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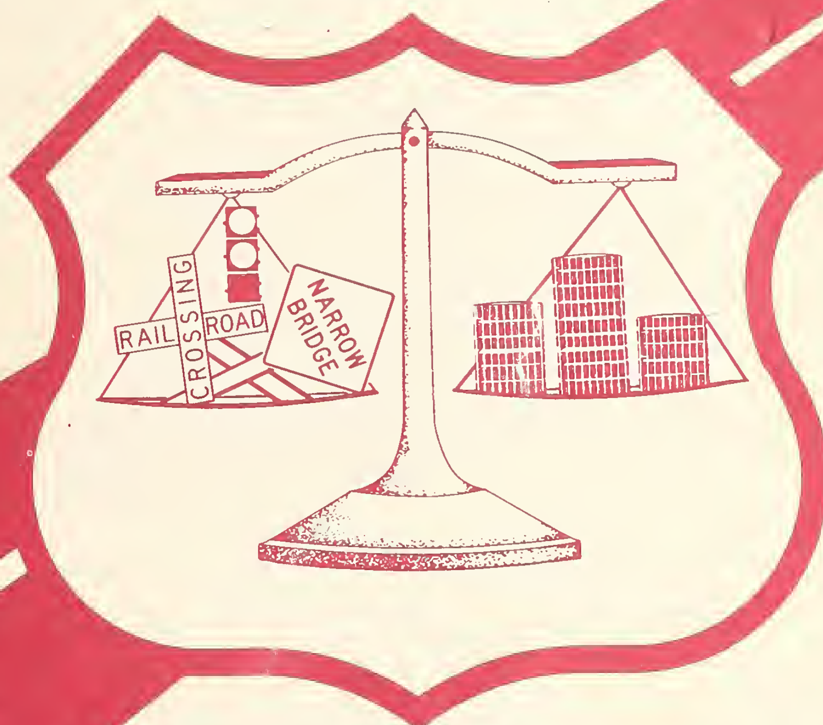
SSESSMENT OF TECHNIQUES FOR COST-EFFECTIVENESS
HIGHWAY ACCIDENT COUNTERMEASURES

January 1979
Final Report



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Washington, D.C. 20590

FOREWORD

This report presents improved cost-effectiveness techniques for evaluating highway safety programs. Three techniques are recommended for use in allocating safety funds: incremental benefit-cost with the improved ranking algorithm; dynamic programming; and integer programming. The report should be of interest to traffic engineers and researchers involved in evaluation of highway safety programs.

Research on evaluation methodology is included in the Federally Coordinated Program of Highway Research and Development as Task 2 of Project 1X, "Highway Safety Program Effectiveness Evaluation." Julie A. Fee is the Project Manager.

One copy is being distributed directly to each regional and division office. Additional copies are available from the National Technical Information Service (NTIS) U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

Charles F. Scheffey

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

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16. Abstract
Improved cost-effectiveness techniques are developed for evaluating highway safety programs. These improved techniques include: better methods of determining accident costs; statistical procedures for calculating accident costs; consistent system for evaluating accident cost and countermeasure effectiveness; and improved incremental benefit-cost algorithm for ranking safety projects. In addition to developing improved cost-effectiveness techniques the report reviews selected accident countermeasure studies and provides a critique of current procedures for evaluating safety programs. Three techniques are recommended for use in allocating safety funds: incremental benefit-cost, with improved algorithm; dynamic programming; and integer programming.

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PREFACE

Over the past decade, several highway safety acts have provided individual states with federal funds for their highway safety programs. Undoubtedly, these expenditures have made highways safer for motorists by decreasing accident losses. While many improvements in the highway environment have been made, it is difficult to specify which of the many programs undertaken over the years have produced these safety benefits, and to what extent particular countermeasures reduce accident losses.

There is no question that roadways with good lighting, well-designed curves, cushioned abutments, and other such improvements are beneficial to the driving public. But there remains much to be learned before funds can be allocated among various competing countermeasures in such a way that maximum possible benefits are obtained.

Some specific questions that need to be answered are:

1. Quantitatively, how effective are specific countermeasures in reducing fatal, injury-producing, and property damage only accidents?
2. How much do these countermeasures cost?
3. How long do different countermeasures last?
4. How much does it cost to operate, maintain and repair different countermeasures?
5. How long does it take to implement one of these countermeasures?
6. To what degree do two or more countermeasures interact, and thus partially cancel or enhance each other's effect?
7. How should funds be allocated among several competing countermeasures?
8. After a particular countermeasure has been implemented, how is the priority of the remaining, unfunded countermeasures altered?

Without valid answers to these questions, there is no guarantee (regardless of past success) that public funds are being allocated optimally, i.e., that the maximum reduction in deaths, injuries, and property damage per dollar spent is being achieved.

The objective of the research documented in this report is to assess the accuracy, sensitivity, and practical use of cost-effectiveness analysis methods for evaluating highway accident countermeasures within the purview of the Federal Highway Administration's responsibilities. Three interim reports [1, 2, 3], published over the course of this project, have documented three of the four phases of the research. Task A analyzed currently available techniques of cost-effectiveness analysis in terms of their applications to the planning and programming of highway safety improvements falling under FHWA responsibility. Task B identified and evaluated the limitations of cost-effectiveness methods in current use in meeting the planning and programming needs of highway agencies. Visits were made to several state highway departments to determine first-hand what methods are being used to allocate highway safety funds. These interviews also helped to determine the nature of data used in these agencies' cost-effectiveness analyses, which was dealt with in Task C. This report defined the scope and quality of data bases needed for achieving valid results from cost-effectiveness analyses and evaluated the quality and amount of data currently available to highway agencies for such analyses. The results of Tasks A, B, and C and the fourth task, Task D, are contained in this final report. The purpose of Task D is to recommend specific cost-effectiveness analysis techniques for use by highway agencies.

This report contains five parts. Part One contains much of the material from Task A, classification and discussion of available methods of cost-effectiveness analysis. Some of these available methods are recommended for further development for possible use by highway agencies. Part Two is based primarily on Task B. It reviews federal highway safety activities and current practices of state and local governments with respect to their highway safety programs. Part Three contains more material from Task B, evaluating cost-effectiveness submodels with regard to accident location identification, estimation of countermeasure effectiveness, accident costs, other highway user benefits, and costs of countermeasures. Part Four discusses methods of determining countermeasure effectiveness and presents a detailed review of the effectiveness and cost of each of seven specific countermeasures, from Task C. Part Five, which includes the

results of Task D, gives general recommendations regarding cost-effectiveness analysis and recommends specific cost-effectiveness methods.

The authors wish to acknowledge the generous assistance of several individuals who aided in the formulation of this report:

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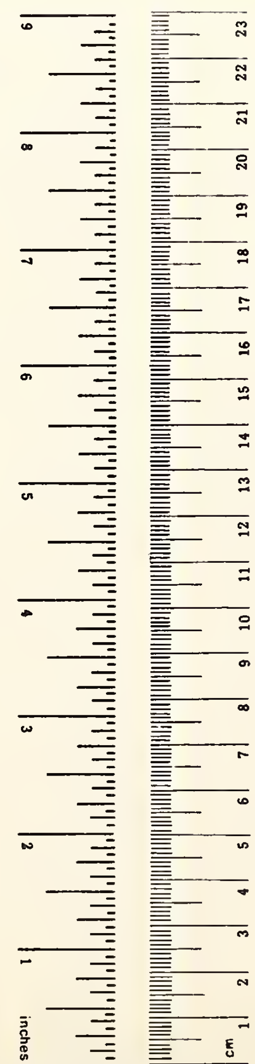
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

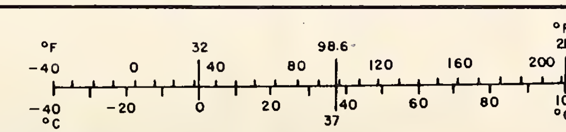
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yerds	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	squere inchss	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	scres	0.4	hectares	he
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yerds	yd^2
km^2	square kilometers	0.4	square miles	mi^2
he	hecteres (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gellons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius tempereture	9/5 (then add 32)	Fahrenheit temperature	°F



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PART ONE: COST-EFFECTIVENESS METHODS

I. Classification of Methods

Definition of Cost-Effectiveness Analysis

The purpose of a cost-effectiveness analysis, as the term is used in this discussion, is two-fold. First, it must set forth a method of comparing alternative highway accident countermeasure at specific highway locations. Second, it is meant to provide a method to simultaneously determine which locations should be improved and which alternative should be implemented at each chosen location.

This objective does not include the method of choosing the locations that will be considered nor does it specify the method to be used in determining which alternatives will be considered at each location. Although this definition omits from the cost-effectiveness analysis the method of choosing candidate locations, it is not intended to imply that there is not a relationship between the method used to choose locations as candidates for improvement and the method used to evaluate candidate locations. Indeed, one of the principle difficulties in evaluating accident countermeasures is associated with clearly defining this relationship. This problem will be discussed in detail later, but this discussion of cost-effectiveness methods will assume that both the locations for countermeasures and alternative countermeasures at each location are given.

Classifications of Method of Analysis

Several authors have categorized decision-making techniques according to different attributes. These classifications are of interest in this report since one of the study objectives is not only to consider methods that currently are used in highway safety evaluations but to also consider other methods that show promise for future use. Before these categories of methods are discussed, a short description of terminology is given.

The terms "cost-effectiveness analysis" and "cost-effectiveness technique" often have been used interchangeably and sometimes with different meanings. Used in its broadest sense, cost-effectiveness analysis sometimes is used to denote a systems analysis whereby information of the effectiveness and cost of alternative systems are used together with specified decision making rules to choose among alternatives. In this report the terms "cost-effectiveness analysis," "systems analysis," "decision analysis," and "cost-effectiveness techniques" all refer to any comprehensive analysis used for comparing and choosing among alternative courses of action. Defined in this way, these terms are intended to be interchangeable and sufficiently comprehensive to encompass all specific methods of analysis.

The term "cost-effectiveness method" is used in a more restricted sense in this paper. This term denotes specific types of analysis whereby the effectiveness of each of several alternatives is measured in physical units. Certain decision rules are applied to the respective cost and physical effectiveness of each alternative in order to reduce the number of alternatives under consideration by the decision-maker.

To further clarify these definitions, it is perhaps instructive to compare them with definitions given by Quade [4], who explained the distinction between systems analysis and cost-effectiveness analysis in the following way:

> As commonly used in the defense community, the phrase "systems analysis" refers to formal inquiries intended to advise a decisionmaker on the policy choices involved in such matters as weapons development, force posture design or the determination of strategic objectives.
>
> Each such [systems] study involves at one stage a comparison of alternative courses of action in terms of their effectiveness and cost. When, as often happens, this stage requires major attention, the entire study is sometimes called a cost-effectiveness analysis.

Thus, the definitions proposed for this study agree with those by Quade in allowing for the interchangeable use of cost-effectiveness analysis and systems analysis.

De Neufville and Marks [5] provide a simple typology for classifying methods of analysis based on several characteristics: linearity, inclusion of risk, dimensionality, and number of decision-makers. They use these characteristics to distinguish among five evaluation methods: (1) standard benefit-cost analysis, (2) consumer's surplus, (3) decision analysis,

(4) multiattribute analysis, and (5) multiobjective evaluation and negotiation. Almost all evaluations of highway accident countermeasures have used the first method, standard benefit-cost analysis, although some states have augmented this analysis with algorithms (dynamic programming) for selecting among alternatives.

A more comprehensive approach to classifying analysis techniques is given by MacCrimmon [6]. He uses several critiera, such as structure of the model, compensation, and preference inputs to classify multiple objective/multiple attribute decision models, as shown in Figure 1. He further develops criteria for specifying the model that should be used in different situations, as shown in Figure 2.

Answering the questions in Figure 2 may provide only a partial solution to a specific problem; it may be possible to combine components from different models to provide a better, eclectic procedure. Another paper by MacCrimmon [7] grouped methods by whether the analysis reduced the attributes of alternatives to a single dimension.

Specification of Methods of Analysis for Highway Safety

It is instructive to answer the questions posed in Figure 2 to determine which methods are most relevant to evaluating highway accident countermeasures. These questions and the answers usually given to them in highway safety are:

1. Is the purpose normative rather than descriptive? Yes.
2. Will a direct assessment of preferences be valid and reliable? Yes.
3. Are there multiple decision-makers with conflicting preferences? No.
4. Will the results of implementing the alternatives be determined by only the best (or worst) attributes values? No.
5. Will the alternatives be designed rather than chosen from a list? No (usually).

With the above answers normally being given to the questions posed, the method of analysis chosen for evaluating safety programs usually is one of those methods in the group in the lower right corner in Figure 2.

A. Weighting Methods

1. Inferred preferences
    a. Linear regression
    b. Analysis of variance
    c. Quasi-linear regression

2. Directly assessed preferences: general aggregation
    a. Trade-offs
    b. Simple additive weighting
    c. Hierarchical additive weighting
    d. Quasi-additive weighting

3. Directly assessed preferences: specialized aggregation
    a. Maximin
    b. Maximax

B. Sequential Elimination Methods

1. Alternative versus standard: comparison across attributes
    a. Disjunctive and conjunctive constraints

2. Alternative versus alternative: comparison across attributes
    a. Dominance

3. Alternative versus alternative: comparison across alternatives
    a. Lexicography
    b. Elimination by aspects

C. Mathematical Programming Methods

1. Global objective function
    a. Linear programming

2. Goals in constraints
    a. Goal programming

3. Local objectives: interactive
    a. Interactive, multi-criterion programming

D. Spatial Proximity Methods

1. Iso-preference graphs
    a. Indifference map

2. Ideal points
    a. Multidimensional, nonmetric scaling

3. Graphical preferences
    a. Graphical overlays

Figure 1. Multiple Objective/Multiple Attribute Decision Methods

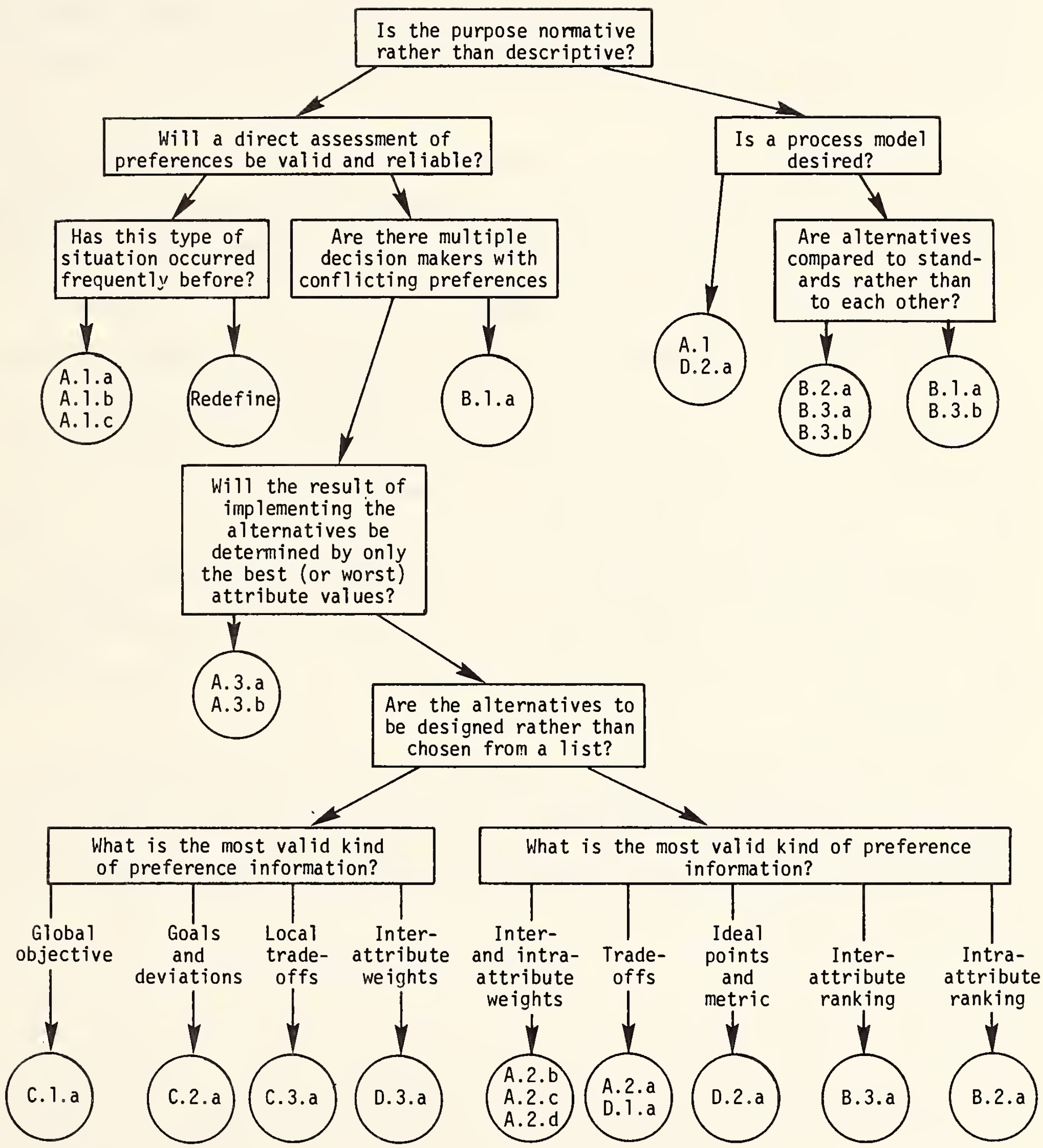


Figure 2. Method Specification Chart

However, those methods in the group in the lower left corner either have been used or can be used.

The principle criterion used to choose among methods in these groups is the choice of the most valid kind of preference information. The most commonly used method is Method A.2.b., "directly assessed preferences: general aggregation, with *simple additive weighting*." Weights are assigned to different measures of effectiveness and costs and these are added together and used in formulas.

Other methods in the A.2 category also are used to compare highway alternatives but have not been as widely used as Method A.2.b. For example, Method A.2.c., using "hierarchial additive weighting," has been widely used by state highway agencies in the form of highway sufficiency ratings.

Other methods that have been widely discussed and often are used to determine the best safety alternative at a specific highway location are the "Sequential Elimination Methods." These methods are referred to in this paper as "the cost-effectiveness methods, *without* weighting of attributes." In some ways, these methods are similar to Method A.2.a., which uses trade-offs, and to Method D.1.a., which uses indifference maps. By stressing comparison of alternatives or attributes on a one-on-one basis, these methods are especially useful in comparing a small number of similar alternatives.

The other principle group of methods that is of primary interest in this study is Group C, "Mathematical Programming Methods." The methods in Group D, "Spatial Proximity Methods," are of less interest and are not discussed in this paper.

II. DISCUSSION OF METHODS OF COST-EFFECTIVENESS ANALYSIS

For methods of cost-effectiveness analysis currently being used in highway safety programs to be evaluated in a meaningful and thorough way, they must be considered within the scheme of the state of the art in cost-effectiveness analysis. This chapter provides such a review, critically discussing several methods of analysis applicable to the planning and programming of highway safety improvement measures in the purview of FHWA program responsibilities.

The methods considered most applicable to highway safety are discussed in detail in this section, in the following order:

1. Weighting methods, with emphasis on simple additive weighting,
2. Sequential elimination methods, with emphasis on the cost-effectiveness methods, and
3. Mathematical programming methods.

Weighting Methods

Weighting methods, the methods most commonly used for evaluating highway safety alternatives, all have the following characteristics [6, pp. 24-25]:

1. A set of available alternatives with specified attributes and attributes values,
2. A process comparing attributes by obtaining numerical scalings of attributes values (intro-attribute preferences),
3. A well-specified objective function for aggregating the preference into a single number for each alternative
4. A rule for choosing the alternative (or rating the alternatives) on the basis of the highest weight.

MacCrimmon [6] discusses nine weighting methods divided into three main subcategories. Two of these subcategories (A.1.X and A.3.X) are not considered very useful with respect to this study and so are discussed only briefly before turning to the most useful subcategory.

Inferred Preferences

The first subcategory of weighting methods involved inferred preferences, where "...the preferences of the decision-maker are inferred from past choices, rather than being obtained by direct query and are inputs to a general linear statistical model" [6, p. 25]. Use of one of these methods in safety evaluations would implicitly assume that past decisions regarding safety have been the correct ones. As such, the model developed would be descriptive of past decisions rather than being a guide to future decisions. While a research study using an inferred preference method might yield interesting information about what factors have actually been influencing decisions, this research is aimed towards developing a prescriptive or normative model.

While it is not believed that weighting methods using inferred preferences are among the better methods for comparing highway accident countermeasures, such methods are quite useful in determining weights to be used in other methods. For example, weights for time savings and lives saved have been developed using the "willingness-to-pay" method of analysis, a weighting method involving inferred preferences based on observed actions of motorists. This particular use of inferred or revealed preferences has been critical to developing values for benefit-cost analysis, a topic discussed more fully later in this report.

Directly Assessed Preferences: Specialized Aggregation

In this subcategory, the decision-maker explicitly states his preferences, and specific attributes are taken to represent the whole alternative (a zero-end aggregation). "Maximin" and "maximax," the two methods in this subcategory, are of questionable use in highway safety analysis since they do not meet the criterion of considering all attributes of alternatives. Nevertheless, it should be recognized that methods of evaluating highway safety projects, methods that use criterion of maximizing the expected reduction in deaths (or deaths plus injuries) for a given budget, can be regarded as a "maximax" strategy. These methods also can be regarded as a simple cost-effectiveness method and in this study are considered to be a subcase of simple additive weighting with nonmonetary weights discussed later.

Directly Assessed Preferences: General Aggregation

This subcategory of weighting methods includes most of the methods used to evaluate highway alternatives. The four methods discussed by MacCrimmon in this subcategory are trade-offs, simple additive weighting, hierarchical additive weighting, and quasi-additive weighting.

Trade-offs

Trade-off analysis is only of limited interest since it is difficult to use if there are very many alternatives. It may be useful, however, in detailed analyses of some types of accident countermeasures. For example, it is of interest to known the trade-offs between, say, reducing fatal accidents but increasing total and injury accidents, given some proposed countermeasure. This trade-off is usually involved when, for example, a barrier is placed in a median to reduce head-on accidents. A result similar to trade-off analysis can be obtained by performing a sensitivity analysis with the simple-additive-weighting method.

