/C ratio, properly computed, leads to this same conclusion. Let IB/IC represent the incremental B/C ratio between a pair of alternatives. Then IB/IC (C) = 2.95 and thus C > do-nothing alternative; IB/IC (D versus C) = ($40 000 - $25 000)/($12 206 - $9137) = 4.89 and thus D > C; IB/IC (B versus D) = ($55 000 - $40 000)/($14 833 - $12 206) = 5.71 and thus B > D; and IB/IC (A versus B) = ($80 000 - $55 000)/($27 143 - $14 833) = 2.03 and thus A > B.

Using both the net equivalent uniform annual cost method and the incremental B/C ratio method, we conclude that

$$A > B > D > C \tag{3}$$

This is not the ranking that results from merely ordering on the basis of project B/C ratios.

In Appendix K of NCHRP Report 162, Alternative Methods of Evaluating Completed Highway Safety Programs, three phases of a program are identified: lighting, signing, and deslicking. Initial construction costs, operating costs, and benefits are given, and the PWOB, PWOC, and resulting B/C ratios are then computed. The results (1, pp. 59-60) are as follows:

Phase	PWOB ($)	PWOC ($)	B/C Ratio
Lighting	66 200	56 550	1.17
Signing	19 650	8 200	2.40
Deslicking	147 900	133 100	1.11

The analysis is correct as far as it goes. However, the authors then state, "Thus, the signing phase of the 1970 program is producing more benefits per dollar spent than the lighting and de-slicking phases. The comparison of these ratios gives top management an indication of the relative merits of each phase of the program" (1, p. 60). This statement is, at best, misleading.

If management's problem is to choose between three alternatives, then closer examination of the data indicates that the deslicking phase is in fact preferable. That is, net PW (lighting) = $66 200 - $56 550 = $9650; net PW (signing) = $19 650 - $8200 = $11 450; and net PW (deslicking) = $147 900 - $133 100 = $14 800.

But perhaps of greater interest in this example is the use of the phrase "more benefits per dollar spent." Does the benefit/cost ratio actually give a measure of economic efficiency in the sense of output (benefits) per unit of input (costs)? The answer is no, and for reasons that may not be sufficiently apparent, particularly because the magnitude of the benefit/cost ratio can be manipulated by judicious planning of certain economic consequences in the numerator or denominator of the ratio. Consider, for example, the following consequences of a proposed investment: PW of construction costs = $100 000, PW of maintenance costs = $50 000, and PW of user benefits = $200 000. There are two possible B/C ratios for this project, both of which are meaningful: (a) B/C = ($200 000 - $50 000)/$100 000 = 1.50 and (b) B/C = $200 000/($100 000 + $50 000) = 1.33. The same project is being dealt with in both cases. The benefit/cost ratio can be either 1.33 or 1.50. In each instance the ratio exceeds unity and the project is thus preferred to the do-nothing alternative.

If the above example represents one phase of a certain program and there is a second phase yielding a B/C ratio, say, of 1.40, does it follow that phase 1 yields "more benefits per dollar spent" than phase 2—or less? The answer, of course, is that the B/C ratio is not a measure of economic efficiency and should not be used to rank alternatives. The significance of an alternative's B/C ratio lies in its relation to unity; i.e., the ratio indicates whether the additional benefits (compared to the alternative) are in excess of the additional costs (compared to the alternative).

It should be noted at this point that, although the magnitude of the ratio can be altered by placing a factor either in the numerator or denominator, it is not possible to change a ratio from less than unity to more than unity. This conclusion—that the position of an economic consequence in either numerator or denominator is irrelevant—has been discussed in detail elsewhere (2).

Table 2 (slightly modified from the table in NCHRP Report 162) was designed to illustrate the objectives of benefit maximization and optimum improvement. It reflects the problem of selecting from among a number of mutually exclusive design alternatives at six problem locations with a budget limitation of $5000. Although only one design may be chosen for any given location, several locations (independent alternatives) may be selected within the overall budget constraint.

NCHRP Report 162 notes: "Under the optimum improvements objective, the candidate projects with the highest net benefit for each location are F-1, C-1, A-3, E-2, and D-2" (1, p. 8). There are six alternatives, including the do-nothing case. With the budget limitation of $5000, improvements A3, C1, and F1 provide the most net benefits as shown below.

Alternative	Initial Cost ($)	EUAC ($)	EUAB ($)	Net Benefits ($)
A3	2500	570	1170	600
C1	1000	228	700	472
F1	1500	342	1200	858
Total	5000	1140	3070	1930

The report also notes that, under the benefit maximization objective, the candidates from each location selected on the basis of highest B/C ratio are E1, A1, D1, F1, C1, and B2 and that improvements E1, A1, D1, F1, and C1 will use up the $5000 budget (1, p. 9).