Simple Additive Weighting

The simple-additive-weighting method is a method that assigns weights to different, independent attributes of alternatives. In public decision making, these attributes usually are referred to as measures of effectiveness (benefits) and costs and are often expressed in formulas. There are two principal subcategories of simple additive weighting, those that use monetary weights and those that use nonmonetary weights, e.g., utility.

Monetary Weights

There are several methods within the monetary-weighting subcategory of simple additive weighting: (1) benefit-cost methods, including the benefit-cost ratio method, the net benefit method, and the incremental benefit-cost method, (2) the total-cost method, (3) the payback-period method, and (4) the rate-of-return method. Other research, most notably Appendix F of NCHRP Report 162 [8], has given formulas for and discussions of all of these methods; no attempt is made here to repeat that work. The emphasis in this study is on benefit-cost analysis, especially the more recent versions of this method, since it is generally agreed that this is the preferable method in this subcategory.

Benefit-Cost Methods. Benefit-cost methods of analysis [9] usually entail the use of a benefit-cost ratio, which is the ratio of the present worth of benefits (stated in dollar terms), taken over the life of a project, to the present worth of initial capital costs and future costs less the present worth of initial capital costs and future costs less the present worth of the salvage value. The project with the largest benefit-cost ratio is considered to be the best project.

The benefit-cost method has been used extensively in evaluating water resource projects [10] and has also been used in evaluation of projects dealing with transportation, land usage, health, and education, according to Prest and Turvey [11]. Among the questions which they emphasize as being important to benefit-cost formulations are:

1. Which costs and which benefits are to be included?
2. How are they to be valued?
3. At what interest rate are they to be discounted?
4. What are the relevant constraints?

Prest and Turvey emphasize that there are many different viewpoints regarding benefit-cost analysis. As an example of the pessimistic viewpoint, they quote Arthur Smithies' two conclusions: "First, judgment plays such an important role in the estimation of benefit-cost ratios that little significance can be attached to the precise numerical results obtained ... Second, competition, is likely to drive the agencies [competing for limited funds] toward increasingly optimistic estimates; and far from resolving the organizational difficulties, computation of benefit-cost ratios may in fact make them worse" [11, p. 200]. In this connection, they conclude [11, p. 203] that

> The case for using cost-benefit analysis is strengthened, not weakened, if its limitations are openly recognized and indeed emphasized. It is no good expecting this technique, at any rate in its present form, to be of any use if a project is so large as to alter the whole complex of relative prices and outputs in a country. It is no good expecting those fields in which benefits are widely diffused, and in which there are manifest divergences between accounting and economic costs or benefits, to be as cultivable as others. Nor is it realistic

> to expect that comparisons between projects in entirely different branches of economic activity are likely to be as meaningful or fruitful as those between projects in the same branch. The technique is more useful in the public utility area than in the social-services are of government.

Of course, many of their comments regarding benefit-cost analysis apply to other methods of analysis as well.

In the highway field, the American Association of State Highway Officials has promoted the use of benefit-cost analysis for project/design-level determination, in their publication commonly known as the Red Book [12], which was originally published in 1952 and updated in 1959. In situations where there are several alternatives, the Red Book recommends that a benefit-cost ratio be used to compare each of these alternatives to the existing condition. The Red Book further says that in some situations there may be advantages in calculating what is called a "second benefit ratio." AASHTO says that the benefit-cost analysis recommended by them in the Red Book "...is not an economic analysis in the broad sense and cannot be used as such. It is an analysis of the relation of road user benefits to capital (and maintenance) costs. It cannot be used to determine the worth of a proposed investment but it can be of great assistance in comparing alternates in location and design for a proposed improvement, and, when used with other factors, can be of assistance in determining priorities of several proposed improvements." The benefits which are considered in the Red Book are changes in road user costs, specifically reductions in travel time, vehicle operating costs, accidents, and discomfort. No specific methods for predicting these reductions are given.

The Stanford Research Institute recently has completely revised the Red Book [13]. This revision is of considerable interest since it probably will be widely used for at least the next decade in conducting benefit-cost analyses of highway alternatives. This revised Red Book gives the decision rule for selecting the set of projects that yields the greatest net present value (NPV), as calculated using the following formula:

$$NPV = \sum_{j=1}^{n} \frac{(B_j - C_j)}{(1 + i)^j} + \frac{R}{(1 + i)^n} \qquad (1)$$

where: B_j = the benefits in year j,

C_j = the costs in year j,

R_n = the residual (or salvage) value at the end of year n,

n = the length of the analysis, and

i = the discount rate.

The revised Red Book further recommends the following formula for calculating benefit-cost ratios [13, p. C-7]:

$$BC = \frac{PV(\Delta U)}{PV(\Delta I) + PV(\Delta M) - PV(\Delta R)} \tag{2}$$

where: PV = present value of the indicated amount,

ΔU = reduction in highway or transit user costs due to the investment,

ΔM = change in annual maintenance, operating, and administrative cost due to investment,

ΔR = change in residual value, and

ΔI = change in investment cost.

Formula 2 is recommended for either highway or transit investments whenever there is a budget constraint. If projects are independent (choosing one project does not preclude the selction of another project at the same time), then selecting projects in declining order of B/C ratio will maximize the net present value of benefits for the available budget. If projects are nonindependent, then formula 2 can be used to select projects if [13, p. C-5]:

1. Each increment of expenditure is compared with the additional benefit associated with that cost increment, starting with the lowest-cost alternative at each location, and
2. At each location, a lower-cost alternative is displaced from the accepted list whenever a higher-cost alternative at that location is accepted.

The revised Red Book is somewhat similar to an earlier version of benefit-cost analysis, reported in NCHRP Report 133 [14], which "...updates, extends, and largely replaces (except for the analysis of queueing, air pollution, and noise)." The authors also say that the revised Red Book:

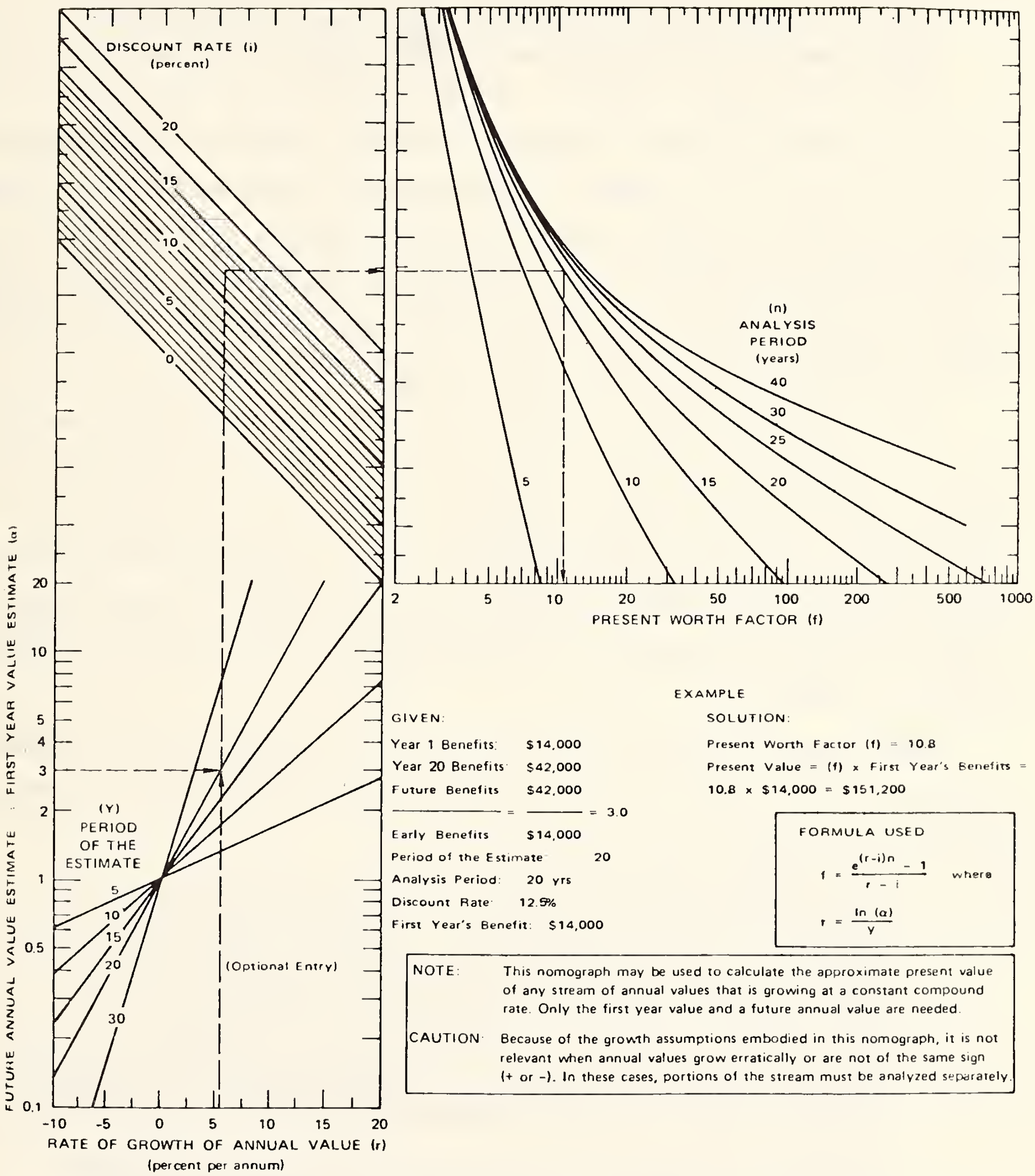


Figure 3. Nomograph for calculating present value from two annual value estimates

Source: Dudley G. Anderson, et al., A Manual for User Benefit Analysis of Highway and Bus Transit Improvements, Final Report, NCHRP Project 2-12/1, February 1977.

...provides current cost factors and short cut procedures for dealing with many of the types of problems considered in Robley Winfrey's *Economic Analysis for Highways* [15] in NCHRP Report 96, *Strategies for Evaluation of Alternative Transportation Plans* [16]; in NCHRP Report 122, *Summary and Evaluation of Economic Consequences of Highway Improvements* [17], and in NCHRP Report 146, *Comparative Analysis of Alternative Multimodal Passenger Transportation Systems* [18].

The revised Red Book gives only limited guidance on predicting accidents; its "method" is based on using average accident rates on different types of highways in California to predict accident costs for different accident types, severities, and locations of occurrence. Costs of accidents also are based on a California study, which in turn was based on the Wilbur Smith study of accident costs in the Washington, D.C. area.

A version of benefit-cost analysis similar to that of the revised Red Book is the Highway Economic Evaluation Model (HEEM), a computerized benefit-cost approach which is currently being used in California and Texas [19]. Like the revised Red Book, HEEM is mainly intended to be used in comparing major highway alternatives, either new or reconstructed; hence the HEEM documentation considers only accident rates for different types of highways.

From the viewpoint of considering safety projects, the principal weaknesses of the benefit-cost methods of both the revised Red Book and HEEM for comparing highway alternatives are:

1. Although the formulas for benefit-cost ratios and incremental benefit-cost ratios are generally correct, no algorithm is given for efficiently comparing large numbers of projects. Also, further discussion of the use of incremental benefit-cost ratios probably would be helpful.
2. Discussion of techniques for predicting reductions in accidents is basically limited to a presentation of statewide accident rates for major design variations.
3. Although different values are given for accident costs, there is no detailed discussion of the methods used to derive these different costs or of the implicit assumptions being made when different methods are used.
4. Increases in highway accident rates (and other motorist costs) during reconstruction of highways are ignored.
5. Changes in measures of effectiveness other than travel time, vehicle operating costs, and accidents need to be

considered in more detail--especially changes in comfort and pollution levels.

Although the above criticisms should be considered in improving the revised Red Book and HEEM, it should be emphasized that these versions represent the most advanced state of the art of benefit-cost analysis for evaluating major highway improvements. As such, they provide a good starting point for this study, and correction for the limitations listed above would provide an acceptable benefit-cost method for this study.

In addition to the above benefit-cost models developed for comparing major highway alternatives, there are several versions of benefit-cost analysis that have been proposed for use in evaluating specific highway accident countermeasures. Perhaps the most noteworthy studies in this area are NCHRP Report 162 [8], which was mentioned previously, and a study by Fleischer [20].

NCHRP Report 162 provides a survey of most of the methods and submodels used in evaluating highway accident countermeasures. It is a valuable reference source and good starting point for this study. Nevertheless, the analysis in NCHRP Report 162, like that in the revised Red Book and HEEM, can be improved in several ways. Specifically, the shortcomings listed previously for the other two versions of benefit-cost analysis are found in NCHRP Report 162.

Like the revised Red Book, NCHRP Report 162 recommends the use of the benefit-cost ratio method for evaluating independent alternatives, in what is called the "AASHTO benefit-cost ratio convention." This benefit-cost ratio is similar to that in the revised Red Book, and the annual maintenance and operating costs are added into the denominator instead of being subtracted from the numerator [8, pp. 41-42]. The various aspects of this convention are discussed by Winfrey [15, pp. 148-150] and Fleischer [21].

For evaluating non-independent projects, NCHRP Report 162 recommends the net annual benefit method, where net annual benefits are equal to annual benefits minus annual costs [8, pp. 44-45]. The decision rule for choosing the optimal alternative from two or more mutually exclusive alternatives is that "...the alternative with the largest, positive net annual benefit is the best." This decision rule is appropriate for unconstrained budgets but often will be inappropriate for constrained budgets, as will be discussed later. This is especially important since it often will lead to nonoptimal decisions when alternatives are nonindependent.

The discussion of incremental benefit-cost analysis in NCHRP Report 162 is lacking in that the use of incremental benefit-cost ratios is discussed only in terms of determining whether extra increments of expenditure are justified in a particular location. No mention is made of how incremental benefit-cost ratios can be used to simultaneously determine the optimum level of expenditure at multiple locations in a complete highway safety program. The only decision rule given is that expenditure on a more expensive alternative is justified if its incremental benefit-cost ratio is greater than one, when compared with the next least costly alternative [8, p. 46]. This rule holds only if there is no budget constraint that limits the safety program.

In a recent Transportation Research Board presentation, Fleischer provides an illuminating critique of NCHRP Report 162, where he partially corrects some of the errors mentioned previously. However, his discussion is still lacking in several respects:

1. He indicates that the benefit-cost ratio "...is *not* a measure of economic efficiency and should not be used to rank alternatives. The significance of an alternatives ratio lies in its relationship to unit" [22, p. 10]. This statement is demonstrably incorrect; the benefit-cost ratio *is* a measure of the project's economic efficiency and *should* be used to rank alternatives.
2. He indicates that certain costs, namely recurring annual costs, may be included in either the numerator or the denominator, apparently at the whim of the decision-maker [19, pp. 10-11]. Whether this cost is included in the numerator or denominator depends upon whether only initial costs are the relevant constraint, in which case recurring costs are included in the numerator, or whether present value of all highway costs is the constrained variable, in which case all highway costs appear in the denominator. Only if funds are unconstrained is his conclusion correct that "...the position of an economic consequence in either numerator or denominator is irrelevant..." [22, p. 11].

It should be pointed out that Fleischer's conclusions are correct if one assumes an unlimited budget, i.e., funds are available for expenditure on all projects with benefit-cost ratios greater than one. It does not, however, appear that Fleischer assumes this.

Fleischer further describes another problem with the analysis in NCHRP Report 162 and gives an example of what he calls the "Pre-Selection Problem" [22, p. 16; 23]:

> One cannot determine the global optimum simply by combining locally optimum solutions. That is, one cannot maximize the net benefits on an entire investment program, with budget constraints, merely by aggregating design alternatives which appear optimal with respect to their mutually exclusive alternatives.

That the global optimum cannot be determined simply by combining locally optimum solutions is demonstrably correct; however, Fleischer further maintains that [22, p. 16]:

> All combinations of programs, or "budget packages," must be identified and the optimal program selected from this set. The number of such programs can be very large. Fortunately, however, certain efficient algorithms have been developed through dynamic programming and linear programming.

Here, Fleischer probably is referring to dynamic programming algorithms that have been developed for use with the benefit-cost ratio method (or net benefit method). Developers of these methods have shown how these combined methods give better solutions than the benefit-cost method; these combined methods are discussed in more detail below.

In this report, it is maintained that use of the incremental benefit-cost method, together with an improved sorting algorithm, both solves the problem outlined by Fleischer and is a more powerful method than has been recognized heretofore. This "incremental benefit-cost method, with an improved algorithm" also has the advantage that there is no longer a need to distinguish between incremental benefit-cost ratios and total benefit-cost ratios, since the latter are a subcase of the former. That is, the total benefit-cost ratio method applied to independent alternatives has only one increment of expenditure.

<ins>Rate-of-Return Method</ins>. The rate-of-return method [24] uses a formulation with which is calculated the rate of return on the initial capital investment. It is presumed that there is an initial capital investment and that there are future costs and benefits for each project. The rate of return is that rate which equates the initial capital cost with the

present worth of all future benefits less all future costs plus the present worth of the salvage value. Using this method, those projects with the highest rates of return are considered to be the optimal projects.

Total-Transportation-Cost Method. In the total-transportation-cost method [25], the total transportation cost is calculated as the sum of the present worths of initial capital costs, future project costs, and future road user costs, less the present worth of the project salvage value. Using this method, projects with the lowest total transportation cost are considered preferable.

Cost-of-Time Method. In the cost-of-time method [26], all benefits, except the time savings of motorists, and all costs are stated in annualized or present-worth dollars. The cost of time is defined as being equal to the present worth of initial and future costs less salvage value and less the present worth of all benefits except time savings, all divided by the present worth of time savings of motorists. Using this method, projects are more preferable the smaller (including negative values) is the cost of time. It is possible, of course, to use a method similar to the cost-of-time method for any situation where all benefits except one can be stated in dollar terms. Moreover, the cost-of-time method can be extended to a consideration of some types of benefits stated in dollar terms and several types of benefits not stated in dollar terms, the extreme case being the simple cost-effectiveness method where no benefits are stated in dollar terms.

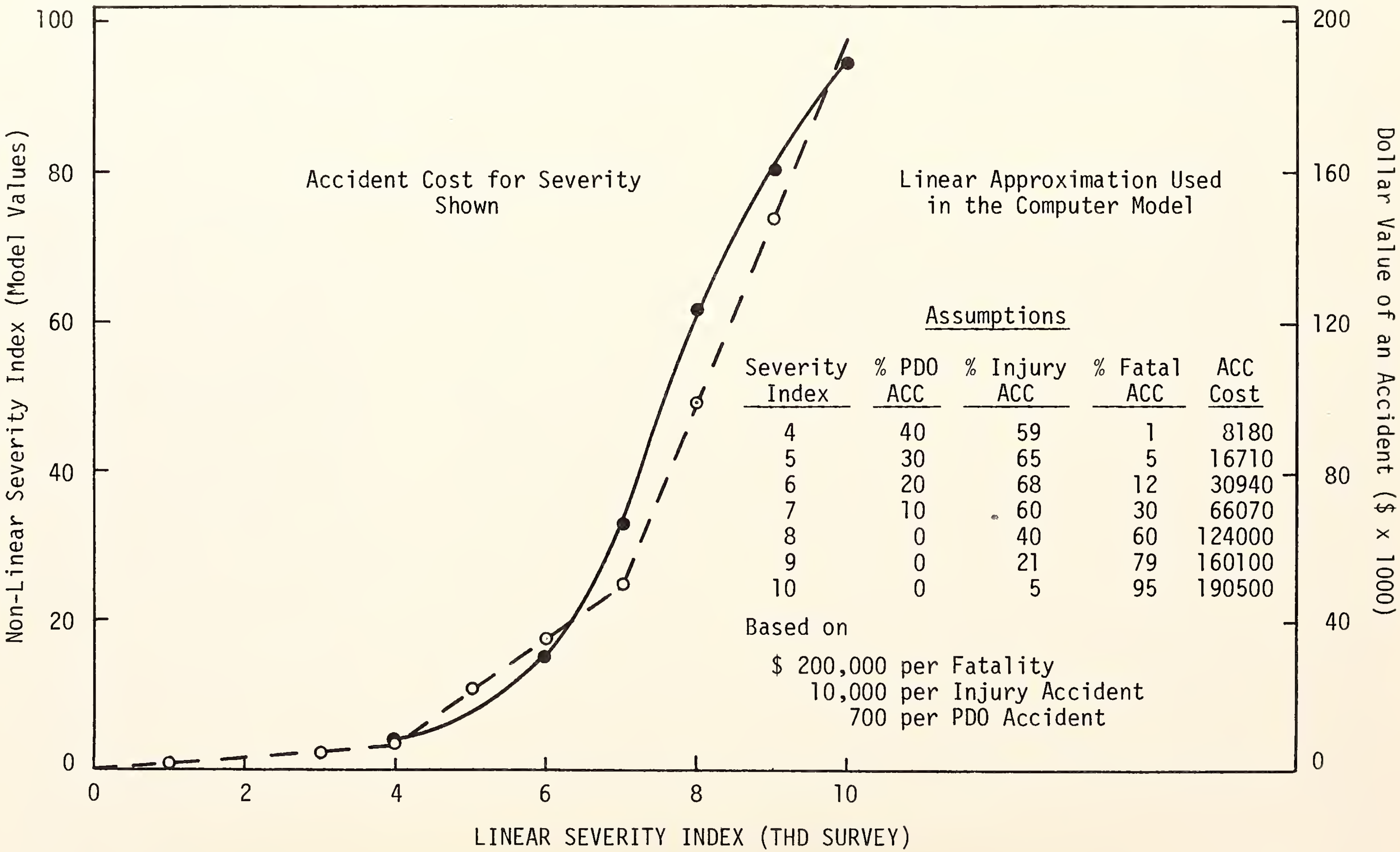
Non-Monetary Weights

Simple-additive-weighting methods with non-monetary weights are conceptually similar to those with monetary weights, the principle difference being that the non-monetary weights assigned to various attributes of alternatives typically are simply assigned by the decision-maker, instead of being calculated from revealed preferences of consumers (motorists). Safety studies sometimes refer to this method as the "cost-effectiveness method." In this study it will be termed either "simple additive weighting, with non-moneatry weights" or the "cost-effectiveness method, with weighting of attributes." This is a stronger version of the cost-effectiveness method than that referred to as the "cost-effectiveness method, without weighting of attributes" as discussed below in the section "Sequential Elimination Methods."