Alternative	Initial Cost ($)	EUAC ($)	EUAB ($)	Net Benefits ($)	B/C Ratio
E1	500	114	500	386	4.39
A1	1000	228	800	572	3.51
D1	1000	228	800	572	3.51
F1	1500	342	1200	858	3.51
C1	1000	228	700	472	3.07
Total	5000	1140	4000	2860	

It is clear in this example that (a) preliminary ranking of mutually exclusive projects by net annual benefit (or net present worth) can lead to suboptimal global solutions when projects are combined and a capital budget limitation is imposed and (b) preliminary ranking on the basis of B/C ratios will lead to the optimal combination of projects.

One should not conclude, however, that ranking by benefit/cost is appropriate in all cases. There are two important reasons for this. First, the EUAC in this example consists solely of the initial cost, annualized by multiplying by the appropriate capital recovery factor. That is,

$$\text{EUAC} = (\text{initial cost}) \left\{ i(1+i)^n/[(1+i)^n - 1] \right\} \quad (4)$$

where i = interest rate used for compounding and N = project life. The denominators in all of the B/C ratios, therefore, are directly related to the input, i.e., the budget. Because the B/C ratios in this case are measures of economic efficiency and do reflect output (benefits) per unit of input (costs), the substitution of a higher efficiency alternative for a lower efficiency alternative will have the effect of increasing the efficiency of the overall budget. In other words, given the need for a $5000 budget package, it is desirable that the components maximize benefits per unit of cost.

In this case, because the denominators are "pure" in the sense that they account only for initial investment, the numerator-denominator issue may not appear relevant. But in real-world applications the denominator is likely to include economic consequences in addition to those dollars that are prospectively part of the agency's capital budget, e.g., annual costs of maintenance or operations or both, terminal salvage values, and construction costs incurred in time periods other than that for which the current budget has been established.

This point is illustrated in the following simplified example.

Alternative Location	Design	Benefits ($)	Maintenance Costs ($)	Initial Costs ($)
X	1	200	50	100
	2	140	0	100
Y	1	145	0	100

If B = benefits, K = maintenance costs, and C = initial costs, then

(B - K)/C	B/(C + K)	B - K - C ($)
1.50	1.33	50
1.40	1.40	40
1.45	1.45	45

There are two mutually exclusive design alternatives in location X; there is only one design alternative in location Y. The projects at locations X and Y are independent but, since only $100 has been budgeted, only one of the two can be selected.

The B/C ratios for these alternatives can be computed by including the maintenance costs (K) in either the numerators or denominators. If the maintenance costs are considered to be negative benefits, then the objective of benefit maximization would lead to the selection of X1. If the maintenance costs are included in the denominator as a cost, this objective leads to the selection of Y1. There should be no ambiguity in this example, however: X1 is preferred to Y1, and Y1 is preferred to X2. This may be seen by examining the net present worths of the three alternatives.

The second reason for using caution in ranking projects by B/C ratios is that such ranking can lead to operational difficulties. In the example given in Table 3, there are two locations, A and B, and two mutually exclusive design options at each location. There are eight possible combinations or budget alternatives (2^3). The maximization objective would lead to the selection of projects A1 and B1 at a total cost of $200. But if $300 were available, then A2 and B1 would be the proper combination. How would the correct solution be identified if the analyst was instructed to select, in each case, the alternative having the highest B/C ratio?

This example is an illustration of the preselection problem (3). One cannot determine the global optimum simply by combining locally optimal solutions. That is, the net benefits of an entire investment program cannot be maximized, with budget constraints, merely by aggregating design alternatives that appear optimal with respect to their mutually exclusive alternatives. All combinations of programs, or budget packages, must be identified and the optimal program selected from this set. There can be a large number of such alternative programs. Fortunately, however, some efficient algorithms have been developed through dynamic and linear programming.

SIGNIFICANCE OF COST/EFFECTIVENESS RATIOS

It is not always possible to evaluate all of the consequences of a proposed investment in economic terms. Evaluations that treat both economic and noneconomic values are referred to as cost-effectiveness analyses; in these evaluations the monetary consequences are costs and the nonmonetary consequences are effectiveness.

NCHRP Report 162 defines cost-effectiveness as "a comparison of cost to achievement of a given unit of effect. Cost/effectiveness is similar to benefit/cost ratio. It is the average cost per unit of benefit" (2, p. 43). A procedure is prescribed in which the analyst is instructed to calculate cost-effectiveness "by dividing the equivalent uniform annual cost by the estimated annual reductions in the unit of effectiveness selected." The next step is to array "the improvements by cost/effectiveness ratio, lowest to highest" (2, p. 44). This view of cost-effectiveness analyses is incorrect. Except in relatively rare situations, the magnitude of the cost/effectiveness ratio has no relevance to rational decision making.

The example used here to demonstrate this point is drawn from NCHRP Report 162 (1). Four mutually exclusive alternative improvements and their cost, effectiveness, and cost-effectiveness per accident reduced are considered, as follows:

Improvement	Cost (EUAC) ($)	Effectiveness (accidents reduced per year)	Cost-Effectiveness (per accident reduced) ($)
A	27 150	32	848
B	14 850	22	675
C	9 150	10	915
D	12 200	16	762

According to the report (1), the order of preference for these alternatives is B > D > A > C.

The problem is shown in Figure 1. Note that the C/E ratio is the reciprocal of the effectiveness/cost (E/C) ratio, and that minimum C/E is equivalent to maximum E/C. Also note that the slopes of the lines drawn from the origin to each of the four points (A, B, C, and D) are the E/C ratios for the four alternatives. Again, the report asserts that improvement A is preferred to improvement C because the C/E ratio for the former is less than that for the latter; i.e., A > C because C/E (A) < C/E (C). If the principle is accepted that only differences between alternatives are relevant, these differences should be examined more closely, as follows:

Alternative	Cost (EUAC) ($)	Effectiveness (accidents reduced per year)
A	27 150	32
C	9 150	10
Difference	18 000	22

The choice between A and C depends entirely on the relation between the additional $18 000 expenditure and the additional 22 accidents/year reduced. Specifically, if the utility of an additional 22 accidents reduced is in excess of the utility of saving $18 000, then the more expensive alternative (A) is preferred. Otherwise, the less

Table 3. Economic analysis of independent and mutually exclusive alternatives.

Alternative	Location	Design	Initial Cost ($)	PWOB ($)	Net Benefits ($)	B/C Ratio
1	A	1	100	150	50	1.50
2	A	2	200	280	80	1.40
3	B	1	100	160	60	1.60
4	B	2	200	240	40	1.20
5	A1 + B1		200	310	110	1.05
6	A1 + B2		300	390	30	1.30
7	A2 + B1		300	440	140	1.47
8	A2 + B2		400	520	120	1.30

Figure 1. Effectiveness versus cost for sample problem.

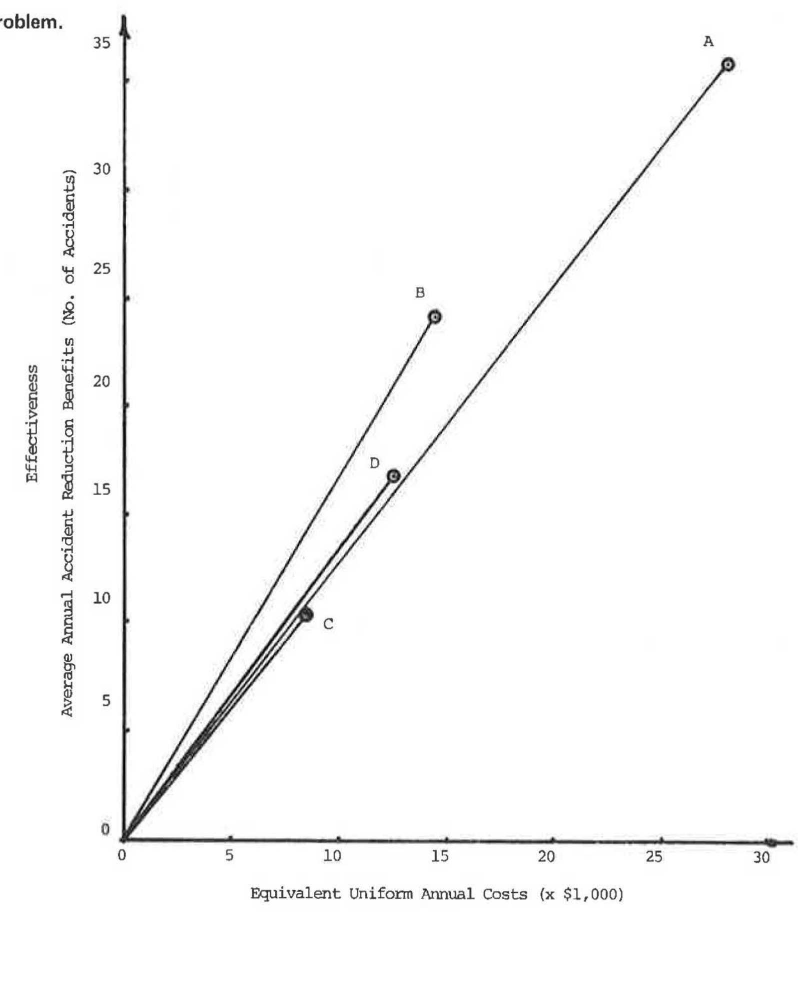
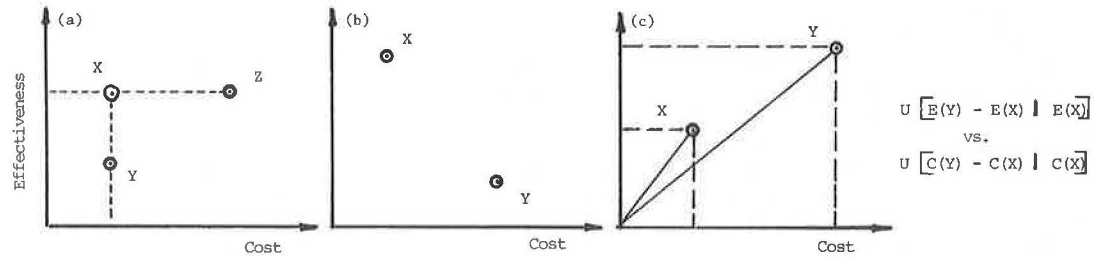