Use of simple additive weighting, with non-monetary weights, entails assigning weights to each of the attributes that are measures of effectiveness. This version of simple additive weighting is discussed in NCHRP Report 162 [8, p. 43] as "Cost-Effectiveness Analysis." In that discussion, the attributes that are considered are different types of accidents which are assigned weights such as: fatal accident = 20, injury accident = 9, and property-damage-only accident = 1. This version of cost-effectiveness analysis was criticized by Fleischer [22, p. 16] as being an inaccurate version of cost-effectiveness analysis. Fleischer was implicitly assuming that the only correct version of cost-effectiveness analysis is that which is described in this report as "cost-effectiveness analysis, without weighting of attributes." Thus, Fleischer actually was criticizing one version of cost-effectiveness analysis using criteria of another version.

As noted in NCHRP Report 162, the "cost-effectiveness method, with weighting of attributes" can be used in an incremental form in much the same way that incremental benefit-cost analysis is used. Incremental cost-effectiveness analysis of this type is required for comparing mutually exclusive alternatives.

In addition to NCHRP Report 162, there are numerous other reports that use this method of analysis. All versions using some type of index for the measure of effectiveness are in this category. A recent example is the use of the severity index in roadside clearance programs [27]. The "non-linear severity index (model values)" is scaled from 0 to 100 and is related to the "linear severity index (THD survey)," which is scaled from 0 to 10. This is depicted in Figure 4. Each roadside obstacle is assigned a severity index from 0 to 10. Roadside improvement programs either remove the obstacle or lower its severity index. This lowering of the severity index (the 0 to 10 rating) is translated into a lowering of the non-linear severity index (the 0 to 100 rating). The non-linear index of an obstacle multiplied by the expected number of



Assumptions

Severity Index	% PDO ACC	% Injury ACC	% Fatal ACC	ACC Cost
4	40	59	1	8180
5	30	65	5	16710
6	20	68	12	30940
7	10	60	30	66070
8	0	40	60	124000
9	0	21	79	160100
10	0	5	95	190500

Based on

$ 200,000 per Fatality
10,000 per Injury Accident
700 per PDO Accident

Figure 4. Severity Index Adjustment Relationships

accidents with the obstacle is an indication of the relative hazard. The relative hazard is reduced by lowering the index (reducing expected accidents). The amount of reduction in the hazard index is the measure of effectiveness. In this version of the cost-effectiveness model, the cost of the countermeasure is divided by the change in the hazard index to obtain a cost-to-effectiveness ratio, which is the cost of reducing the hazard index by one unit. (It should be noted that, in the report cited [27, pp. 2-3], the severity index also is said to be "the number of fatal and non-fatal injury accidents per total accidents," but this definition does not appear to be consistent with Figure 4). In this specific use of a severity index, the basis for constructing the index is the weighted accident cost associated with different values of the linear severity index, as depicted in Figure 4. In some uses, no such relationship is developed, and a severity index such as the linear index (0 to 10) is used. As shown by this example, this can lead to a considerable bias with respect to the "better" adjusted index.

Comparison of Simple Additive Weighting Methods

These methods can be used to compare alternatives and to determine the level of expenditure on a particular project, by means of a rule or, in the case of the non-monetary weighting method, an explicit value judgment. In many cases, it is often necessary to simultaneously determine both the level of expenditure and the preferred alternative. In these cases, different levels of expenditure on a particular project can usually be treated as different alternatives.

If the level of expenditure is unconstrained, except for some rule which determines the cutoff level of expenditure on individual projects, then, under conditions outlined below, the benefit-cost, rate-of-return, total-transportation-cost, and cost-of-time methods all indicate the same optimum level of expenditure on each project. The cutoff level of expenditure on an individual project is defined as the optimum level of expenditure as determined by a rule which depends on the method of analysis being used.

For the benefit-cost method, the cutoff rule is that expenditures should be made up to the point where the incremental or marginal benefit derived from the project equals the incremental expenditure or marginal cost of the project. In other words, expenditures should cease whenever the ratio of marginal benefit to marginal cost falls to one. For invisible funding increments, expenditure should stop at the point where average incremental benefits, measured in dollars, per dollar of expenditure become equal to one.

For the rate-of-return method, the level of expenditure on a project is increased to the level at which the rate of return at the margin of expenditure equals the minimum acceptable rate of return. For consistent expenditure determination, this minimum rate of return should equal the interest rate used for discounting in the other methods of analysis.

If the total-transportation-cost method is used, the level of expenditure on a project is increased to the level at which total transportation cost stops decreasing. In other words, this rule stipulates that highway costs should be increased if decreases in user cost more than offset the increase in highway costs. Since these user cost decreases are the benefits which are employed in the benefit-cost method, the total-transportation-cost method and the benefit-cost method usually give the same results. The total-transportation-cost method may give misleading results in some situations, however, if the highway analyst does not understand fully the implications of the method. For example, a decrease in user costs may occur because a particular type of design causes decreased travel. In the extreme, if the goal is to minimize total transportation cost, then the prescribed action would be to have no expenditure and no travel. A misleading interpretation such as this results from using decreases in user costs as estimates of benefits.

If the cost-of-time method is used, expenditure should be increased if the cost of time for the increment of expenditure is not greater than some maximum acceptable level. For this method to give the same results as the other methods, this maximum acceptable cost of time per hour of time saved should equal the value of time per hour which is assigned to time saving in calculating benefits for use with the other methods.

The above discussion indicates that if the level of expenditure is unconstrained except by optimizing rules, then all four methods of analysis will indicate the same optimum level of expenditure. If the level of expenditure is subject to a budget constraint, however, this conclusion is not generally valid. Even when a budget constraint limits the level of expenditure, so that only some of the project increments which meet the acceptance criteria can be enacted within the budget period, three of the above methods (all except the rate-of-return method) prescribe the same level of expenditure on each project. If the budget constraint limits expenditure such that some increments of each project which have benefit-cost ratios greater than one, or rates of return greater than the minimum acceptable level, cannot be constructed, then the rate-of-return method and the benefit-cost method will not give the same results if there are any costs other than initial capital costs. The magnitude of the difference in results between the two methods depends upon the ratio of variable costs to initial costs and upon the length of the analysis period. Use of the benefit-cost method results in the choice of projects, and project increments, which maximize the benefits obtainable from a given amount of total cost, including initial capital cost and future cost. Use of the rate-of-return method results in choices which maximize the benefits obtainable from a given amount of initial capital cost. Eckstein explains [10, pp. 62-63] that:

> ...if in each year, those projects are started which have the highest benefit-cost ratios, and if the marginal increment of each project has a benefit-cost ratio equal to the cutoff ratio of the program in the period, then the total return on federal expenditure will be maximized. Federal expenditure is considered the rationed commodity, and given this condition the present value of the future income stream that can be created is maximized. It can thus be seen that the choice of expenditure criterion is determined by the choice of the budgetary constraint which is assumed to limit the program.

Thus, if the budget constraint dictates a cutoff level yielding, on the marginal increment of expenditure for each project, benefit-cost ratios greater than one and rates of return greater than the minimum acceptable rate of return, then the choice of criteria depends on whether total cost or initial capital cost is assumed to be the relevant constraint. If used consistently, the total-transportation-cost and the cost-of-time methods will give the same results as the benefit-cost method and thus different results than the rate-of-return method.

The monetary weighting techniques usually can be used for determining priorities if similar projects are compared or if it is felt that all benefits and costs can be estimated accurately. The American Association of State Highway Officials recommends the use of benefit-cost analysis to determine the amount of expenditure on particular highway projects. They further recommend that benefit-cost analysis not be used for priority determination, that is, for determining which of several road improvements has priority. The principal reason the highway officials do not recommend the use of benefit-cost analysis in priority determinations is that, with the procedures outlined in the Red Book, such analysis omits consideration of land and community benefits. Furthermore, to the extent that land and community benefits are different for different levels of design, this same criticism also applies to the use of benefit-cost analysis to determine the amount of expenditure on particular highway projects.

Spending of scarce highway funds in a way that maximizes total benefits over time necessitates not only that the benefit-cost criterion be used to determine the level of expenditure on each project, but also that the marginal benefits per dollar of expenditure be equal for all roads. The failure to recognize this latter point probably is related to the misconception that total benefits are maximized when the ratio of benefits to costs is maximized. Although it sometimes is stipulated that a second benefit-cost ratio may be used, the Red Book gives no special reason for such a calculation. Moreover, even if a second ratio is calculated, only one increment of expenditure above the level of expenditure which maximizes the ratio of benefits to costs is considered. So, in effect, not only is a second ratio required in many cases for a correct analysis, but also are a third, a fourth, and so on, until all increments which give more benefits than costs are considered. The main reason that the Red Book stipulates that incremental ratios may be used, but that it is not necessary that they be used, is that negative or confusing ratios may be obtained. Such ratios can be avoided, however, by using an incremental analysis and by omitting from consideration those alternatives which cost the same or more, but give the same or less benefits, than some other alternative.

Eckstein argues correctly that incremental benefit-cost ratios must be used for the best allocation of funds. Even if it is agreed that incremental ratios are to be used, however, it still is necessary to determine whether additional increments of expenditure are to be made on particular projects. Eckstein points out that having an optimal expenditure on each project requires that the last increment of expenditure on each project in the budget have an incremental benefit-cost ratio larger than any feasible increment which is not included in the budget.

Although more recent versions of the monetary, simple-additive-weighting methods correct some of the deficiencies of the Red Book, errors still are made in describing the ways in which these analyses should be used, especially with respect to the use of incremental benefit-cost analysis. Similar errors remain in the analogous versions of other incremental methods.

The non-monetary simple-additive-weighting methods can be used to compare mutually and non-mutually exclusive alternatives if it is assumed that the different magnitudes of weighted values are a clear indication of the worth of a project. Incremental procedures should be used for these methods in exactly the same way as for the monetary methods. The non-monetary methods do not give any precise indication of the desired cutoff level for expenditures. This should not present a problem, however, if the decision-maker is satisfied that expenditures on all projects within the budget constraint are justified.

Hierarchical Additive Weighting

Hierarchical additive weighting is described by MacCrimmon [6, p. 28] as:

> ...a more sophisticated additive weighting method, [which] recognizes that attributes may simply be means toward higher level objectives. Hence, the decision-maker assigns values or preferences to the higher level objectives and then he assessed the instrumentality of each of the attributes in

attaining these higher level objectives. In this way, he infers the inter-attribute weightings from his direct assessment of the higher level objectives. In some forms of this method [28] the hierarchy is specified to preclude cross-linkages in order to avoid violating the independence assumption, while in other cases [29] cross-linkages are allowed.

An example of the use of hierarchical additive weighting in highway safety is provided by Solomon, Starr, and Weingarten [30]. They assigned seven analysis elements weights totaling 2,000 points. In addition to their basic weighting scheme, they used three alternative schemes for weighting the seven elements. One alternate scheme assumes equal weights for each of the seven elements, another emphasizes saving lives and injuries, and a third emphasizes monetary savings. The seven analysis elements and the weights assigned under each of these schemes [30, pp. 8, 17] are:

Analysis Element	Weights by Scheme			
	Basic Weights	Equal Weights	Lives + Injuries	Monetary Savings
1. Rate of return in percent	600	286	100	900
2. Lives saved per $ million	300	286	600	100
3. Injuries saved per $ million	200	286	400	100
4. Benefits in $ million per year	100	286	100	600
5. Lives saved per year	100	286	500	100
6. Injuries saved per year	100	285	200	100
7. Mean reliability in percent	600	285	100	100
TOTAL	2,000	2,000	2,000	2,000

Fifty-seven types of safety efforts were studied using these four weighting schemes. The results:

> ...showed that about 2/3 of the 57 safety efforts changed in rank less than 10 places. However, 1/7 of the safety efforts changed by 15 places or more. Therefore, for future analyses, continued attention should be given to different weighting schemes.

In addition to using different weighting schemes, Solomon, et al. performed a sensitivity analysis of major elements used in calculating safety benefits. They used different values for value of time ($1, $3, and $5 per person-hour), interest rates (6 and 12 percent), and values for pain and suffering. The pain and suffering values are:

	Nothing	Low	Medium
Per death	0	$10,000	$100,000
Per injury	0	$ 100	$ 1,000

They found that neither changes in the weights for pain and suffering nor changes in the interest rate have much effect on rankings.

Some analysts might describe the Solomon method as a complicated version of simple additive weighting, but the method's use of seven elements, each of which is weighted and measured by a separate formula, qualifies it as a two-hierarchy method. The seven different elements, each of which represents different though inter-related goals, are combined in the following way:

$$WVSE = \sum_{i=1}^{7} W_i Y_i^*$$

where: WVSE = weighted value of safety effort,

W_i = weight for the ith safety element, for the weighting scheme chosen, and

$Y_i^* = Y_i/\Sigma Y_i$, where ΣY_i indicates the sum of Y_i over all seven safety elements.

The Y_i values for safety elements $i = 1, 2, \ldots, 7$ are calculated using the following seven formulas:

$$Y_1 = \frac{\sum_{i=1}^{3} C_i X_i + X_4 + C_4 C_4 X_5 + \sum_{i=6}^{8} X_i}{N\ [X_9 + X_{12} + X_{13} + A_N\ (X_{10} + X_{11})/N]}$$

If the denominator of Y_1 is called ND, then

$Y_2 = X_{3/D}$

$Y_3 = (X_2 + X_3)/D$

$Y_4 = DY_1$

$$Y_5 = X_{3/N}$$

$$Y_6 = (X_2 + X_3)/N$$

$$Y_7 = \frac{\sum_{i=1}^{13} R_i}{13 - (\text{number of } R_i\text{'s equal to zero due to no input data})}$$

The definition of the constants and input values used in the above formulas are given below, together with the input values used for one of the safety measures considered in the Solomon report (Item 2, Interstate, Interurban safety expenditures). The constants used in the analysis are:

	Constants	Value	Symbol
1.	Cost of one accident	\$ 500	C_1
2.	Cost of one nonfatal injury	1,200	C_2
3.	Cost of one death	75,000	C_3
4.	Persons per vehicle	1.7	C_4
5.	Value of time	\$3 per hour	C_5
6.	Interest rate	6%	C_6
7.	No. of years over which benefits and operating costs are calculated[1]	20	N
8.	Present worth factor[2]	11.47	A_N

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[1] A few safety efforts used 10, 11, or 12 years.

[2] Different values were employed for 10, 11, or 12 years.

The input data consist both of inputs denoted by X's and their associated Reliabilities, denoted by R's, as follows:

Input Data	Value Number	Value Symbol	Reliability Number	Reliability Symbol
1. No. of Accidents Saved	12.550×10^6	X_1	90	R_1
2. No. of Injuries Saved	2.500×10^6	X_2	90	R_2
3. No. of Lives Saved	$.113 \times 10^6$	X_3	90	R_3
4. Other Safety Benefits	None	X_4	None	R_4
5. Travel Time Saved	25×10^9	X_5	90	R_5
6. Operating Cost Reduced	None	X_6	None	R_6
7. Maintenance and Repair Cost Reduced	None	X_7	None	R_7
8. Other Nonsafety Benefits	None	X_8	None	R_8
9. Initial Cost	37.9×10^9	X_9	90	R_9
10. Operating Cost	None	X_{10}	None	R_{10}
11. Maintenance and Repair Cost	None	X_{11}	None	R_{11}
12. R&D and/or T&E Cost	None	X_{12}	None	R_{12}
13. Other Cost	None	X_{13}	None	R_{13}

The Reliability ratings (R's) are ratings of the quality of the input data rated as follows:

90% = Excellent data, well conducted and controlled studies, ample scope

79% = Good data, deficiencies in studies and/or limited scope

50% = Engineering judgment, some related information as aid, or fair data

30% = Poor data, poorly conducted studies, or very limited in scope

10% = No supporting information

Using the above constaints and input values for the Interstate, Interurban safety program, the values calculated for the seven analysis elements (the Y's) and their associated weights (W's) using the basic weighting scheme are:

Analysis Element	No.	Symbol	No.	Symbol
1. Rate of return	19%	Y_1	600	W_1
2. Fatalities saved per $ million	3	Y_2	300	W_2
3. Injuries saved per $ million	69	Y_3	200	W_3
4. Total benefits in $ millions per year	7.3×10^9	Y_4	100	W_4
5. Total lives saved per year	5650	Y_5	100	W_5
6. Total injuries saved per year	131×10^9	Y_6	100	W_6
7. Mean reliability	90	Y_7	600	W_7
Total			2,000	

Another example of the use of hierarchical additive weighting is the use of Highway Sufficiency Ratings, also called Deficiency Ratings or Adequacy Ratings. These ratings are an index for different roadway conditions, usually consisting of three cateogries - structural, functional, and safety. These categories are assigned weights, typically summing to 100 points. For example, the safety and structural categories might be assigned 30 points each, with 40 for functional. In general, the structural rating is a measure of the physical condition of the roadway, the functional rating measures the ability of the road to carry traffic and thus stresses geometric adequacy, and the safety rating is related to the expected number and type of accidents on the road or to factors believed to affect accidents. Each of the three basic cateogries is divided into subcategories, such as lane width, shoulder width, number of intersections per mile, or condition of pavement surface. Each of these subcategories is assigned a certain number of the points associated with its basic category. Traffic lane width often is a subcategory within the functional category and might, for example, be assigned 6 points of the total functional category weights. The wider the lane, the more points a pavement would receive.

A majority of the states either now uses sufficiency ratings or has used them at some time in the past to rate roadways. The weightings of categories, and subunits within categories, differ from state to state, but the same three categories are used in almost all states.

Sufficiency ratings have been used to determine whether roadways should be reconstructed or upgraded but have not been used to directly evaluate any type of highway safety program or countermeasure. That the method has not been used to directly evaluate programs is related to its principal shortcoming as an evaluation method: sufficiency ratings only indicate "how bad a roadway is" and give no measure of the benefits or the costs associated with improving the roadway.

The use of hierarchical additive weighting in evaluating traffic control systems is summarized in the Traffic Control Systems Handbook [31, pp. 474-486], where the method is called the cost utility approach [also see 32]. This form of the method involves setting goals and assigning weights to each goal. These goals are analogous to the Solomon study's "analysis elements." Each goal is divided into individual items, or requirements, which make up the goals. These individual items represent subgoals which usually are rated by several individuals on a scale of, for example, zero to ten. The individual ratings are averaged to obtain a rating for that subgoal. A formula similar to that in the Solomon study then is used to derive a weighted total point rating for each alternative.

Other examples of hierarchical additive weighting are found in various warranting procedures used, or proposed for use, in many states. A good recent example is the application of warrants to the need for roadway lighting [33].

Many of the studies performed under the category of hierarchical additive weighting have several weaknesses:

1. There often is no logical, consistent method of determining inter- and intra-attribute weights, and there always exists the problem of determining which weight to use.
2. The hierarchical structures sometimes include as final goals elements that are intermediate goals.
3. Elements that measure reliability of effectiveness are added to those that measure degree of effectiveness.
4. Incremental effectiveness of alternatives sometimes is not considered.

Quasi-additive Weighting

If properly formulated, additive weighting models assume that the utility of the multiple attributes is equal to the sum of the utilities of each of the individual attributes. If the assumption of independence of utilities does not hold, the utility of an alternative may depend upon the joint distribution of attributes. MacCrimmon [6] explains that there may be cases where utilities are not independent but that "...by obtaining conditional utility functions on the attributes [where] some of the attributes are utility independent of others, an overall preference assessment can be made in a quasi-additive form" [6, p. 29]. He cites the use by deNeufville and Kenney [34] of a multiplicative form of quasi-additive weighting, whereby they

> ...studied the development of the Mexico City airport facilities using a multiplicative utility over attributes. Conditional utility functions for the attributes - cost, capacity, access time, safety, displacement, and noise pollution - were assessed along with necessary scaling constants. The necessary conditions for a multiplicative function were verified [6, p. 29].

Another example of the multiplicative form is the use of modified sufficiency ratings by some highway agencies. This involves multiplying the basic sufficiency rating, calculated as described previously in the discussion of hierarchical additive weighting, by an index based on traffic volume. However, it should be pointed out that this formulation is not based on a rigorous examination of the form of (implicitly assumed) utility function.

Sequential Elimination Methods

Sequential elimination methods are characterized by [6, p. 30]:

1. A set of available alternatives with specified attributes and attribute values,
2. Scalings, perhaps only ordinal, or attribute values (intra-attribute preferences) and in some cases an ordering across attribute,
3. A set of constraints (but in some cases empty) across attributes, and

4. A process for sequentially comparing alternatives on the basis of attribute values so that alternatives can be either eliminated or retained.

There are three main subcategories of sequential elimination methods, and their distinguishing properties are [6, p. 30]:

1. A comparison across attributes for a given alternative-comparing the attributes of the given alternative with the attributes of a standard (i.e., a set of constraints),
2. A comparison across attributes for two alternatives-comparing the attributes of one alternative against the attributes of the other, and
3. A comparison across alternatives for a single attribute-comparing the attribute value of all alternatives.

The principle method in this group that has been used in comparing highway alternatives is that of *dominance*. In the terminology used in this paper, this method is also referred to as the cost-effectiveness method, without weighting of attributes. As mentioned previously, it is this version of cost-effectiveness analysis that is described by Fleisher [22, pp. 16-20] in his recent critique of NCHRP Report 162.

The cost-effectiveness method, without attribute weighting, usually is used in terms of the equal-cost criterion and the equal-effectiveness criterion. The equal-effectiveness criterion is used to compare alternatives with equal effectiveness; the alternative which is considered most effective is the preferable alternative. The equal-cost criterion is used to compare alternatives with equal cost; the least costly alternative is the preferable one. To these two criteria may be added the obvious rule that some alternatives may dominate other (inferior) alternatives with respect to both effectiveness and cost.

It should be emphasized, however, that when two alternatives have equal costs, one of the alternatives must have equal or greater effectiveness for all attributes and must have greater effectiveness for at least one attribute. It is not sufficient that one be equal or superior to the other in n-1 attributes and inferior in even one; to imply differently is to assign inter-attribute weights (in which case it would be a weighting method). This restriction severely limits the use in safety evaluations of the cost-effectiveness method without attribute weighting, since most safety evaluations involve comparisons of many alternatives. A possible exception to this limitation would be the use of this method to evaluate alternatives within a specific safety program that met two conditions: (1) there were no measures of effectiveness other than countermeasure accident rates, and (2) different types of accidents always could be expected to be reduced in a fixed proportion--in which case expected reduction in total accidents would be an acceptable measure of effectiveness.

Mathematical Programming Methods

Mathematical programming methods have the following common characteristics:

1. An infinite, or very large, set of alternatives which are inferable from a set description (i.e., constraints specified on the attribute values),
2. A set of technological (or sometimes preference) constraints,
3. An objective function, either global or local, that is compensatory, and
4. An algorithm to generate more preferred points in order to converge to an optimum.

Mathematical programming methods discussed in this paper are linear programming, goal programming, integer programming, dynamic programming, and network analysis techniques.

Linear Programming

Programming problems in general are concerned with the use or allocation of scarce resources--labor, materials, machines, and capital--in the "best" possible manner so that costs are minimized or profits are maximized. In using the term "best" it is implied that some choice or a set of alternative courses of action is available for making the decision. The best decision is found by solving a mathematical problem. The term "linear programming" merely defines a particular class of programming problems that meet the following conditions:

1. The decision variables involved in the problem are non-negative, i.e., positive or zero.
2. The criterion for selecting the "best" values of the decision variables can be described by a linear function of these

variables, i.e., a mathematical function involving only the first powers of the variables, with no cross products. The criterion function is referred to as the "objective function."

3. The operating rules governing the process (e.g., scarcity of resources) can be expressed as a set of linear equations or linear inequalities. This set is referred to as the "constraint set."

Linear programming (LP) is one of the most widely applied methods of mathematical programming. LP and its applications undoubtedly occupy a larger proportion of the OR/MS literature than any other research area. The ways in which LP can be applied to the planning and design of highway safety systems and accident prevention countermeasures is numerous, ranging from linear models of budget distribution and resource allocation to input-output planning models. In addition, nonlinear problems may frequently be reduced to the solution of an approximate LP problem or to a series of LP problems. Likewise, when discrete (integer) decision variables are present, LP serves as a basis for more advanced methods which require repetitive solutions by LP. This makes it particularly important to take advantage of the latest computational refinements in solving problems of this nature.

The LP problem and its associated dual are familiar to most readers; the notation (canonical form) has been generally accepted as follows:

Primal

$$\text{Maximize} \quad Z = \sum_{j=1}^{n} c_j x_j$$

$$\text{subject to} \quad \sum_{j=1}^{n} a_{ij} x_j \leq b_i \qquad i = 1, 2, \ldots, m$$

$$x_j \geq 0 \qquad j = 1, 2, \ldots, n$$

Dual

$$\text{Minimize} \quad Z = \sum_{i=1}^{m} b_i y_i$$

$$\text{subject to} \quad \sum_{i=1}^{m} a_{ij} y_i \geq c_j \qquad j = 1, 2, \ldots, n$$

$$y_i \geq 0 \qquad i = 1, 2, \ldots, m$$

Algorithms may be directed at either the primal LP or its associated dual problem. Many successful algorithms exploit the relationships which exist between the primal and dual problems; each of these approaches is discussed below. For a simple introduction to the fundamentals of LP, the operations research text by Phillips, et al. [35] is recommended; a more in-depth treatment may be found in any linear programming text [e.g., 36].

The most common method for solving an LP problem is some form of the "simplex algorithm" originally derived by Dantzig [37]. Many commercial codes use a refinement of this approach, called "revised simplex method," often using a multiplicative form of the inverse [38]. This particular refinement is characterized by high computational efficiency and smaller computer storage requirements. The "dual-simplex algorithm" [39] is most often embedded inside other procedures, such as cutting plane integer programming methods, but is not widely applied as a general purpose LP solution method.

Linear programming has not been widely applied to the selection of highway safety countermeasures, although a notable exception is the use of LP by Operations Research, Inc., in what is sometimes referred to as the ORI cost-effectiveness procedure [40, especially Vol. I, pp. 139-169]. Other allocation models considered by ORI, before they chose linear programming, include indifference curve analysis, Lagrangean optimization, Monte Carlo simulation, and graphic illustration. The linear programming formulation chosen is directed toward allocating expenditures among different safety standards. Further study of their formulation will be made in the future to better determine its applicability to highway accident countermeasures. Evaluation to date indicates that their formulation possibly could be used to allocate funds among safety programs but could not be easily employed to evaluate accident countermeasures for specific locations.

Goal Programming

The most important yet most difficult area in the field of management science is "management by multiple objectives," where managers must make decisions involving conflicting multiple objectives. During the past several years, much attention has been given to a promising analytical technique called goal programming, originally introduced by Charnes and Cooper [41]. A powerful tool of decision-making analysis, goal programming (GP) draws upon the well-developed and tested linear programming technique, but GP provides a simultaneous solution to a complex system of objectives. It can handle decision problems having a single goal with multiple subgoals, as well as problems involving multiple goals and subgoals.

In general, the GP model is a linear mathematical model in which the optimum attainment of objectives is sought within the given decision environment. The decision environment determines the basic components of the model, namely the constraints (system and goal), decision variables, and the objective function. A GP model is useful for three types of analysis: (1) to determine the input (resource) requirements to achieve a set of goals, (2) to determine the degree of attainment of defined goals with given resources, and (3) to provide the optimum solution under the varying inputs and priority structures of goals.

The general goal programming model is:

$$\text{Minimize} \qquad Z = \sum_{k=1}^{K} \sum_{i=1}^{m} P_k \, (w_i^- d_i^- + w_i^+ d_i^+)$$

$$\text{subject to} \qquad \sum_{j=1}^{n} a_{ij} X_j + d_i^- - d_i^+ = b_i \qquad (i = 1, \ldots, m)$$

$$X_j, \; d_i^-, \; d_i^+ \geq 0$$

where P_k is the preemptive priority weight assigned to goal k, w_i^- and w_i^+ are numerical (differential) weights assigned to the deviational variables of goal i at a given priority level, d_i^- and d_i^+ represent the negative and positive deviations, a_{ij} is the technological coefficients of X_j in goal i, and b_i is the i^{th} goal level.

The system constraints represent the absolute restrictions imposed by the decision environment on the model. For example, there are only seven days in a week (time constraint), the production capacity in a short run is limited to certain available hours (manpower constraint), the production should be limited to demand and storage capacity (physical constraint). The system constraints must be satisfied before any of the goal constraints can be considered.

The goal constraints represent those functions that present desired levels of certain measurements. Desired level of pollution control, desired level of profit, desired diversification of investments among various available alternatives, and desired market share for each product are illustrations of goal constraints. In order to achieve the ordinal solution, negative and/or positive deviations about the goal must be minimized, based on the preemptive priority weights assigned to them. Thus, the low priority goals are considered only after higher priority goals are achieved as desired ($P_k > P_{k=1}$). When there are multiple goals at a given priority level, differential weights (w_i) are assigned, based on the numerical opportunity costs. A detailed discussion of model formulation, application areas, and limitations of goal programming is presented by Lee [42].

In conclusion, the application of cost efficient and cost effective countermeasures often involve the rationalization and compensation of conflicting objectives (goals). Further research in this project will be cognizant of goal programming methodologies, and applications of this new and powerful technique will be considered.

Integer Programming

This brief discussion will be devoted to the study of integer linear programming problems. An integer linear programming problem, henceforth called an "integer program," is a linear programming problem wherein some or all of the decision variables are restricted to be integer values. A "pure integer program" is one where all the variables are restricted to be integers. A "mixed integer program" restricts some of the variables to be integers while others can assume continuous (fractional) values.

Integer programming (IP) is a valuable operations research tool having tremendous potential for applications in the design and analysis of highway systems. Although there has been considerable theoretical research in the last two decades, progress in the computational aspects of large scale integer programming problems are not yet impressive.

The general integer linear programming problem is directed toward finding the optimal values of a set of variables xj (j = 1, 2, ..., n) by solving the following problem:

$$\text{Maximize } x_0 = \sum_{j=1}^{n} c_j x_j$$

$$\text{subject to} \quad \sum_{j=1}^{n} a_{ij} x_j \le b_i \qquad i = 1, 2, \ldots, m$$

$$\text{integer } x_j \ge 0 \qquad j = 1, 2, \ldots, n$$

The zero-one IP problem is one in which each solution variable is restricted to only binary values. Any general IP problem can be converted to a zero-one IP problem using the following transformation on each solution variables:

$$x_j = \sum_{\ell=0}^{k} 2^{\ell} Y_{\ell} = Y_0 + 2Y + 4Y_2 + \ldots + 2^k Y_k$$

where: k = smallest integer such that $2^{k+1} \ge U + 1$

U = smallest upper bound on x_j

This procedure obviously increases the size of the original problem, but it transforms the general problem into the zero-one problem for which available solution techniques are more efficient.

Several algorithms have been proposed for a solution to the IP problem. The algorithms that have been most widely used are the "cutting plane" algorithms developed by Gomory in which new linear constraints are generated so as to obtain a derived problem whose optimum extreme point is an integer. These algorithms yield dual feasible solutions, so that a primal feasible integer solution is not available until the optimal integer solution is reached. This is a major disadvantage in the Gomory schema. However, primal algorithms which continually maintain a feasible integer solution have recently been developed by Young [43] and Glover [44]. Other recent algorithms use branch-and-bound methods for implicitly (or explicitly) enumerating the space of all feasible integer solutions. These include the algorithms developed by Land and Doig [45], Balas [46], Cook and Cooper [47], Krolak [48], Hillier [49], and Geoffrion [50].

Integer programming has recently been applied quite successfully to a number of highway programs. Researchers at Texas A&M University have recently applied a specialized zero-one IP code to a resource allocation problem involving over 2700 constraints and 6000 decision variables.

An IP problem of particular interest is that given by the following formulation:

$$\text{Maximize} \quad \sum_{j=1}^{N} C_j X_j$$

$$\text{subject to} \quad \sum_{j=1}^{N} A_j X_j \leq G$$

$$X_j = 0, 1 \qquad j = 1, 2, \ldots, N$$

This particular formulation is known as the "knapsack problem" and represents a wide class of practical formulations characterized by capital budgeting problems. Brown has recently applied this formulation to a highway safety problem in Alabama. Although Brown actually solved a five-integer programming problem, he used a technique known as dynamic programming [51; also see 52 and 53].

Dynamic Programming

In most operations research problems the objective is to find the optimal (maximum or minimum) values of the "decision variables," that is, those variables which can be controlled within the problem structure. Usually, these variables are dealt with simultaneously, or collectively. Each of us, however, has been faced with problems in which it might be possible to break our decisions up into small components (decomposition) and then recombine our previous decisions in some form or another to obtain the desired answer (composition). This approach is called "multistage problem solving"; dynamic programming (DP) is a systematic technique for reaching an answer in problems of this nature. Numerous algorithms have been developed to solve both linear and nonlinear objective functions subject to various constraint configurations. One might think that all procedures could be classified as those dealing with either linear or nonlinear functions, but dynamic programming cannot be uniquely classified in either category. Properly applied, DP cuts across all fields of mathematical programming. Important applications have surfaced in inventory control theory, network flows, job-shop scheduling, production control, integer programming, and many other areas. Dynamic programming has also proved useful in solving problems relevant to all fields of engineering. Like all operations research techniques, DP has its limitations and weaknesses; when applicable, however, the technique is quite efficient computationally.

Network Analysis Techniques

An area of mathematical modeling which has received considerable attention in recent years is that of network analysis. Although the mathematical structure of network analysis (NA) algorithms stems from a linear programming formulation, there are two good reasons for using NA rather than LP. First, many real-world problems can be depicted as network representations, and such representations are readily acceptable by management and can be interpreted visually. Second, NA algorithms use streamlined and/or special-purpose basis-changing rules which avoid normal simplex operations. Very efficient NA algorithms exist for solving large-scale LP formulations; for example, trans-shipment problems with over 10,000 notes and 50,000 arcs have been solved using network analysis.

This brief discussion will relate to a fundamental set of network problems which have known, efficient solution procedures. The reader should be aware that there is a wide range of special-purpose algorithms which extends this basic set. The models and algorithms discussed here have been successfully applied for over twenty years, although most have not been widely applied to highway planning problems or accident countermeasure formulations. The notable exception to this is the project scheduling area using PERT/CPT concepts.

Perhaps the best known network analysis technique is use today is the "shortest-route problem." Simply stated, the problem is to find the shortest (minimum cost/time) path from a start node (source) to an end node (sink), given a directed network with distances assigned to arcs. A related problem is finding the shortest path between all pairs of nodes in the network. This is called the "multiterminal shortest-chain problem." Most algorithms which solve one problem will also solve the other.

Aside from the pure network analysis of the shortest-path algorithms, the most widely used and popular network applications have been in the area of transportation/assignment/trans-shipment problems. Such formulations appear frequently as major problems or subproblems in related algorithms. There have been spectacular reports made, claiming solution to extremely large problems as well as fast computer solution times.

The minimum-spanning tree problem is another formulation which has been widely applied. A minimum-spanning tree is a set of connected arcs such that every node in a network is connected to every other node such that the sum of the arc costs, or times, is a minimum. A closely related problem is the maximum-spanning tree.

In assessing the usefulness of network flow techniques to highway safety and accident prevention countermeasures, there are no known applications in the current literature. However, due to the flexibility and computational advantages of network flow formulations, these techniques show great promise in solving special linear programming formulations. Specific potential applications and attractive areas of use will be explored during the course of this research.

III. METHODS SELECTED FOR FURTHER DEVELOPMENT

Several methods of analysis were selected at the end of Task A for further study as possibilities for evaluating highway accident countermeasures. These methods are:

1. Incremental benefit-cost analysis with improved algorithm,
2. Use of benefit and costs with dynamic programming,
3. Simple additive weighting with nonmonetary weights for at least some effectiveness measures,
4. Hierarchical additive weighting, and
5. Mathematical programming methods.

Three major research needs were identified upon completion of Task A. These are: (1) to further develop the improved algorithm for use with incremental benefit-cost analysis, (2) to compare the results of this method with those obtained with dynamic programming, and (3) to further evaluate use of market-oriented techniques for evaluating life saving and to compare values developed using this approach to values developed by the National Safety Council and the National Highway Traffic Safety Administration.

It also was determined that the method of simple additive weighting with nonmonetary weights and the hierarchical additive weighting method each need to be developed in a more logical, consistent format for specific safety applications. Further study of these alternatives indicated that research should be devoted to logical ways of determining weights or utilities for these methods. Guidelines should be developed on which weights and/or utilities to use.

A decision also was made at the end of Task A to further study mathematical programming methods to determine the specific forms that can be used in evaluating safety programs. Dynamic programming, integer programming, and network analysis were identified as the techniques that appear to show the most promise for evaluating the large scale optimization problems encountered in safety analyses. Goal programming also was identified as a relatively new technique that, like the weighting methods, is worthy of study in future research. Further study of mathematical programming methods led to the conclusion that this project should emphasize dynamic programming and integer programming, in addition to incremental benefit-cost analysis. These are the methods recommended for use in Chapter XIV.

PART TWO: REVIEW OF CURRENT PRACTICE

IV. FEDERAL HIGHWAY SAFETY ACTIVITIES

The role of the federal government in highway traffic safety has increased substantially over the past decade. The passage of several federal highway safety acts has provided funds for expansion of federal-, state-, and local-level programs specifically related to highway safety. The expanded federal role in highway safety has spawned several studies concerned with allocating federal funds among various federal-level highway safety programs. A discussion of some of these studies follows a brief review of recent highway safety acts.

Federal Highway Safety Programs

The Highway Safety Act of 1966 (80 Stat. 731) [54] amended Title 23 of the United States Code to contain a new chapter entitled "Highway Safety." Section 402 (a) of Title 23 states:

> Each state shall have a highway safety program approved by the Secretary, designed to reduce traffic accidents and deaths, injuries, and property damage resulting therefrom. Such programs shall be in accordance with uniform standards promulgated by the Secretary. Such uniform standards ... shall include but not be limited to, provisions for an effective record system of accidents, injuries, and deaths, vehicle registration, operations, and inspection, highway design and maintenance (in-causes of accidents, injuries, and deaths, vehicle registration, operations, and inspection, highway design and maintenance (including lighting, markings, and surface treatment), traffic control, vehicle codes and laws, surveillance of traffic for detection and correction of high or potentially high accident locations, and emergency services.

Subsequent to this legislation, and by the authority vested in him through this legislation, the Secretary of Transportation set forth thirteen (now eighteen) highway safety standards intended to increase the uniformity of traffic safety measures among the states and thereby to reduce the loss of life, limb, and property on the nation's roads and highways. Four of the standards promulgated by the Secretary are partially or wholly under the supervision of the Federal Highway Administration [55, pp. 43-46]:

1. Standard No. 9--*Identification and Surveillance of Accident Locations:* To identify specific locations which have high or potentially high accident experience, as a basis for establishing priorities for improvements to eliminate or reduce the hazards.
2. Standard No. 12--*Highway Design, Construction and Maintenance:* To maintain existing streets in condition to promote safety, to modernize or build new roads to meet safety standards, and to protect motorists from accidents at construction sites.
3. Standard No. 13--*Traffic Engineering Services:* To assure application of modern traffic engineering principles and uniform standards for traffic control.
4. Standard No. 14--*Pedestrian Safety* (shared responsibility with NHTSA): To emphasize the recognition of pedestrian and bicycle safety as an integral, constant, and important element in community planning, and to insure continuing programs to improve such safety.

It should be understood that the funds allocated to the states by the federal government for implementing the standards were relatively small. That is to say, the funds authorized under 402 were never intended to be used for massive reparations of existing highways or for construction of new highways. Rather, these monies were intended to "seed" the highway safety effort within the several states and to promote uniform, minimal standards of safety throughout the nation. Paragragh (g) of section 402, Title 23 U.S. Code is quite explicit on this point:

> Nothing in this section authorized the appropriation or expenditure of funds for (1) highway construction, maintenance, or design (other than design of safety features of highways to be incorporated into standards) or (2) any purposes for which funds are authorized by section 403 of this title.

Title II of the Highway Act of 1973 [56] provides for larger allocations of federal funds to improve highway safety efforts within the states in five specific areas:

1. *Section 203 - Rail-Highway Crossings:* Provisions of this section allocate funds to survey railroad-highway grade crossings with the intent to identify hazardous locations. But further:

   > At least half of the funds authorized and expended under this section shall be available for the installation of protective devices at rail-highway crossings [203(b)].

2. *Section 205 - Pavement Marking Demonstration Project:* As the title suggests, funds allocated under this section are to be used for the marking or delineation of highways. Funds

are not limited to the federal-aid system but are excluded from the Interstate System. Rural roads are to be given priority.

3. *Section 209 - Projects for High Hazard Locations:* The states are required to survey and identify high-hazard locations, according to this section for:

   > ...projects to eliminate or reduce the hazards at specific locations or sections of highways which have high accident experience or high accident potentials... [Amendment to Chapter 1, title 23, USC, section 152 (b)].

4. *Section 210 - Program for Elimination of Roadside Obstacles:* Similar in intent and provision to Section 209, this Program also applies to high-hazard locations. Again, funds are to be used only on the federal-aide system.

5. *Section 230 - Federal-Aid Safer Roads Demonstration Program:* Funds are to be allocated for "...public roads or segments thereof not on a federal-aid system needing improvements to correct safety hazards..." States are allowed to choose "...projects to improve highway markings and signing, to eliminate hazards at railroad-highway grade crossings, and to correct high-hazard locations..." [Amendment to Chapter 4, title 23, USC, section 405(c)].

Title II of the Highway Act of 1976 continued the categorical funding philosophy initiated in 1973. The categorical programs from 1973 were changed in the following ways [35, pp. 41-42]:

1. Projects for high-hazard locations and for the elimination of roadside obstacles (Sections 209 and 210) have been combined into one program.
2. Funds for the elimination of rail-highway crossings have been doubled for fiscal years 1977-1978.
3. There is more freedom to transfer funds between categories. The existing 30 percent limit has been raised to 40 percent. It also allows 100 percent transfer of rail-highway crossing funds with appropriate approvals and when such funds "... cannot be used for such projects." However, "...Highway Trust Fund money may not be transferred to any program for which general fund money is available and vice versa."
4. Priority for pavement marking projects no longer need "...be given to those on the federal-aid secondary system and those which are not on any system."

Federal Highway Safety Studies

Prior to the Highway Safety Act of 1966, there was no need at the federal level for any type of economic analysis to determine optimal allocation of federal-aid highway funds among safety programs. The emphasis then was not on specific highway safety programs but rather on initial highway construction and major reconstruction projects, although safety considerations were taken into account when interstate highways were designed.

This is not to say, however, that safety was completely ignored; concern for motorist safety led to the development of "highway sufficiency ratings" by engineers of the Bureau of Public Roads. Beginning in 1973, this agency was required to note on maintenance inspection reports the condition, safety, and service features of federal-aid highways; by 1947 the agency had developed a system for numerically quantifying the structural adequacy, safety, and service conditions of federal-aid primary roadways. By 1951, this systemwas employed nation-wide as an integral part of maintenance inspection procedures [57, p. 1]. Many states adopted sufficiency ratings for use with state-level programs; a 1960 survey [58, p. 84] shows that by that time thirty-eight states were using these ratings.

Since 1965, when President Johnson began to take an active interest in highway safety, the federal role in highway safety has expanded to include specific large-scale highway safety programs. Such programs necessitate the development of economic analyses that can be used at the federal level to determine the best allocation of federal-aid funds among various safety programs. These analyses include (1) a Federal Highway Administration study by Solomon, et al. [30] that evaluates several highway safety programs, (2) Dale's studies [59, 60] for the Federal Highway Administration that review the cost-effectiveness of numerous countermeasures employed by various state highway agencies, and (3) the *National Safety Needs Report* [61] and supporting material [62] prepared in response to section 225 of the Highway Safety Act of 1973.

The Solomon Study

In response to a request from the Federal Highway Administration (FHWA), a special task force was established in 1969 to study the safety efforts of priorities of these efforts. The methodology and results of the work of the ad hoc task force are documented by Solomon, et al. [30] in an analysis of various benefits and costs of safety measures.