Figure 2. Differences in cost-effectiveness between a pair of alternatives: (a) equal effectiveness (X and Z) and equal cost (X and Y), (b) dominance (X > Y), and (c) no dominance.



expensive alternative (C) should be preferred. In the absence of the relevant utility function, i.e., without knowing anything about the trade-off between costs and accidents reduced, the alternatives cannot be ordered and no preferences can be determined.

The above argument relates to only one comparison (A versus C) in the example given in NCHRP Report 162 (1). The same argument can be applied to any of the six comparisons (A versus B, A versus C, A versus D, B versus C, B versus D, or C versus D) given in that example.

Conditions are detailed below and shown in Figure 2 in which alternatives cannot be rank ordered on the basis of their C/E ratios alone because effectiveness and cost are unequal between alternatives (x) and (y) or no dominance exists:

$$I(x) = E(x)/C(x) \quad (5)$$

$$I(y) = E(y)/C(y) \quad (6)$$

where I = index of cost-effectiveness. The following decisions can be made by using C/E ratios [I(x)] and [I(y)]:

1. Given $E(x) = E(y)$ or $C(x) = C(y)$, if $I(x) > I(y)$, then $x > y$.
2. Given $E(x) \geq E(y)$ and $C(x) \leq C(y)$, there is dominance and $x > y$.
3. Given $E(x) \geq E(y)$ and $C(x) \leq C(y)$, or $E(x) \leq E(y)$ and $C(x) \leq C(y)$, if I(x) and I(y) may be computed but have no decision-making significance, then no conclusions may be inferred.

There are only three conditions under which ranking by C/E or E/C ratios is appropriate.

1. Effectiveness for all alternatives is equal. Then ranking by ratios is equivalent to ranking on the basis of decreasing costs.
2. Costs for all alternatives are equal. Then ranking by ratios is equivalent to ranking on the basis of increasing effectiveness.
3. Dominance obtains. Consider any pair of alternatives, x and y. If $E(x) \geq E(y)$ and $C(x) \leq C(y)$, then alternative x is said to dominate alternative y. Under these conditions, of course, $E/C\ (x) \geq E/C\ (y)$ and likewise $C/E\ (x) \leq C/E\ (y)$.

Unfortunately, in the real world these conditions rarely occur. The usual case is one in which an increase in effectiveness is brought about by an increase in project or program costs. When this occurs, it is not possible to establish a unique, unambiguous ordering of alternatives without knowledge of the utility function relating cost and effectiveness.

SUMMARY AND CONCLUSIONS

NCHRP Report 162 is intended to affect significantly the methods and procedures used by public agencies to evaluate improvements in highway safety. Unfortunately, several key concepts presented in the report are critically defective and adherence to these concepts could lead to misallocation of resources. The serious problems in NCHRP Report 162 appear to result from failure to consider properly the following principles.

1. B/C ratios cannot, in general, be used to rank order a set of competing investment alternatives. Only incremental B/C ratios are significant; that is, given two alternatives, x and y, the appropriate statistic is $IBC = [B\ (y) - B\ (x)]/[C\ (y) - C\ (x)]$.
2. The magnitude of the ratio is relevant only in regard to whether or not it exceeds unity. That is, y is preferred to x if and only if (a) $IBC > 1.0$, if $C\ (y) - C\ (x) > 0$; or (b) $IBC < 1.0$, if $C\ (y) - C\ (x) > 0$. Otherwise, y is not preferred to x.
3. The magnitude of the ratio can be modified by moving consequences from numerator to denominator. However, the result of the relevance test above cannot be changed by this modification.
4. When effectiveness and costs are unequal between alternatives, and where no dominance exists, alternatives cannot be rank ordered on the basis of their respective C/E ratios alone.

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