Input data for the analysis are obtained from safety-oriented efforts of the Bureau of Public Roads. The fifty-seven safety efforts, including both current and proposed projects, used in the analysis are taken from the five programs sponsored by the Bureau in 1969--Railroad-Highway Grade Crossings, Safety Improvement, Interstate, ABC (federal-aid funding categories for primary, secondary, and urban roadways), and TOPICS (Traffic Operations Program to Increase Capacity and Safety, for improvement of traffic control devices in urban areas). In several cases, major safety projects are subdivided, such as by average daily traffic volume or urban vs. rural location.

Each safety project is analyzed on the basis of seven weighted elements [30, p. 8]:

Analysis Element	Weight
1. Rate of return, percent	600
2. Lives saved per $ million	300
3. Injuries avoided per $ million	200
4. Benefits in $ million per year	100
5. Lives saved per year	100
6. Injuries saved per year	100
7. Mean reliability of input data	600

For each project, the numerical values of the seven analysis elements are weighted as indicated and summed together to provide one number that indicates the relative value of the particular project. Rate of return is weighted heavily because this element is supposedly the best overall measure of benefits and costs. Weights are assigned to elements two through six so as to indicate the relative sizes of these benefits. Mean reliability is weighted heavily because the sounder the data the more valid the inference made from that data.

Input data include costs and both safety and nonsafety benefits of each project, estimated over a twenty-year period in most cases [30, p. 4]. Project costs consist of research, development, engineering, and initial construction costs, as well as future operating, maintenance, and repair costs (discounted at six percent). Safety benefits consist of the number of accidents avoided, the number of injuries avoided, and the number of lives saved. Dollar values assigned to these input data are $500 per accident, $1,200 per injury, and $75,000 per fatality [30, p. 6]. Nonsafety benefits include travel time savings in terms of vehicle-hours (1.7 persons per vehicle, three dollars per person-hour), reductions in vehicle operating costs, and reductions in roadway maintenance and repair costs.

Each cost or benefit input item is accompanied by an estimate of the reliability of that datum, based on the following scale [30, p. 4]:

10 percent: No supporting information

30 percent: Poor data, poorly conducted studies or very limited in scope

50 percent: Engineering judgment, some related information as aid or fair data

70 percent: Good data, deficiencies in studies and/or of limited scope

90 percent: Excellent data, well conducted and controlled studies, ample scope

Results of the study indicate [30, p. 9] that only eight of the fifty-seven safety projects analyzed have mean data reliabilities of 70 or greater; most mean reliability values are 60 or less, many of the data being little more than guesses. These results emphasize the fact that data reliability is often the weak link in cost-effectiveness analyses of highway safety projects.

The study reaches three major conclusions. First, the limited availability of good data implies that the results of the study should be used with caution; the results are indicative only of the relative importance of the various safety efforts analyzed [30, pp. 10-11]. To help overcome the problem of low data reliability, better quality data should be obtained on reductions in accidents, injuries, fatalities, and travel time and on savings in operating, maintenance, and repair costs [30, p. 18]. Second, attention should be paid to so-called secondary variables such as average daily traffic volume. Because they frequently have significant effects on the effectiveness of safety efforts, secondary variables should be considered in any economic analysis of highway safety programs. Third, although the weighted values of the seven analysis elements are fairly insensitive tochanges in value of travel time, pain and suffering, and interest rate used in determining present worth of future operating and maintenance costs, the study suggests using two or more different weighting schemes for the analysis elements. Since the rank ordering of safety efforts changes with changes in relative weights, several weighting schemes should be examined in any analysis of highway safety projects.

The Dale Reports

The Federal Highway Administration (FHWA), concerned with how states carry out spot highway safety improvements projects, published two reports [59, 60] by Dale, documenting the states' practices. The program documentation called for the following to be maintained on a continuing basis:

1. A system of ranking proposed safety projects based on the potential for reducing the number and/or severity of accidents.
2. A "before-and-after" accident evaluation program to permit the measurement of the effectiveness of various improvements.

The first report [59], published in 1971, analyzes 257 project evaluation studies submitted by twenty-seven states. Eighty percent of these studies are concerned with rural areas. One-third of the study sites have average daily traffic (ADT) of less than 5,000 vehicles; two-thirds have ADT of less than 10,000. Classified according to sixteen FHWA improvement codes for safety projects, the 257 projects have an average project cost of $134,774 ranging from a low of $276 for upgrading of traffic signs to a high of $1,088,763 for highway division and widening.

The report compares the sixteen improvement types three ways. The first involves finding the percentage of total construction costs (of all 257 projects) expended in each improvement category and the percentage of the total accident reduction (of all 257 projects) accounted for by that improvement code. However, the report makes no attempt to use these data to compute the cost-effectiveness of each type of improvement.

The second comparison establishes cost-effectiveness of each improvement type in terms of cost per accident reduced and cost per fatality reduced. Some of the improvements that rank high in percentage accident reduction (the first comparison) rank low in cost-effectiveness, due to the small numbers of accidents reduced.

Third, changes in accident rates per million vehicles are computed as a measure of cost-effectiveness. The results of this analysis are similar to the percentage reductions in total numbers of accidents (the first comparison).

The report concludes that certain categories of improvements are more cost-effective than others. Limitations of the study are noted; in particular, the 257 projects studied represent only a small, unrepresentative portion of the thousands of safety improvement projects being implemented nation-wide, and, for the most part, the 257 projects are rural improvements with low traffic volumes.

The second report [60], published in 1973, expands the original 257 projects to 634. Initial construction costs are converted to equivalent uniform annual costs at an interest rate of seven percent over the appropriate economic life of each project. These changes in the analysis result in no significant changes in the cost-effectiveness rankings established by the first report [59] for the sixteen safety improvement types.

The National Safety Needs Study

In response to the Congressional directive expressed in Section 225 of the Highway Safety Act of 1973, the U.S. Department of Transportation prepared the *National Highway Safety Needs Report* [61], accompanied by supporting appendices [62], to provide Congress with information pertaining to the allocation of highway safety funds. The report examines "... the pattern of expected fatalities and injuries for the next ten years in order to isolate major problem areas and to assemble and evaluate countermeasures that may be effective in dealing with them" [61, p. 2]. From thirteen problem areas, such as bad driver behavior, roadside hazards, motorcycles, bicycle and pedestrian safety, and young drivers, a list of over 200 potential countermeasures was narrowed down to thirty-seven that "...offer the highest promise of reducing future highway fatalities and injuries" [61, p. 2].

The thirty-seven countermeasures chosen for study are ranked by dollar cost of implementation per fatality forestalled. Ranking with respect only to reductions in fatalities is indicative of the report's emphasis on reducing fatalities, with less emphasis on reductions in injury and property damage only accidents [61, pp. 5, A.1.1].

Cost data are obtained from a nationwide survey of twenty states and 593 local jurisdictions. Costs are estimated in 1974 dollars over the ten-year period and converted to present value terms using a ten percent interest rate. Capital costs are adjusted for countermeasure service lives greater than ten years; implementation costs are adjusted for anticipated time lags of implementation.

The reader is instructed to keep in mind three caveats that apply to each data item or statement throughout the report [61, p. I-5]:

1. The expected effects, in terms of reducing fatalities and injuries, of each countermeasure are expressed by one single-valued estimate. Largely subjective, these estimates are intended only as a guide for relative comparisons among countermeasures within the context of this study, not as a computational item in different applications of the countermeasures studied in this report.
2. The findings of this report are on a national basis and are intended only as guidance to the individual states. The effectiveness values contained in this study should not be directly applied to any individual state study.
3. The benefits and costs of each countermeasure are incremental, i.e., each countermeasure is regarded as an addition to the existing highway safety system. The analysis recognizes only safety costs and benefits; any spillover costs or benefits are not considered.

Together these caveats imply that the importance of this study is not to identify specific countermeasures for implementation but rather to provide a methodology for developing countermeasures and improving the use of highway safety resources and to provide a *relative* ranking of the effectiveness of different countermeasures on a national scale [61, p. I-7].

Although dollars expended per fatality forestalled is considered the dominant measure of effectiveness, a procedure is presented for combining reductions in fatalities, injuries, and property damage. Because relative weighting of fatalities and injuries is primarily subjective, "...[t]he reader is invited to make use of the one he feels is most appropriate"; the analysis uses injury-to-fatality equivalences of 10:1, 30:1, and 50:1. Ranking of countermeasures changes with choice of equivalence values, but not substantially [61, p. A.1.1].

Limitations of Current Practice

There are several limitations of current practice at the federal level that must be considered. These limitations are concerned with certain benefits and costs associated with countermeasures, accident costs, countermeasure interaction, measures of effectiveness, and data reliability.

Nonsafety Benefits and Costs

Many studies addressing cost-effectiveness of safety improvements on the national scale include as benefits only safety-related benefits and costs. A notable exception is the report by Solomon, et al. [30] that includes reductions of travel time, operating costs, and maintenance and repair costs as nonsafety benefits. However, even this study omits costs related to anything other than the implementation of the safety improvement. A theoretical analysis by Stockton, et al. [63] indicates that, under certain conditions, the added vehicle operating costs associated with installing stop signs could exceed the anticipated safety benefits.

In addition to the tangible benefits of both a safety and a nonsafety nature, there are also unquantifiable benefits that should enter into the decision-making process. These benefits, such as increased driver psychological comfort associated with edgeline striping, need to be identified. Unfortunately, the site-specific nature of such benefits makes them almost imponderable at the federal level of analysis.

Accident Costs

There is a host of discrepancies in accident costs used to establish the effectiveness of various safety improvements. These costs vary not only between the various levels of government but also at the federal level. It should therefore be recognized that the reported effectiveness of a countermeasure will likely vary considerably depending on the source of the analysis. Such discrepancies should be studied carefully before a value is established for cost-effectiveness.

Interactions Among Countermeasures

Because of the massive volume of information required to estimate even the isolated effectiveness of individual countermeasures, an analysis of the interaction among countermeasures has heretofore been largely omitted at the federal level. It is especially important to consider interaction among countermeasures that accomplish the same objective. For example, edgeline striping and post-mounted delineators both are intended to assist the driver in determining the path of the roadway. However, little is known about the effectiveness of one, given that the other is already in place. Therefore, considerable caution should be exercised when planning a broad spectrum of improvements to ensure that funds are not unnecessarily allocated to overlapping improvements.

Measures of Effectiveness

A limitation of considerable concern in current practice is the lack of consistent use of measures of effectiveness. Solomon, et al. [30] use six different measures of effectiveness in a weighted form. Dale [59, 60] reports five different measures of effectiveness. Multiple measures of effectiveness are reported in the *National Highway Safety Needs Report* [61, 62]. A summary of the various measures of effectiveness is presented in Table 1.

From Table 1, the emphasis in effectiveness measures has been on the lives or injuries saved per dollar expended. Effectiveness measured in this manner avoids the volatile, though pertinent, issue of the dollar value of a life or an injury. Unfortunate as the circumstance may be, this type of analysis still leaves the decision-maker to form a subjective determination of how many lives and/or injuries saved is cost-effective.

It is apparent, then, that to complete a cost-effectiveness analysis the actual dollar benefits anticipated must be considered.

Data Reliability

One of the most pronounced limitations recognized in each of the federal level reports reviewed above is the poor reliability of data used in safety countermeasure cost-effectiveness analysis. Although some types of projects

Table 1. A Summary of Measures of Effectiveness

	Solomon [7]	Dale [8, 9]	NHSNR [10,11]
Rate of Return	X		
Lives Saved per Million Dollars	X		
Injuries Saved per Million Dollars	X		
Benefits per Year in Millions of Dollars	X		
Lives Saved per Year	X		
Injuries Saved per Year	X		
Cost per Accident Forestalled		X	
Cost per Injury[1] Forestalled		X	X
Cost per Fatality[2] Forestalled		X	X

[1] Inverse of Injuries Saved per Million Dollars

[2] Inverse of Lives Saved per Million Dollars

have fairly reliable data [30], most have questionable data reliability in nearly all aspects of analysis. Data of questionable reliability often are used for accident costs, anticipated lives and injuries to be saved, values of anticipated benefits, and environmental conditions before and after improvements are made. Some analyses include a numerical factor for reliability, while others imply the need for caution in applying cost-effectiveness measures. Generally, then, poor data reliability is recognized as one of the most significant drawbacks to the use of cost-effectiveness measures in federal programs.

Needed Development

In order to adequately plan for future safety improvment programs at the federal level, several areas need to be addressed. These areas include the following:

1. Consideration should be given to the grouping of countermeasures so that the interaction among countermeasures can be more accurately identified and thus unnecessary overlaps can be reduced.
2. More definitive procedures and forms for data collection need development to improve the reliability of data used in analyses.
3. A more accurate picture of the effects of accidents and countermeasures needs development, in both the tangible and the intangible or psychological senses. These intangibles include such factors as motorist comfort and convenience and pain and suffering of accident victims.

V. CURRENT PRACTICES OF STATE AND LOCAL GOVERNMENTS

The types of cost-effectiveness techniques used by state and local governments to determine expenditures on specific accident countermeasures have been documented in several surveys and research publications. This chapter summarizes the results of previous questionnaire surveys and also gives examples of different types of cost-effectiveness techniques used by state highway agencies.

Reviews of Current Practice

Several surveys of state and local highway agencies have been conducted during the last fifteen years to identify the methods used to compare highway alternatives. Comprehensive surveys to determine the types of economic analysis used by state highway agencies were conducted in 1962, 1966, and 1974. These surveys were directed toward identifying the methods used to compare alternative highway locations, highway designs, interchange designs, pavement designs, etc.; the 1974 survey covered safety improvements as well [64, 65, 66]. Another survey, conducted in 1973, encompassed both state and local highway agencies specifically to determine the techniques used to compare highway safety alternatives [8]. Other studies have reviewed reports of states' comparisons of highway alternatives to determine the techniques used [67, 68]. The following discussion first considers surveys made during the 1960s and then gives results of more recent surveys.

Results of Surveys Made During the 1960s

A 1962 survey of state highway agencies, which was made by the Highway Research Board, found that the benefit-cost ratio method of analysis was used by a vast majority of states; only one responding state reported that it did not use that method on at least some occasions [64, p. 121]. However, the survey also indicated that some organizational units within the highway agencies used other methods "...concomitant with the benefit-cost ratio method" [64, p. 121]. For those projects which might possibly be considered safety-oriented, however, economic analysis usually was not used; economic analysis was used in only about ten percent of maintenance projects and only about thirty-five percent of traffic engineering projects.

In Oglesby's 1962 study [68] analyzing 130 reports from thirty-four states, the District of Columbia, and Puerto Rico, ninety-five agencies reported using road-user benefit analyses of proposed alternatives including alternate highway locations, river crossing schemes, grade separation studies, and surface type determinations. In the reports which stated a source for the procedures of analysis, "...almost all referred to the 'Red Book'" [68, p. 131].

The 1962 Highway Research Board survey collected information on the use of economic analysis by the states, by organizational units within the highway departments and by type of projects on which the economic analysis was used. The different organizational units using economic analysis upon some occasion were those responsible for projects involving advance planning, preliminary design, location studies, traffic engineering, final design, programming, and maintenance. No specific mention was made of highway safety studies.

The highway departments used economic analysis most frequently for interstate highways, next for the state primary systems, third for urban roads, and least frequently for the secondary systems; this was true whatever the organizational unit. For no organizational unit or system of highways was economic analysis used in more than half the cases in which it might have been [64, pp. 122-124].

The study reported by Oglesby revealed that, in general, user costs were calculated for design-year or terminal-year traffic, and user costs were assumed uniform over the period of analysis. Most of the states which used terminal-year design standards chose 1975 as the terminal year, giving an average analysis period at that time of approximately fifteen years in length. Another researcher reported that, in general, the period of analysis used was twenty-years because it was felt that this is the maximum period for which projection of traffic growth is reliable [69, p. 76].

Most states used the user costs as recommended in the various charts and tables in the Red Book although some states used fixed user unit costs. Also, of the 135 reports reported by Oglesby, only five reports (from two states) included accident costs in road-user costs. Grant and Oglesby reviewed eighty-five studies (from thirty-five states) which made comparisons of alternate highway locations, and they also found that "...relatively few of the studies place any money valuation on the prospect of reduction in highway accidents" [67, p. 2]. Thus, even though alternatives that affected accident rates were compared, accident costs usually were not considered; this aspect is discussed in more detail in a later section of the report.

Although use of incremental benefit-cost analysis often is necessary for analyses to be correct, there were indications that incremental analysis was seldom used. "Of the 68 analyses that used the benefit-cost ratio method, a 'second benefit ratio', also called an incremental benefit-cost ratio, appeared in seven reports; yet all but five studies considered multiple alternatives" [68, p. 131].

A later Highway Research Board survey [65] of state highway agencies, which received replies from only twenty-one states, gave results similar to the 1962 survey. The 1966 survey indicated an increase in the number of states considering accident costs; four of the twenty-one agencies replying in 1966 considered accident costs, as compared to only two of fifty agencies in 1962 [66, p. 24].

Recent Surveys

In 1974, a survey [66] of state highway agencies was made to determine the methods of economic analysis used and also to obtain recommendations for revising the Red Book. Of thirty-nine states replying to this survey, twenty-seven conducted limited studies [66, p. 21]. From the survey results, it was estimated that from fifty to seventy percent of the states performed economic analyses on a more or less regular basis; it further was estimated that this was a ten to twenty percent increase over the proportion performing such analyses on a regular basis in 1962 [66, p. 21].

The 1974 survey also determined that the Red Bookstill was the primary reference source used for conducting economic analyses. Thirteen states still used the original 1959 unit prices that were given in the 1960 Red Book, and another twelve states used the 1960 Red Book format but used updated cost values. In addition, five states used the NCHRP Report 111 [70], seven used the NCHRP Report 133 [14], fourteen used Winfrey's textbook [15], and seven other states used other references [66, p. 24. It also was reported that California was developing a computerized benefit-cost procedure and that Oregon had a highway investment rate of return program. An additional three states reported using computers in their analyses.

Only six of the states responding to the 1974 survey indicated that they used "accident experience" data in their highway economic analyses. However, the weighted percentage of states performing economic analyses of safety improvement projects was forty-four percent. In addition, twenty of the thirty-nine responding states indicated that they had average accident costs for use in economic analyses of highway projects [66, p. 22].

Another survey made in 1973 and reported in the NCHRP Report 162 [8] canvassed not only state highway agencies but also many local governments in the United States, as well as a few foreign governments. This survey was different from those surveys previously discussed in that the objective was to determine the specific types of analyses used for safety improvement projects rather than for general types of highway improvement projects. The NCHRP Report 162 questionnaire was sent to ninety-one highway agencies; fifty-one agencies responded to the survey. The survey indicated that the following methods were used (or not used) to evaluate highway safety projects [8, p. 68]:

	Number of Agencies	
Method	Used	Not Used
Benefit-Cost Ratio	32	9
Total Benefit	10	31
Rate of Return	7	34
Present Worth	4	37
Incremental Benefit-Cost Ratio	1	40
Other	-	-

It is not clear exactly what was meant by the evaluation methods denoted as "present worth" and "total benefit." In the absence of further information, it perhaps can be presumed that these methods are some variation of a net benefit formula by which the "present worth" of net benefits or "total benefits" less costs is maximized. Whatever the meaning of these two terms, it seems clear that most agencies used some variation of benefit-cost analysis, and the others used the rate-of-return method.

All fifty-one agencies responding to the NCHRP Report 162 survey indicated that they either used or planned to use accident experience data to identify accident problem locations. This is quite different from the results obtained in the 1974 survey of state highway agencies that indicated only six of the thirty-nine responding agencies used accident experience data to evaluate projects. These results may indicate that accident experience data are used, as might be expected, to evaluate safety projects but are not ordinarily used in evaluations of major highway improvements. In evaluations of major highway improvements, it appears that instead of using accident experience data, states often either omit accident costs or use average accident rates for the general types of highway improvement being considered. Apparently, the main benefits considered in major highway improvements are reductions in travel time costs and vehicle operating costs, even though some states do consider accident costs. Evaluations of safety projects usually consider only reductions in accidents or accident costs as benefits.

In 1972, the Comptroller General of the United States prepared a report that reviewed problems in implementing the Highway Safety Improvement Program. A later Government Accounting Office (GAO) report [71] submitted in 1976 updated that review and also attempted to determine the impact of the categorical safety funds provided by the Highway Safety Act of 1973. In preparing the 1976 report, the GAO reviewed highway safety programs in California, Idaho, Louisiana, Maryland, Nevada, Pennsylvania, Texas, and Washington.

The GAO Report found the following types of weaknesses in the states' safety programs [71, pp. ii-iii, 7]:

1. Some accident data were not being analyzed to determine the most hazardous locations.
2. Safety improvement projects were not always selected on the basis of cost-effectiveness.
3. Inventories of cost-effective projects were not being used to determine priorities.
4. Projects financed with federal-aid construction funds were not selected through a systematic approach.
5. Federal-aid highways under some local jurisdictions were not considered and did not receive safety funds.

The GAO report cited specific examples of states' weaknesses in these areas [71 , pp. 7-13]. Many of these examples relate to the states' not using federal-aid funds either in certain urban areas or on federal-aid highways under the control of local governments.

The GAO report found that, of the eight states reviewed, "...four did not use cost-effectiveness analysis and another did not consistently use its method for selecting safety improvement projects" [71, p. 9]. Specific comments with respect to four of the eight states reviewed were [71, pp. 9-10]:

1. Maryland officials had not made cost-effectiveness studies. They said that because the available safety improvement funds were sufficient for all the State's planned projects, there was no need to establish project priorities. The State's 1975-76 funds for high-hazard locations were used mainly on one improvement--a $2.6 million project to build an interchange at an intersection. The intersection did not rank high on the State's accident listing; however, State officials selected the project because the engineering plans and specifications were on the shelf at the time funds became available and some safety benefits would be achieved. Maryland officials told us in August 1976 that they have initiated cost-effectiveness studies and are establishing project priorities.

2. Louisiana had established safety improvement priority lists but the priorities were not based on cost-effectiveness. Instead they were based on engineering judgment and analysis of accident data. The weakness in this system is that the improvements are not related to anticipated benefits. The State expects to implement a cost-effectiveness method in the future.

3. Nevada used high-hazard location safety funds for installing illuminated street name signs. The project justification submitted to the Highway Administration stated that the street signs were to be installed at hazardous intersections; however, a cost-effectiveness analysis had not been prepared.

4. California did not make cost-effectiveness studies before selecting rail-highway grade crossing projects. The State was using $2.8 million of its federal funds to construct grade separations at two rail-highway crossings. The State selected these projects because it believed projected increases in automobile traffic would increase the possibility of accidents at the crossings. In September 1975, the Highway Administration told the State that grade separation projects would appear very low in cost-effectiveness and in the future would require individual justifications of cost-effectiveness.

In response to the GAO report the Federal Highway Administration noted that [71, p. 27]:

> Although [highway safety] program requirements were established in 1966, it was not until passage of the Highway Safety Act of 1973 that the program was given major status by the provision of categorical safety funds for construction of highway safety improvements.
>
> Since passage of the Highway Safety Act of 1973, most states have made significant progress in implementing their overall highway safety programs including their highway safety construction efforts.

Additional discussion of current practices is included in the discussion in Chapters VI and VII of specific submodels of cost-effectiveness techniques. The remainder of this section gives examples of practices of specific states.

Examples of Current Practice

The preceding discussion documents how many state and local governments use some type of benefit-cost analysis to compare both major highway alternatives and highway safety alternatives. In this section, several examples of current practice are given. Discussions of Texas and California are included as examples of well-developed procedures for conducting benefit-cost analysis. The recent use of dynamic programming in Alabama and Kentucky is given as an example of the use of an advanced technique for simultaneously determining which accident locations and improvement alternatives should receive priority treatment. Operations Research, Inc.'s cost-effectiveness technique using step-wise linear programming also is given as an example of an advanced theoretical technique that has been pilot tested in several states.

Use of Benefit-Cost Analysis in Texas and California

Texas

The Texas Department of Highways and Public Transportation uses different types of economic analysis procedures for different types of highway expenditures. For major construction and reconstruction, the Texas Highway Economic Evaluation Model [19] is used to calculate benefit-cost ratios. For safety type projects, a safety improvement index which indicates the relative rating of individual safety projects is computed.

Highway Economic Evaluation Model

The Highway Economic Evaluation Model (HEEM) used in Texas is a computerized procedure that calculates an economic ratio for improvement projects. This economic ratio is basically an incremental benefit-cost ratio for different alternative highway improvements. Benefits included in the program are travel time savings, reductions in vehicle operating costs, and reductions in accident costs. Detailed computerized procedures are used to calculate travel time costs and vehicle operating costs for different highway alternatives.

In HEEM, different accident rates are used for highways with different geometric features. These accident rates were developed from information collected in the Houston, Dallas, and Fort Worth districts of the state highway agency [19, pp. 2-7]. The average accident costs used in the Texas HEEM are [19, p. A-20]:

	Rural	Urban
Freeways	$ 2,300	$ 1,800
Expressways	2,300	1,800
Conventional	1,800	1,700

These accident cost estimates were developed from California cost estimates, weighted by Texas experience, using values as follows:

		Cost per Accident	
	Total Accidents	Urban	Rural
Fatal	0.4%	$110,000	$140,000
Injury	14.6	3,500	4,500
PDO	85.0	1,000	1,400
Average		1,800	2,300

The costs of different accident types are calculated using "actual lifetime earnings" for fatalities, "lost earnings and medical costs" for injuries, and "average repair costs" for property damage [19]. Since the California accident costs were in turn based on a Wilbur Smith study of the Washington D.C. area, the accident costs used in HEEM actually are updated modifications of that data. The Wilbur Smith and California accident costs also are used extensively in the revised Red Book, as discussed in the section dealing with accident costs in Chapter VII.

Safety Improvement Evaluations

Different types of safety improvement projects are evaluated in Texas by the twenty-five District Offices working together with Headquarters Divisions [72, 73]. Safety programs dealing with High-Hazard Locations, Elimination of Roadside Obstacles, and Pavement Marking Demonstrations are the responsibility of the Division of Maintenance Operations' Safety Section (D-18S). Rail-Highway Crossings and Bridge Replacment projects are handled by the Bridge Division (D-5). Major construction and reconstruction and pavement design projects are handled by the Highway Design Division (D-8).

High-hazard locations and elimination of roadside obstacles. In order to identify projects and allocate funds on a priority basis for these two programs, districts submit projects to the Headquarters Divisions each year. Those projects submitted for inclusion but not financed in the previous funding periods for the Statewide Highway Safety Improvement Program are resubmitted. Utilizing computer printouts of accidents, the districts identify those locations where improvements are necessary to alleviate safety hazards. Three guidelines are suggested to aid in identifying these locations:

1. Five or more accidents per year for 1/10 mile (.17 km) section (rural)
2. Three or more accidents per year at intersections (rural)
3. Urban accident lists

After identifying the hazardous locations, the districts make an analysis of the problem, explore alternative solutions, and choose one of these solutions based on engineering assessment and judgment as to what would best alleviate the particular problem.

The districts submit a Safety Evaluation Report for each project in their respective jurisdictions. Each report includes location data, accident data (numbers of fatalities, injuries, and PDO accidents), number of years of accident experience, traffic data (present and future ADT), expected life of project, total cost of project (including maintenance costs), and a description of the proposed work.

Based on the solution recommended by a particular district, the Division Office assigns an Accident Reduction Factor to the project using data furnished by the State of California Transportation Department in 1971 (see next section of report for California's Accident Reduction Factors). These Accident Reduction Factors will be validated or modified by Texas as accident reduction data are received from the districts following the implementation of specific countermeasures. Because of the uncertainties and complexity involved, no attempt is made to determine the interactions of several treatments to a location.

Existing computer programs are used to compute a Safety Improvement Index. This index is essentially based on the cost savings resulting from the reduction in accidents over the life of the project. Current accident costs obtained from the National Safety Council are used in computing the index. Projects are then rank ordered according to the index, and funds are allocated to the highest priority projects until the budget is exhausted.

Safer roads demonstration. Priority allocation of funds is accomplished in a manner similar to that for the High-Hazard Locations and Eliminations of Roadside Obstacles programs.

Pavement marking demonstration. Allocation of funds for this program is based on ADT rather than on any specific cost-effectiveness computations. The program over the years has included the following types of projects:

1. Striping on highways with ADTs that did not previously warrant striping (with ADTs ranging between 250 and 300)
2. Edgeline striping
3. Raised pavement markings

Off-system roads projects. Off-System Roads projects are also handled through the Division of Maintenance Operation-Safety (D-18S). Allocation of funds is made on a priority basis using the procedure and safety index computer program discussed above.

Rail-highway crossings [74]. The State of Texas had an active rail-highway crossing safety program as far back as 1967 when the State Legislature appropriated $1.5 million per year which was to be used for rail-highway crossing devices. The Highway Safety Acts of 1973 and 1976 provided additional impetus to the state program.

There are two categories of systems for the federal program, On-System and Off-System. Texas does not use a cost-effectiveness approach but rather utilizes a Hazard Index formula so that rankings can be developed in each category. Either a five-year accident history or the number of accidents that occurred since the installation of a previous device are used. One characteristic of the Hazard Index is that it becomes inflated whenever two or more accidents occur at a location. In addition to the Hazard Index, repetition of accidents at a specific location is considered.

The state feels that the accident and volume data that the division offices receive for the On-System are good, although data for the Off-System are suspect. Therefore, before an Off-System is selected, the division and districts conduct further investigations. The districts field-inspect the sites and evaluate data; using the information they compile, they then submit the project to the division for funding consideration. After the project has been selected for funding, a diagnostic team consisting of members of the federal, state, and local governments involved and the railroad involved investigate the site to determine the control devices that should be implemented. An interesting note is that the 1976 Highway Act requires the states to install passive devices at all crossings to bring them up to minimum MUTCD standards.

Bridge replacement [74]. Texas is working under both state and federal bridge replacement programs. Bridge replacement for the federal program is based on a Sufficiency Rating formula, dictated by FHWA, having weighting factors for certain types of deficiencies. FHWA will accept any project having a sufficiency rating of 50 or less. Projects having a rating in this range are further scrutinized by the state; projects are selected for submission to FHWA based on the state's assessment of importance.

Generally, complete bridge replacement is necessary for a project to be eligible for FHWA funding (72-25 participation). Replacement of only the bridge deck is normally not an acceptable project.

The bridges must be on a federal-aid route. Although most projects thus far have been on the state system, the federal money can also be used on federal roads that are not on the state system (e.g., urban system).

1975 Statewide Highway Safety Improvement Program [73]. In the 1975 Statewide Highway Safety Improvement Program, Texas made separate lists for four categories of projects: High Accident Locations, High Hazard Locations, Roadside Fixed Objectives, and Skid Prone Locations. This was done in order to place more emphasis in needed categories other than solely high accident locations. The projects were broken down further by Interstate and non-Interstate highways. A separate list of off-federal system locations was submitted through the Governor's Office of Traffic Safety from lists furnished by the cities and counties.

The purpose of having four categories was to provide a means of rating those proposed projects on highway sections that were hazardous and did not have enough actual experience to be rated very highly in the accident listing. Thus, a program could be formulated using the higher priority projects from four lists rather than just one list. However, because of funding limitations, only the High Accident Location category was used. The rationale for this approach was that there were not enough funds to cover all of the high accident location projects.

After the highest accident locations have been improved, funds probably will be expended on other categories. It is expected that additional data for evaluating potential accident locations will be developed at that time.

California

The state highway agency of California has developed comprehensive procedures for evaluating both major highway improvements and highway safety improvements. For evaluating major highway improvements, California has a computerized benefit-cost ratio procedure that includes consideration of travel time costs, vehicle operating costs, and accident costs. As discussed later in this report, the accident rates and accident costs used in California also are included in the revised Red Book for possible use in other states.

California's method for evaluating highway safety improvements, which was described in detail in 1970 [75], is a good example of a comprehensive approach that has several procedures for different types of safety improvements. Key ingredients to their approach are:

1. Statewide accident rate studies provide a base for evaluating new highways, major reconstructions, and safety projects.
2. Accident costs are used together with project costs to calculate a "safety index," which actually is the project's benefit-cost ratio multiplied by 100. The costs used for accidents include direct costs plus some indirect costs but do not include the full societal costs.
3. The effectiveness of accident countermeasures usually are calculated as percentage reductions in actual rates (if these are significantly different from average rates) or percentage reductions in the base rate.

California's overall approach is one that combines several of the better techniques now available for comparing accident countermeasures.

Method for Determining Accident Costs

One important aspect of the California approach which is not used in other states is their use of statistical concepts in determining average accident cost for comparing improvement and nonimprovement alternatives [27, p. 30]. If accident severities on the highway facility that is a candidate for improvement are not significantly different from the average severities (i.e., are "normal") for that type of highway, then the average (total) accident costs for that type of facility are used (see Table 2). Also, it is assumed that the severity mix will be normal on new highways. If accident severities are not normal, accident costs are calculated using average costs by severity type [75, p. 30]:

> Before estimating accidents that would occur on the existing facility with no improvement, a statistical test [29] is made of the severity distribution of the accidents occurring over the past several years on the existing road. If the distribution is normal, or approximately so, the average cost of accidents for that road type is used. If, however, the accidents are more severe than normal, a higher accident cost is used to reflect the higher costs of fatal and injury accidents. Conversely, if the accidents are less severe than usual, a lower cost is used. In this manner, considerably more weight is given to the fatal and injury accidents than to the "fender benders."
>
> For instance, the reported accidents on most rural freeways in California are composed of about 4 percent fatal, 43 percent

Table 2. Costs by Accident Severity

Highway Type	Fatal	Injury	Fatal and Injury	Property Damage Only	Total
Rural					
2-lane	95,000	3,000	8,800	1,000	4,600
3-lane	95,000	3,000	10,500	1,000	5,000
4 or more lane undivided	95,000	3,000	6,700	1,000	3,400
4 or more lane divided	95,000	3,000	7,800	1,000	3,900
Divided expressway	95,000	3,000	9,500	1,000	4,800
Freeway	95,000	3,000	10,100	1,000	5,300
Urban					
2-lane	76,000	2,400	4,000	700	1,800
3-lane	76,000	2,400	4,800	700	1,900
4 or more lane divided	76,000	2,400	3,700	700	1,700
4 or more lane undivided	76,000	2,400	3,700	700	1,700
Divided expressway	76,000	2,400	4,900	700	2,300
Freeway	76,000	2,400	4,300	700	2,200

Source: [75, p. 31].

> injury, and 53 percent property-damage-only accidents. We have developed a curve ... that indicates, for any given accident sample size, how much variation there must be between the observed and expected distribution of severities to be statistically significant. This curve is based on the Poisson distribution, at the 85 percent confidence level, and is another form of the "liberal test" curve shown in Figure 3 of the Morin report [76]. For instance, if in 100 accidents on a rural freeway there are 6 fatal accidents instead of 4, are the 6 fatal accidents really different from the expected 4 or are they merely a reflection of the usual statistical fluctuations in accident frequency? Figure 5 shows that with an expected frequency of 4 accidents, an actual occurrence of 1 to 7 is "normal." Therefore, the 6 is not abnormally high. If there had been 8 fatal accidents out of the 100, then it could be said with reasonable assurance that this is not a chance occurrence but that 8 fatal accidents occurred because there is something especially hazardous about this section of road.

stimating Accident Rates and Effectiveness

For major highway improvements such as building new highways or wid- ng freeways, California predicts future accident rates for existing and facilities by using actual rates on existing facilities. The general odology is summarized in Table 3, which refers in some situations to 4, (which in turn refers to Figure 6). Table 5 gives the percentage down of accidents by severity, used to calculate predicted number of nts by severity.

r spot safety improvements, California has developed a set of acci- duction factors, shown in Table 6, which are percentage reductions d for different types of safety projects. These percentage reduc- pply to accident rates, either per million vehicle miles or per vehicles. At the time these were published, these reduction fac- ere based on approximately 500 "before and after" accident studies. ternate methods of predicting accidents are used [75, p. 37]:

> he analysis technique also provides for two alternative methods f predicting accidents on improved facilities. The first pro- ides for the engineering analysis of individual accidents and a etermination of which accidents are susceptible to correction y the specific improvement proposed. This percentage reduction actor can be used as long as the reduced accident rate remains t or above the base rate. The reason for this limitation is hat analysts sometimes neglect to consider trade-offs. For xample, signal installations usually reduce right-angle acci- ents but often increase rear-end accidents. The other alterna- tive analysis can be used in the case of guardrail projects, for

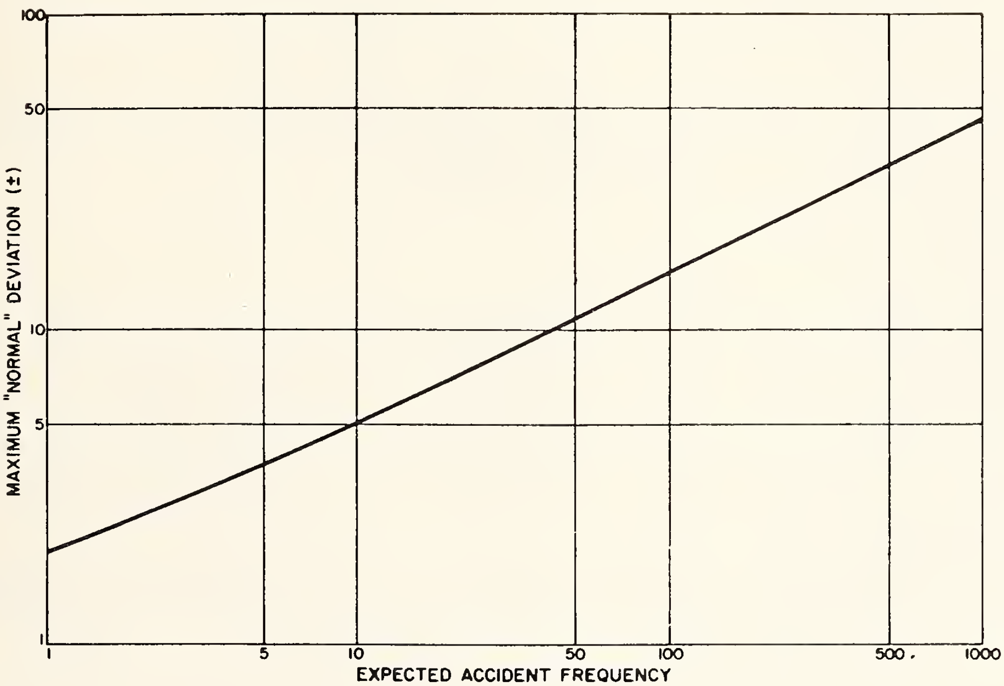


Figure 5. Maximum Expected Deviation at 85 Percent Confidence Level

Source: [75, p. 30].

Table 3. Methodology Summary for Estimating Future Accident Rates

Type of Facility	How to Predict Future Accident Rate
Existing conventional highway and urban expressway	Current rate of existing highway
Existing rural expressway	New rate = $(A/B) \times C$[a]
Existing freeway	New rate = $(A/B) \times C$[a]
New conventional highway and urban expressway	0.8 of latest statewide 3-year average (Table 4)[b]
New freeway and rural expressway	Figure 6, 0.8 rate values[c]
Widened freeway	
4 to 6 lanes	60 percent of expected rate for 4 lanes[d]
4 to 8 lanes	50 percent of expected rate for 4 lanes
6 to 8 lanes	80 percent of expected rate for 6 lanes
6 to 10 lanes	75 percent of expected rate for 6 lanes
8 to 10 lanes	90 percent of expected rate for 8 lanes
Shoulder widened on conventional highway	0.8 to 1.0 of statewide average (Table 4)
Widened conventional highway 2 lane to multilane	0.8 to 1.0 of statewide average (depending on standards proposed) for type of multilane proposed

[a] A = current accident rate; B = statewide average rate for current ADT; and C = statewide rate for future ADT.

[b] If new facility is to be constructed to less than current standards, use 1.0 of latest statewide rates.

[c] If new facility is to be constructed to less than current standards, use 1.0 rate value in Figure 6.

[d] Expected rate calculated for existing rural expressway and freeway.

Source: [75, p. 34].

Table 4. Statewide Accident Rates
(1966-68 Average)

Highway Type	Rural Statewide Average	Rural 0.8 Value	Urban Statewide Average	Urban 0.8 Value
2-lane conventional	2.50	2.0	5.35	4.3
2-lane expressway	1.70[a]	1.4	2.74[a]	2.2
3-lane conventional	2.91	2.3	5.38	4.3
4 or more lane undivided	3.55	2.8	6.15	4.9
4 or more lane divided	2.53	2.0	5.30	4.2
Divided expressway	(see Figure 6)			
Freeway		(see Figure 6)		

Note: Rates are total accidents per million vehicle-miles.

[a]1968 average rate only.

Source: [75, p. 29].

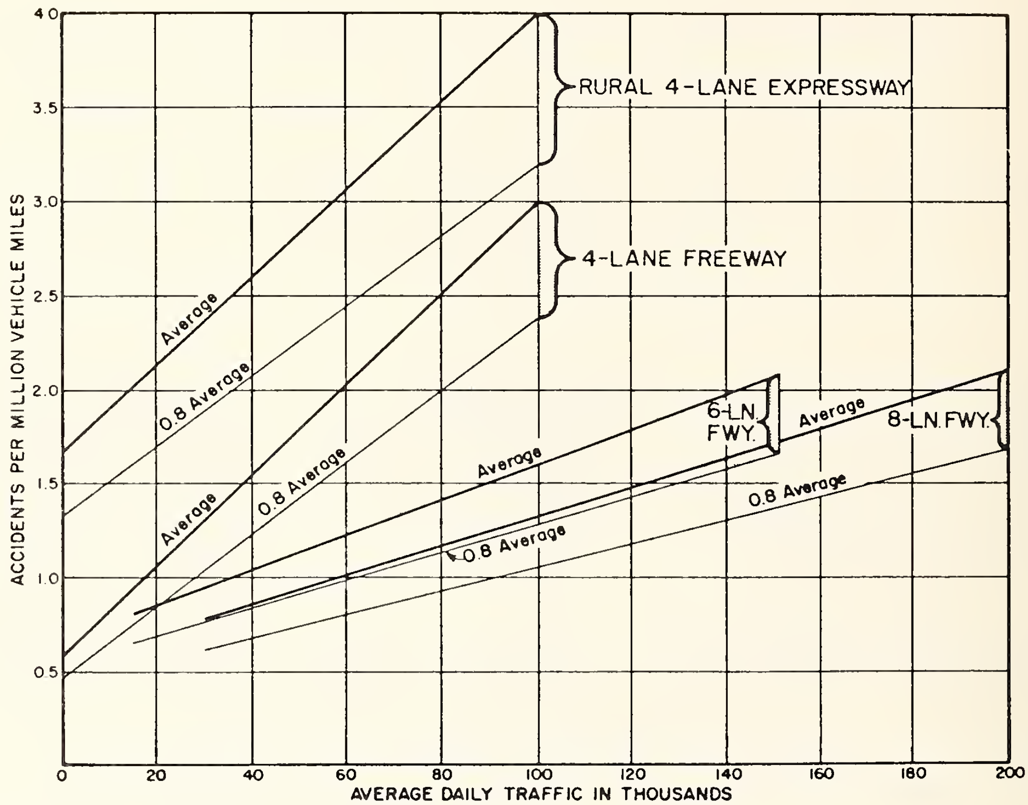


Figure 6. Accident rates for freeways and expressways with varying numbers of lanes.

Source: [75, p. 29].

Table 5. Percentage Distribution by Accident Severity

Highway Type	Fatal	Injury	Fatal and Injury	Property Damage Only	Total
Rural					
2-lane	2.9	43.0	45.9	54.1	100.0
3-lane	3.4	38.7	42.1	57.9	100.0
4 or more lane undivided	1.7	39.7	41.4	58.6	100.0
4 or more lane divided	2.2	39.8	42.0	58.6	100.0
Divided expressway	3.2	42.0	45.2	54.8	100.0
Freeway	3.6	43.2	46.8	53.2	100.0
Urban					
2-lane	0.7	31.0	31.7	68.3	100.0
3-lane	0.9	28.4	29.3	70.7	100.0
4 or more lane undivided	0.6	33.8	34.4	65.6	100.0
4 or more lane divided	0.6	31.5	32.1	67.9	100.0
Divided expressway	1.3	35.6	36.9	63.1	100.0
Freeway	1.1	40.7	41.8	58.2	100.0

Source: [75, p. 31].

Table 6. Accident Reduction Factors for Highway Safety Factors

Type of Improvement	Average Accident Reduction	Accident Base Rate[a]
New signals	15	
Modified signals	10	1.00 A/MV in urban areas
New signals with channelization	20	1.25 A/MV in rural areas
Modified signals with channelization	35	
Left-turn channelization		
At signalized intersections	15	0.80 A/MV
At nonsignalized intersections		
With curbs and/or raised bars	65	0.40 A/MV
Urban area	70	0.40 A/MV
Rural area	60	0.50 A/MV
Painted channelization	30	0.80 A/MV
Urban area	15	1.00 A/MV
Rural area	50	0.60 A/MV
Flashing beacons		
Intersection flashers		
4-leg, red-yellow	50	1.10 A/MV
3-leg, red-yellow	50	0.70 A/MV
4-way, red	75	0.80 A/MV
Railroad crossing	80	0.20 A/MV
Advance warning flashers		
Curve and intersection	30	1.00 A/MV
New safety lighting		
At intersections	75[b]	0.80 A/MV[c]
At railroad crossings	60[b]	NA (assume 1.00 A/MV)[c]
At bridge approach	50[b]	NA (assume 1.00 A/MV)[c]
At underpasses	10[b]	0.70 A/MVM[c]
Delineation		
Median double yellow	5	0.45 A/MVM
Right-edge lines	2[d]	1.85 A/MVM
Reflectorized raised pavement markers	5	NA (assume 2.00 A/MVM)
No passing stripes	65[e]	2.60 A/MVM
Reflectorized guide markers		
At horizontal curves	30	1.10 A/MV
At bridge approaches	40	0.10 A/MV

Table 6. Accident Reduction Factors for Highway Safety Projects (continued)

Type of Improvement	Average Accident Reduction	Accident Base Rate[a]
Protective guardrail		
At bridge rail ends	50	0.30 A/MV
At embankments	50	1.20 A/MV
Pavement grooving		
Lengths less than 0.50 miles	75[f]	Dry accident rate
Lengths greater than 0.50 miles	75[f]	Dry accident rate
Signing		
Curve warning arrows	20	2.50 A/MV
Advance curve warning with advisory speed	20	1.80 A/MV
4-way stop	70	0.50 A/MV
Advisory speed sign	36	2.28 A/MV
Special curve warning arrow with stated speed	75	1.30 A/MV
Reconstruction and miscellaneous[g]	20[h]	
Less than 0.50 miles in length		
Rural conventional roads		1.00 A/MV
Urban conventional roads		1.33 A/MV
Rural and urban freeways		0.50 A/MV
Greater than 0.50 miles in length		_[i]

[a] A/MV = accidents per million; A/MVM = accidents per million vehicle-miles.

[b] Night accidents only.

[c] Nighttime rates based on one-third ADT.

[d] Or 25 percent of ran-off-road accidents.

[e] Or 85 percent of passing accidents.

[f] Wet pavement accidents only.

[g] Widen, superelevation, correct, construct shoulder, increase curve radii, and increase sight distance.

[h] Or reduction based on study of individual accident reports.

[i] Applicable statewide accident rates in Table 1, or 0.8 of rates if constructed to high standards.

Source: [75, p. 38].

example, where studies have shown that a reduction in the number of accidents may not be possible, but that a reduction in average accident severity (percentage of accidents that are fatal and injury) can be expected.

The California method can be illustrated with two examples which were given in a 1970 article:

Example No. 1: Major Construction Project [75, pp. 35-36].

A conventional 2-lane rural road is to be converted to a 4-lane freeway at a cost of $8,600,000 (unbudgeted construction plus unbudgeted right-of-way). The 1970 traffic is 11,500 vehicles per day, and 29,000 is predicted in 1990. Capacity of 24,000 vehicles per day of the 2-lane road is reached in 1984. No other parallel local road exists or is planned because the existing state highway crosses a marshy tideland.

The travel that will occur with and without the freeway construction and the observed and expected accident frequency for the past 3 years is shown in the following example of an existing 2-lane highway, 6.9 miles long, proposed to be improved to a 4-lane freeway, 6.5 miles long. The construction and right-of-way cost (unbudgeted) is $8.6 million, and the project life is 20 years. Traffic data are as follows:

Item	No Improvement	With Improvement
Vehicles Per day		
1970	11,500	11,500
1984	24,000[a]	-
1990	24,000[a]	29,000
Vehicle-miles generated	987,000,000	958,000,000

[a]Capacity of 2-lane road; no alternate routes available.

The accident experience for the past 3 years is as follows:

Accident Severity	Observed[a]	Expected[a]	Significant[b]
Fatal	14	3.6	Yes
Injury	48	52.9	No
Fatal and injury	62	56.5	No
Property-damage-only	61	66.5	
TOTAL	123	123.0	

[a]Based on 2.9 percent fatal, 43.0 percent injury, and 54.1 percent property-damage-only.

[b]See Figure 5.

Note that the number of fatal accidents is abnormally high for a total of 123 accidents (only 4 are expected). Therefore, it is necessary to compute the specific accident cost for this 2-lane road. Specific average cost of accidents on the existing road is as follows:

Fatal	14 x $95,000 =	$1,330,000
Injury	48 x 3,000 =	144,000
Property-damage-only	61 x 900 =	61,000
TOTAL	123	1,535,000
Average Cost	$1,535,000/123 =	$12,480

The accident costs and savings are as follows:

	Number of Accidents	Cost of Accidents
2-lane road	987 x 1.93 = 1,905	1,905 x $12,480 = $23,770,000
4-lane freeway	958 x 0.85[a] = 815	815 x $ 5,300[b] = 4,320,000
Savings	1,090	$19,450,000
Safety Index		($19,450,000/8,600,000) x 100 = 230 percent

[a]0.8 average accident rate at average ADT of 20,200 (Figure 6).

[b]Average cost of rural 4-lane freeway accident with normal distribution of severities (Table 2).

Example No. 2: Spot Improvement Project.

An example of the calculation of a spot improvement project is given as follows [28, pp. 37, 39]:

...it is proposed to improve a 2-lane conventional highway in a rural area by constructing left-turn lanes. The cost is $22,000 for construction; no additional right-of-way is required. The project life is 20 years. The 1969 ADT is 5,000 on the state highway and 1,600 on the county road; the 1989 ADT is expected to be 8,000 on the state highway. Travel generated is 62.6 million vehicles based on the sum of the ADT on the state highway and county road and on the assumption that the ADT on the county road will increase in the same proportion as that on the state highway. The existing accident rate is 0.98 accidents per million vehicles. The accident experience on the existing highway for the past 4 years is as follows:

Accident Severity	Observed	Expected[a]	Significant
Fatal	0	0.3	No
Injury	8	3.8	Yes
Fatal and injury	8	4.1	Yes
Property-damage-only	1	4.9	
TOTAL	9	9.0	

[a]Based on 2.9 percent fatal, 43.0 percent injury, and 54.1 percent property-damage-only (Table 5).

The fatal category is not significantly high, but the injury category is. Therefore, the average cost of the past accidents (and the assumed cost of accidents in future without any improvements) is calculated as follows:

Fatal and injury	8 x $8,800[a]	=	$70,400
Property-damage-only	1 x 1,000	=	1,000
TOTAL	9		71,400
Average Cost	$71,400/9	=	7,930

[a]Average cost of fatal plus injury accident (Table 2).

Table 6 gives a 50 percent accident reduction and a base rate of 0.60 A/MV with painted channelization at a rural, unsignalized intersection. A 50 percent reduction would give a final rate of 0.49 A/MV, which is lower than the base rate. Therefore, the base rate is used to predict accidents on the improved facility. Also, the average unit accident cost is used because the improvement should make the severity distribution normal.

The number and costs of accidents with or without the improvement is computed as follows:

Rate x million vehicles = number of accidents x unit cost = total cost

The savings with the improvement are, therefore, as follows:

Without improvement	0.98 x 62.6 = 61 x $7,930	=	$484,000
With improvement	0.60 x 62.6 = 38 x $4,600	=	$175,000
Savings	23		309,000
Safety index	($309,000/22,000) x 100	=	1,400 percent

Needed Improvements

The Texas and California approaches to safety evaluation have the advantage of being comprehensive, in that detailed benefit-cost procedures have been developed for major construction projects as well as safety improvement projects. Their procedures for evaluating major construction projects use incremental benefit-cost analysis and have detailed procedures for estimating reductions in accident costs. Each state uses the accident reduction factors based on California "before-after" studies for predicting the effectiveness of safety improvement projects.

While some aspects of the Texas and California procedures should be of interest to other states, there are several areas of possible improvement in the two methods:

1. Additional studies should be performed to determine accident rates for new and improved highways. Current procedures basically assume that new highways will have accident rates that are some percentage of average rates for old highways of that type.
2. The somewhat unique statistical procedure used in California for estimating accident costs based on accident severity frequencies appears promising for use by other states.
3. The accident costs used in California and Texas are based on orare similar to those of the National Safety Council and the Wilbur Smith study of the Washington, D.C. area. Accident costs derived using this method do not include full accident costs, as discussed in a later section.
4. Both states usually assume, in effect, that the types of accidents that will be reduced by safety improvements are the same as the types occurring on the highway or highway type being considered. The validity of this assumption needs to be examined carefully.
5. The "before-after" studies used for estimating accident reduction factors needs to be rigorously examined for accuracy of the statistical design of experiments.
6. Improved methods need to be developed for determining accident locations that are candidates for improvement.
7. It probably would be desirable to use cost-effectiveness analysis to compare alternative improvements at each accident location, in addition to the current practice of comparing locations on a cost-effectiveness basis.
8. Benefits (and disbenefits) other than reductions in accident costs usually are not considered for safety improvement projects.

9. Texas' new procedures for predicting run-off-road accidents appears promising but also could be improved in several ways.

10. Neither Texas nor California considers interactions among countermeasures.

Use of Dynamic Programming in Kentucky and Alabama

The process of determining which projects to implement under a limited budget is central to state-level highway safety programs. Increasing numbers of potential spot improvement projects and ever-larger budgets, especially since the Federal-Aid Highway Safety Act of 1973, make a computerized priority allocation algorithm helpful in the selection process. One increasingly popular method of budget allocation is dynamic programming (DP), originally introduced by Bellman [77] and enlarged upon by others in the area of highway safety programs [78, 79, 80, 81, 82, 83]. Two states, Kentucky and Alabama, have developed and implemented highway safety spot improvement programs that involve DP in project selection under a budget constraint. Their programs are outlined in published research reports [51, 52].

Kentucky

Kentucky's study [52] evaluates multistage DP as a means of assigning priorities to and allocating funds for spot safety improvement projects throughout Kentucky. The study is based on Alabama's work [81, 82, 83] but has "...[s]ignificant modifications ... to evaluate the data which were available for the spot-improvement program in Kentucky" [52, p. 3].

Sixty-one high-accident locations, previously improved under Kentucky's spot improvement program, provide test data for the study. The improvement alternatives used in the analysis consist of those improvements that were actually made at the various 61 locations.

The benefit, in terms of accident loss reduction, of each improvement project is based on estimated accident costs and on the expected reduction in accidents after implementation of the project. Accident cost values are those used by the National Safety Council, 1971 [84]:

$45,000 - Fatal accident
2,700 - Injury accident
400 - PDO

Since 1968, accident records for 447 improvement projects around the state of Kentucky have been studied to determine changes in the accident rate associated with each type of improvement. For a particular location, the annual benefit of a specific type of improvement project is the expected or average reduction in the accident rate at the location in question times accident costs. The total benefit of the project is the discounted or present value of the benefits over the estimated life of the project, using an interest rate of ten percent and a factor to account for an expected four percent annual growth rate in traffic volume.

The cost of a particular project is its initial construction cost plus the present value of annual maintenance costs over the estimated life of the project. The ten percent interest rate is used in the present value calculation.

The costs and benefits of the alternative projects at the 61 locations serve as inputs to the multistage DP algorithm. Given a specified budget increment, the DP procedure finds the optimal, i.e., benefit-maximizing, combination of alternatives for each budget level. In this study, budget levels range from $10,000 to $80,000 with a budget increment of $250. The results of the DP procedure, the total benefits of the optimal set of projects at each budget level, are compared to results of a benefit-cost analysis of the same data. The total benefits of the projects chosen by DP are shown to be greater at each budget level than the benefits of projects chosen by benefit-cost analysis.

The major conclusion of the Kentucky study is that, as long as project costs are stated as multiples of the specified budget increment, the DP procedure will always pick the benefit-maximizing set of alternatives for each budget level. In this case, DP is unambiguously superior to benefit-cost analysis. If it is not possible to express project costs as multiples of the budget increment, then the DP algorithm will not quarantee the optimal choice at each budget level. In this case it is recommended that both benefit-cost analysis and DP be tested.

Alabama

The Alabama study [51] further documents the results of Alabama's CORRECT (cost/Benefit Optimization for the Reduction of Roadway Environment Caused Tragedies) system [81, 82, 83] as they apply to the allocation of Section 209 funds (for spot improvement of high-hazard locations) made available by the Federal-Aid Highway Safety Act of 1973. The report gives an overview of the procedure by which the CORRECT system accumulates data, identifies hazardous locations, chooses improvement alternatives and allocates Section 209 funds by multistage DP, and evaluates implemented countermeasures.

The 160 locations considered in the study are taken from the CORRECT data base. This data base, maintained since January 1971, is compiled from Uniform Accident Reporting Forms that report all accidents that occur in Alabama to the state highway department's head office in Montgomery. The data is analyzed by the AIM (Accident Information Modules) accident classification system. The AIM programs identify those locations throughout Alabama that have relatively high accident rates, such as the 160 locations chosen as test data for this study.

The benefit of each alternative project is estimated on the basis of a HALIForm (High Accident Location Investigation Form) for each improvement location. This data form quantifies accident frequency and severity costs of countermeasures, and the effect of each countermeasure on accident frequency and severity. The expected accident rate reduction of a proposed improvement is estimated from observed reductions resulting from similar countermeasures previously implemented at similar locations. The accident costs used in this report are [85, p. 54]:

$37,000 - Fatal accident
2,200 - Injury accident
360 - PDO

The benefit of a particular improvement project, then, is the present value of the sum of annual benefits over the expected life of the project, where the annual benefit is the reduction in the accident rate at that project's location times accident costs. An interest rate of zero percent is used in considering the present value of benefits over the life of each project; no allowance is made for expected changes in traffic volume.

The cost of an individual project is its initial implementation cost. Future maintenance costs are not included for the dynamic programming analysis.

The benefit and cost information supplied by the HALIForms is input into the multistage DP analysis that finds the optimal set of spot improvement projects for each budget level. For budget levels from $500,000 to $3,000,000, an increment of $500,000 is used; for budget levels from $3,000,000 up to $6,000,000, alternating increments of $400,000 and $600,000 are used. The DP results are compared to the results of a benefit-cost analysis picking lowest cost/benefit ratio first, demonstrating the superiority of the DP selection procedure over benefit-cost analysis at every budget level.

Projects selected by DP are subject to review and possible revision by decision-makers, after which they are implemented in increasing order of cost/benefit ratio. Accident histories of the improved locations are maintained, and, usually one year after implementation of the projects, the Accident Countermeasure Evaluation (ACE) system evaluates the effectiveness of each improvement with a before-after study. The ACE studies provide state and local investigating teams with updated information on which to base estimates of future accident reductions.

Although the CORRECT system was developed with respect to the allocation of Section 209 funds, its usefulness does not end here. The State of Alabama Highway Department is currently (August, 1977) applying the system in the allocation of Section 203 (rail-highway crossings) funds [86].

Possible Improvements

The Kentucky and Alabama reports provide ample evidence that DP is becoming increasingly popular as a means of allocating funds and selecting spot improvement projects on a statewide basis. With its computational ease and selection superiority to such traditional approaches to the capital allocation problem as benefit-cost, present value, and rate-of-return calculations, DP appears to be a preferable alternative to these techniques and will doubtless come into more widespread use in the allocation of state funds. One important point should be noted, however, with respect to both studies.

Each study is different in its treatment of improvement project costs. The Kentucky study, while including the present value of future maintenance costs in its calculation of project costs, is not clear as to the type of budget constraint it faces. The manner in which maintenance costs are included implies that the budget covers future periods as well as the current period; highway improvement budgets typically are concerned only with allocation funds for the present period. The Alabama study, on the other hand, deals with a typical, clearly defined budget that is concerned only with initial project costs that occur in the current period, but such a treatment of costs fails to account for future maintenance costs. Ignoring these costs in the dynamic programming analysis optimizes project selection only with respect to initial project costs. A possible modification of the input data to the dynamic programming procedures in both studies would be to include only initial, current-period costs in the cost input but modify the benefits input to account for future maintenance costs. Rather than being expressed as simply the present value of future annual benefits over the expected life of the project, total benefits of a particular project should be expressed as the present value of benefits less maintenance costs in each future period, over the project's expected life. This modification would lead to selection of projects that maximize *net* future benefits for a given initial cost budget. This would give results similar to those obtained using the incremental benefit-cost ratio procedure that subtracts maintenance costs from benefits in the numerator and includes only initial costs in the denominator. These methods are discussed further in Chapter XIV.

The present Kentucky procedure of maximizing benefits for a given total present cost is somewhat similar to incremental benefit-cost ratio procedure that includes maintenance costs in the denominator. However, it is difficult to use if the objective is to select a group of projects for a fixed initial cost budget, which presumably can be accomplished only by solving the dynamic programming problem for different total (initial plus future) cost budgets and using an iterative procedure to determine the total cost budget that has associated with it the fixed initial cost budget.

The Kentucky approach allows for future growth in benefits by assuming that future benefits grow at a stipulated rate per year [52, p. 48]. The Alabama procedure assumes that annual benefits are constant [51, pp. 20-37]. Neither state considers benefits other than reductions in accident costs.

The ORI Approach Using Linear Programming

Perhaps the most comprehensive and complex attempt at structuring a cost-effectiveness system for generation of optimal safety expenditures was undertaken by Operations Research, Inc., between about June 1967 and June 1970 [40]. This research effort was directed at the purpose of generating a mathematically based decision-making system which would optimally allocate both state and federal funds to competing traffic safety programs.

The system developed by ORI required the delineation and accomplishment of the following five objectives:

1. Design of a *program structure* that displays alternative groupings of activities directed to reducing crashes and crash damage.
2. Development of a model that can be used to estimate empirically the influence of the countermeasures on alternative measures of damage reduction, i.e., that can be used to estimate the effectiveness of the standards.
3. Design and development of an analysis that can be used to estimate empirically the total costs imposed on all sectors of the economy owing to the enactment and enforcement of the standards.
4. Development of a model that uses the cost-effectiveness information concerning the countermeasures generated in the previous two steps to determine the most efficient *allocation* of funds.
5. Limited testing of the operational readiness of all system components.

System Overview

The ORI approach to cost-effectiveness optimal allocation of highway safety funds involves three main components of work: (1) development of an effectiveness model, (2) development of a cost model, and (3) development of a capital allocation model which utilizes the effectiveness and cost data to generate an optimal set of expenditures for each safety standard included in the decision-making process. The function of each model may be generally stated as follows:

1. The *effectiveness model* estimates the anticipated reduction in mortality, injury, and property damage, owing to the implementation of a new standard or a change in the level of implementation of an existing standard.
2. The *cost analysis* estimates the total system costs generated by implementing a new standard or changing the level of implementation of an existing standard.
3. The *allocation model* determines, on a cost-effectiveness basis, the best mix of the standards being considered by the Bureau decision-makers and the expenditure level for each standard to achieve a maximum reduction in mortality, injury, and property damage subject to specified resource constraints.

The interaction of these major components is graphically portrayed in Figure 7.

Brief Description of System Models

The following discussion provides an overview of the cost-effectiveness evaluation system, i.e., the system components and their relationship, and a condensed exposition of the operation of these components, i.e., the effectiveness, cost, and allocation models.

The Effectiveness Model

The effectiveness model is based on the assumption that the relationship between implementing standards and reducing damage can be statistically measured by relating standards to damage data. This direct macro approach is apparently well suited to the precision of the data and the ability of the current state of the art to quantify the numerous factors that, in conjunction with safety standards, effect changes in the number and severity

Cost Data from
Cost Model

Effectiveness Data from
Effectiveness Model

↓

MODEL

Maximum reduction in M, I, PD subject to budget limits, upper limits on standard implementation, linearity of all impacts.

OR

Minimize cost of achieving a given reduction in M, I, PD subject to same set of constraints

↓

OUTPUT

Optimal solution to LP allocation model, i.e., the amount of reduction achieved, the standards responsible for the reduction, and the level of the standard implementation necessary to achieve the reduction. Total federal expenditure by state and/or by standard for the preferred solution. The degree of sensitivity of the solution to variations in the constraints.

M- Mortality
I - Injury
PD- Property Damage

Figure 7. Schematic Flow Chart of the Operating Logic of Each Component of the Allocation Model

of accidents. The approach provides reasonable rigor in defining the relationships and permits the postulated relationships to be validated statistically.

The Cost Model

The cost analysis, although less elaborate than the effectiveness model, is adequate for assessing the magnitude and incidence of total system cost generated by implementation of individual standards. The primary reasons for its relative simplicity is that the focus is on cost identification to determine the necessary estimation guidelines. The current technique simply codifies all major cost elements, sums the measurable values, and carries the nonmeasurable values in a parallel development.

The Allocation Model

The cost and effectiveness analyses provide the inputs to the allocation model in which evaluations of alternative resource allocations are made. The allocation model is the most sophisticated of the three system components in that it incorporates the results of innovative linear programming. This model was specifically designed to determine a (federal) budget allocation that would minimize mortality, morbidity, and property damage in combination rather than individually. Its design permits the decision-maker to explore fully the results of specifying alternative groupings of reductions in terms of total (federal) costs and the corresponding mix and level of standards to be implemented. The model also provides the decision-maker with a device for examining the potential safety impact of adding or subtracting a standard or changing the level of standard implementation and the potential budgetary impact of changing the mix of the desired reductions. For example, it provides insights regarding such questions as the budgetary impacts of specifying a given change in the desired reduction of mortality, morbidity, and property damage.

Relationship Between the Effectiveness Model and the Allocation Model

The two major components of the ORI study involve a measure of system effectiveness and the optimal allocation of funds. The cost model serves the function of translating effectiveness directly to cost, which in turn is dealt with in the cost of allocation model.

Since the primary influence of preventive standards is directed toward accident reduction, whereas NHSB safety objectives are stated primarily in terms of damage reduction, a mechanism was constructed to translate crashes by type into the average number of deaths, injuries by severity class, and property damage associated with each crash type. However, since the ameliorative-restorative countermeasures operate directly to reduce crash damage, no translation is needed. After aggregating over the different environmental and locational characteristics, the analysis derives an expression for the total damage reduction that can be expected as a result of a change in a preventive or ameliorative-restorative countermeasure.

The final step in determining a measure of standard influence involves the modification of the estimated results as a prerequisite to their use in the allocation model. In the case of the effectiveness model, the estimated influence is assumed to be curvilinear where more and more dollars spent on a standard exert less and less influence (decreasing returns to a factor). These curvilinear relationships were established through the use of curvilinear regression analysis. The regression coefficients were suitably derived considering both environmental and regional characteristics. However, in the allocation model (a linear program) the influence of each standard must be strictly proportional to the amount spent on the standard.

The modification for converting from a nonlinear to a linear (proportional) relationship between influence and spending is accomplished by dividing the impact curve, shown in Figure 8, into several straight lines by connecting the dots. These connected straight lines will approximate the curve as closely as desired. This technique (piece-wise linear approximation) ensures that the impact measure developed for each countermeasure can be used in deriving the cost-effectiveness ratios required in the allocation model. The estimated influence is assumed to be curvilinear--more and more dollars spent on a standard exert less and less influence (decreasing returns to dollars expended).

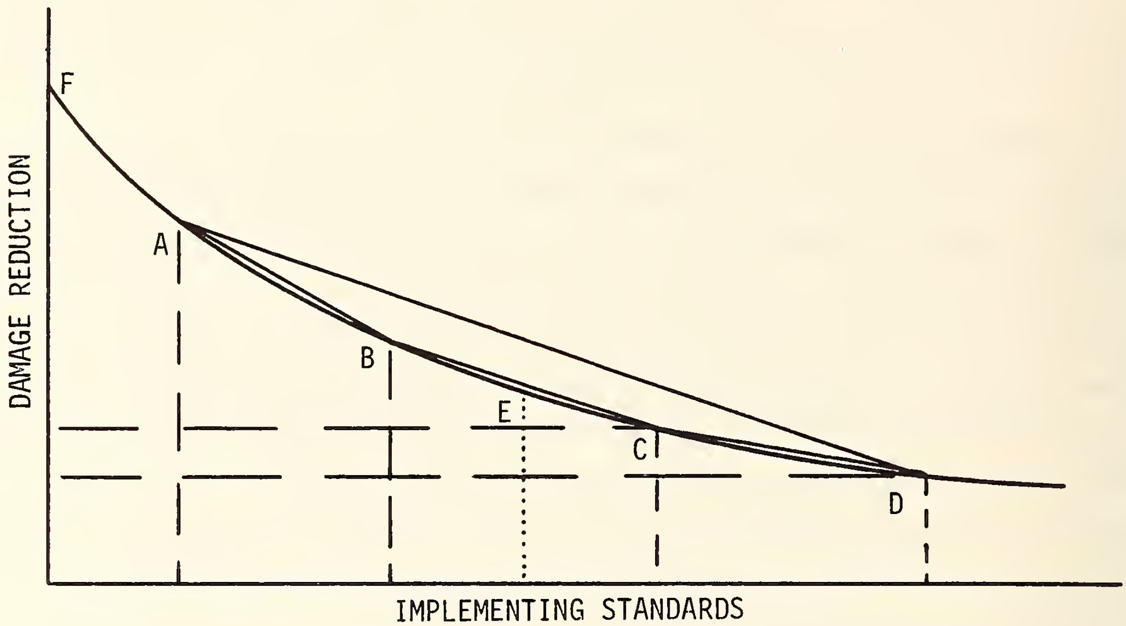


Figure 8. Piece-wise Linear Approximation of a Nonlinear Effectiveness Curve

Implementation of the ORI System

To date, ORI has field tested its cost-effectiveness system in six states [40, 87, 88]. The following years are the periods selected for analysis in each of the states:

Arizona	1963-1968 (accident data not available for 1966)
New Jersey	1962-1967
North Carolina	July, 1965-June, 1968 (1969 accident data available but not used because standard expenditures and costs unavailable)
Maryland	1965-1968
Utah	1965-1968
Wisconsin	1962-1967

ORI developed the cost-effectiveness system over a 24-month period using Maryland as a test bed. Arizona, New Jersey, North Carolina, Utah, and Wisconsin were later selected for field demonstration projects. General findings are:

1. Extremely severe problems were encountered in attempting to collect data on the motor vehicle standards, owing to multiple factors (see ORI final reports for details).
2. Owing to the lack of data on motor vehicle standards, the state and city data base focused on the expenditure data on the various highway safety standards. An immediate problem involved the identification of expenditures in standard areas.
3. Significant problems arose in assembling the large quantity of data necessary to demonstrate the system over a cross-section of states. The incomplete availability of crash data, the variation in record formats between communities (and within a given community over time), and the incompatibility among tapes created extreme data manipulation problems.
4. The political organization of states and localities posed the usual problem of functional overlap and duplication of outputs between departments. This problem was encountered in dealing with both accident data and state expenditure figures.
5. Reliable quantities of crash data were either incomplete, unavailable, or categorized in forms which proved incompatible with model requirements.

It is also worth noting that ORI suggests the following guidelines as mandatory if the ORI model is to be successfully used:

1. Hire a competent analyst.
2. Establish close cooperation between analysts and operational decision-makers.
3. Initiate extensive collection of high quality data which satisfies model requirements.

Program Success

In spite of the large amounts of preprocessing required (regression analysis, data compilation, model installment, etc.) and the levels of skill needed to successfully generate and interpret the final results, ORI indicated that the test results show that the ORI system can provide a useful, effective tool for resource allocation. The usefulness of the ORI study to state officials is summarized in the following description of attributes of the three-model system:

1. Provides a framework for systematic cost-effectiveness analysis of existing highway safety programs.
2. Provides decision-makers with a rational tool for allocating funds to highway safety programs and geographic areas.
3. Provides an on-going system which can be adapted to accept either revisions in existing programs or new programs once the changes are implemented and data become available.
4. Identifies areas in which information gathering and reporting at the activity level (in the field) should be examined.
5. Three-model system is fully documented and adaptable to most third generation computers.

Although the ORI method has been tested extensively in several states, it has not actually been implemented as a working system. One of the primary reasons that states have not used the method is that it is relatively complex. Another reason is that the method attempts to relate accident reductions, by type of accident in a geographic area, to the dollars of expenditure for specific accident programs in that geographic area. The difficulty of developing good estimating relationships of this type is perhaps the primary weakness of the ORI method.

PART THREE: EVALUATION OF COST-EFFECTIVENESS SUB-MODELS

VI. IDENTIFICATION OF ACCIDENT LOCATIONS AND ESTIMATION OF COUNTERMEASURE EFFECTIVENESS

A critical submodel in any cost-effectiveness technique for evaluating accident countermeasures is identifying accident locations and evaluating countermeasure effectiveness. The techniques used by highway agencies to identify accident locations that are candidates for safety improvement and to predict the effectiveness of accident countermeasures at those locations are perhaps the most important elements in the overall safety program. In addition to improving these techniques, there is a need to develop better means for considering interactions among accident countermeasures.

Identifying Accident Locations to be Analyzed

Traffic accidents are not random events which occur throughout the highway environment. Rather, some highway sections and locations produce accident frequencies well above average expectations, while most sections and locations produce accident frequencies at or slightly below average expectations. If those sections and locations associated with high accident rates can be identified, the potential exists to alter the section or location in question to reduce the accident rate (or severity) at that section or location.

In 1973 Roy Jorgensen and Associates, Inc. sent a questionnaire to ninety-one highway and safety agencies to determine, among other things, how these organizations go about identifying hazardous highway sections and locations [16]. Responses to some of the survey questions were:

1. Do you use or plan to use accident experience to identify your safety problem locations?

   Yes - 51, No - 0

2. Are you identifying potentially hazardous locations using nonaccident information such as observed traffic conflicts or hazardous geometric or roadside features?

   Yes - 26, No - 16

   Specific information: special investigation teams, photo logs, skid tests

3. How do you integrate non-accident-based safety problem information with accident-based information?

   Typical response: engineering judgment

4. Do you conduct field investigations at identified highway safety problem locations?

   Typical response: Yes

   Method of evaluating source and degree of hazard: Traffic counts, short counts by movement, conflict counts, photographic studies, night investigation, skid testing, driving the location

A perusal of Appendix M to NCHRP Report 162 [8] suggests that the standard means whereby highway departments identify hazardous locations involves a two-step process:

1. Locations with high accident rates and/or high rates of severe accidents are identified. This step is traditionally accomplished by sorting the accident data by hand or by machine, e.g., locating accidents on a map with pins or printing out accident frequencies by milepost along specific highways.
2. After a number of hazardous locations have been identified according to step one, further analysis is performed to determine the extent and etiology of hazard at each location. This additional analysis is accomplished by means of collision diagrams, accident profiles, field studies, etc.

While states differ considerably in the level of sophistication with which these steps are conducted, the two-step process itself does seem to be the generally accepted procedure wherewith state agencies attempt to identify high hazard locations.

Needed Improvements in Identifying High Accident Locations

A previously cited report [71] by the United States Comptroller General, General Accounting Office, indicates that the means by which the states are defining hazardous accident locations is inadequate [71, p. 7]:

> The basis of a successful highway safety program is identification and analysis of accident locations on all highways to determine which hazardous locations should be considered for safety improvements. This involves summarizing all accidents by location. Then, the most hazardous locations are identified.

This is done by weighting the severity--in terms of fatalities, injuries, and property damage--of the total number of accidents on similar highways with similar traffic volumes.

Although the eight states we reviewed have accident reporting systems, they did not obtain all the information required for identifying the most hazardous locations, and when available it was not always used. These problems were found to a greater degree for highways under local jurisdictions; however, gaps also existed in the information gathered for state-administered highways.

Before a state's highway safety dollars can be spent with the realistic hope of producing a maximum return on investment, it is essential that a state be able to locate its high hazard locations and specify the reasons why those locations are hazardous. Until this step is taken, further steps are premature.

Estimating Countermeasure Effectiveness

Once a state has identified its high accident locations, the next logical consideration is what countermeasures are available to correct specific deficiencies at specific locations. If, for example, a particular bridge has sustained a large number of accidents over a three-year period, what treatments could be implemented at that location to redress the problem? Widening the bridge, addition of approach rails, resurfacing, signing, and replacement are five countermeasures which could be implemented. Which one of these countermeasures will be chosen depends upon several considerations--total available funds, available funds in given categories, alternative locations at which other countermeasures might be deployed, and, perhaps most importantly, the effectiveness of the various countermeasures in reducing accident frequency and/or severity.

How do the states determine the effectiveness of countermeasures? Again, referring to Appendix M of NCHRP Report 162 [8], current practice is documented:

1. Have you developed any statistical models for determining the potential effectiveness of proposed safety problem solutions?

   Yes - 5, No - 36

2. Do you use the published results of previous experience from other agencies in determining the potential value of a proposed problem solution?

   Yes - 25, No - 17

3. Do you use the results of special in-house research to determine the potential value of a proposed safety problem solution?

   Yes - 18, No - 22

4. How are benefits (accident and severity reduction and other users' benefits) determined?

   National Safety Council accident cost values - most frequently used

   Accident cost values obtained from in-house accident cost studies - second

   Accident cost values obtained from NCHRP research tables - third

   NHTSA accident cost values - least frequently used

Finally, most of the responding agencies indicated that they review the effectiveness of countermeasures after implementation. Twenty-five agencies indicated that the reviews of the effectiveness of previously deployed countermeasures are used in determining the deployment of new countermeasures. Of the agencies which review the effectiveness of previously deployed countermeasures, the most common technique is the before-after study. Unfortunately, many, if not most, of the highway accident countermeasures which have been initiated to *date have never been evaluated to determine whether they are accomplishing their intended goals.*

The Solomon, Starr, and Weingarten study [30], published in 1970, established priorities for the implementation of fifty-seven different highway accident countermeasures. Priorities were based on the costs of implementing, operating, maintaining, and repairing each countermeasure, and on the effects of each countermeasure in reducing deaths, injuries, and property damage. The authors found that, unfortunately, very few evaluations of countermeasure effectiveness were available. The authors felt that they had "good to excellent" estimates of the effectiveness on only eight of the fifty-seven countermeasures under consideration. For the remaining forty-nine countermeasures, effectiveness estimates were "... based either on engineering judgment, involved only fair or poor data, or were little more than guesses" [30, p. 9].

Five years later, Council and Hunter discovered that valid evaluations of highway accident countermeasures were still scarce [89, p. 6]:

> ...there is a wealth of information concerning programs which appear to be effective in reducing accident frequency or accident severity. However, a critical review of these studies indicated problems which make difficult any attempt to use the results in cost-effectiveness analysis, and ultimately, in related program implementation decisions.

The reasons why highway accident countermeasures are not adequately evaluated are numerous; they include insufficient funds, poor data bases, and lack of personnel [90]. For whatever reasons, valid evaluations of highway accident countermeasures are not plentiful. While relatively few effectiveness evaluations of highway accident countermeasures have been conducted, it is even more unfortunate that many, perhaps most, of those evaluations which have been undertaken are biased and invalid. The traditional design which has been used to evaluate the effectiveness of highway accident countermeasures is the simple before-after design. By the dictates of this design, accident data, e.g., deaths, injuries, property damage, are collected along a particular section of highway, at a given intersection, or throughout some geographic area for a period of several weeks, months, or years. The same countermeasure is deployed--a bridge is widened, an intersection is illuminated, a median barrier is installed. Finally, accident data are collected once more. To the extent that the rate of deaths, injuries, or property damage is reduced after installation of the countermeasures, the countermeasure is said to be effective.

At first blush, the before-after design described in the previous paragraph seems reasonable; but, in fact, this design is invalid. The invalidity of this design rests on two tacit assumptions which underlie the design:

1. If the countermeasure had not been deployed, the accident rate (deaths, injuries, or property damage) would have remained at the "before" level.
2. If accident rate is reduced after implementation of the countermeasure, then the countermeasure "caused" the reduction.

Either or both of these assumptions can be wrong. To the extent that they are wrong, the design is fallacious [90, 91].

Adding to, and thereby exaggerating, the before-after design weakness is the "regression toward the mean" fallacy [90]:

...Regression toward the mean is a mathematical phenomenon which, simply sated, says that if two measures are associated with less than perfect correlation, unusually high or low scores on one measure will tend to be associated with more average (mean) scores on the second. If the number of traffic violatetions which people commit one year are minimally or moderately associated with the number of traffic violations they commit the second year, and if a given individual commits an exorbitant number of violations one year, it should be predicted that he will commit a more average number of violations next year. Similarly, if an individual is free of violations one year, the best guess of the number of violations he will commit the next year is a number above zero and less than average.

Assume that the number of accidents sustained at an intersection one year is only modestly associated with the number of accidents that will be sustained at that intersection the next year. Now, further assume that the intersection has witnessed an unusually high number of accidents this year. How many accidents will occur at this intersection next year? The best guess is a number less than occurred this year, but more than average. Even if no attempt is made to improve the intersection this year, even if no new crosswalks are installed, no lights or signs set in place, no additional enforcement personnel are added to our bad intersection, it is *not* proper to conclude that the difference can be accounted for by the treatment imposed. Indeed, a reduced number of accidents would have been expected had nothing at all been done. Many, perhaps most, of the effectiveness evaluations of highway accident countermeasures have committed either or both of these fallacies.

Countermeasure Interaction

At several points in their report it has been suggested that many, if not most, highway accident countermeasures have never been adequately evaluated. To this indictment, some might respond, "All right, if we do not know how effective our accident countermeasures are, then we should go out and evaluate our countermeasures and resolve just how effective they are--once and for all." Unfortunately, due to system complexity, the effectiveness of countermeasures cannot be resolved "once and for all." A countermeasure which reduces fatalities by, say, forty percent in 1977 may reduce fatalities by, say, thirty or fifty percent in 1987. A countermeasure which is effective today may be ineffective a decade from now. A countermeasure which is of little benefit in the present highway environment may be more beneficial as that environment is altered. For example, at the present time there are several methods of treating the ends of guardrails to prevent them from skewering errant automobiles when struck end-on. One common method is to twist the end of the rail and bury it in the ground. The effect of this treatment is to substitute a twisted, inclined rail for a rigid horizontal rail located two feet above the ground level. Vehicles striking the twisted rail are deflected upward or they hit the incline and the energy of the collision is dissipated as the vehicle slikes along the rail and the accompanying vertical support posts. The probability of a vehicle occupant surviving such a collision is considerably greater than the probability which he would experience if the vehicle had struck an upright rail. One deleterious side-effect to twisted guardrail ends which allegedly makes them hazardous is that when small cars strike the twisted inclined rail, they have a tendency to become airborne and roll over. If this allegation is true, and if twisted-end guardrails are, in fact, advantageous, then they are advantageous in spite of the "roll-over" liability to small cars. However, if in the future the proportion of small, subcompact cars on the road is increased, the net benefit derived by the driving public from twisted, downturned guardrail ends may very well diminish. In other words the same device located in the same geographic location may undergo alterations in effectiveness as the composition of the national motor vehicle fleet changes.

Taking another example, consider the possibility that by the year 1990 the majority of passenger cars on the road will be equipped with air bags. The purpose of air bags is, obviously, to mitigate the potentially injurious and fatal consequences of vehicular collisions which occur in the frontal mode. However, at the present time, environmental countermeasures already exist which act to reduce the consequences of frontal vehicular collisions at predetermined points along the highway. Crash cushions of crash attenuators have been used for several years now at various hazardous spots along the highway, such as in front of bridge piers, to provide protection to vehicles which stray from the highway and strike what would otherwise be an unforgiving object. In other words, crash cushions and air bags are intended to produce their effects in similar crash situations. To the extent that the devices constitute redundant countermeasures, the effectiveness of one or the other is reduced. If an air bag will assure survival in a forty mile per hour crash into a fixed object, and if bridge piers or other fixed objects are never struck at speeds greater than forty miles per hour, then the additional effectiveness to be derived from placing crash cushions in front of bridge piers or other fixed objects is lessened. If air bags were installed in all passenger cars today, the effectiveness which is currently afforded by crash cushions might be reduced to such an extent that highway safety funds might better be spent to try to prevent accidents rather than mitigate their consequences. If all cars contained air bags, it might be more cost-effective to allocate safety funds for widening roads, improving roadway geometry, improving signing, etc., rather than installing crash cushions.

Nothing in the previous paragraphs should be construed to mean that turned-down guardrail ends and crash cushions are ineffective accident countermeasures. All evidence indicates that both of these measures are effective in reducing injury and death. The point to be made is that the effectiveness of a safety system or device is, in general, variable. What is effective today may be more or less effective tomorrow. And, conversely, countermeasures which are insufficient or ineffective today may take on increased value as drivers, vehicles, and roadways change.

If countermeasure effectiveness can be altered by changes in roadways in the future, it stands to reason that the compounding of two or more accident countermeasures at a given highway location today can produce an overall effect which is less than, equal to, or greater than the effectiveness of the sum of the individual countermeasures. Assume, for example, that a hazardous railroad-highway grade crossing is treated with three countermeasures--flashing lights at the crossing, general illumination at the crossing during hours of darkness, and advance caution lights warning that a grade crossing is located 500 feet ahead. If these countermeasures are installed simultaneously, and if the net effectiveness of the treatment reduces accidents by sixty percent, there is no way to determine the extent to which each of the three countermeasures contributed to the improvement. Perhaps the three countermeasures interacted synergistically to produce a net benefit in excess of the benefits derived from each of the countermeasures taken alone. Perhaps all three countermeasures were addressed to the same root cause of accidents at the grade crossing, producing a situation whereby the effectiveness of one countermeasure overlapped and thereby cancelled the effectiveness of another countermeasure. Perhaps the deployment of any one of the three countermeasures would have produced the same benefit that was derived from the deployment of all three.

In concluding this section, several points should be made:

1. If we are ever to deploy highway accident countermeasures on a cost-effective basis, it is imperative that more and better quality evaluations be conducted.
2. It should be understood that the evaluation of accident countermeasures is an ongoing process, not a one-time endeavor.
3. In order to accurately determine the most cost-effective complement of countermeasures to deploy within a given jurisdiction, more information about the interaction of countermeasures with other extraneous variables must be developed. Once the effects of common, extraneous variables on countermeasure effectiveness are closely defined, the process of determining which countermeasures should be employed and where they should be used will be made easier, and indirectly, the process of deploying accident countermeasures on a cost-effective basis will be enhanced.

VII. ACCIDENT COSTS, OTHER HIGHWAY USER BENEFITS, AND COSTS OF COUNTERMEASURES

In order for analyses of highway improvement projects to be carried it is necessary that not only project costs but benefits as well be :red. Although there are several measures of benefits currently in hese measures have their limitations and thereby create a need for d benefit measures.

Accident Costs

Definitions of Accident Costs

cident cost values are calculated, of course, on the basis of cer- ssumptions; the literature identifies four basic types or defini- of accident costs. The first calculation of accident costs includes e costs directly associated with an accident - property damage, expenses, lost worktime from injuries, legal costs, damage awards, vehicle use.

second type of accident costs includes both direct accident costs present value of future net production lost to society as the re- an accident. Net production is the present value of expected future s less the accident victim's expected consumption. Net production, future earnings, is a measure of the value of a human being to ; it represents the future output of goods and services that society ng the deceased) loses when an individual is killed or rendered ently and totally disabled by an accident. By excluding the accident s expected future consumption, this method seems to imply that the is not himself a member of society.

e third type of accident costs differs from the second in that it es gross or total future production, not net future production, of cident victim. By including the victim's expected future consumption accident cost value, this measure of the value of the person to y includes him as a member of society.

The fourth type of accident costs is based on willingness to pay avoid a fatal accident. Unlike the others, this method is not in curr use. Although extensive research has been done, so far no really sat factory way of implementing this measurement technique has been develo In addition, this method, as developed thus far in the literature, has relative disadvantage that it measures only the value of a person's l to himself [92, 93, 94, 95, 96, 97, 98, 99] or to others [100]; it doe measure the loss to society of a nonfatal injury or property damage on accident. The advantage that this measurement has over the others is it includes intangible yet significant factors valued by society, such relationships with family and friends.

Different highway and safety agencies use different accident cost values, each value based on a particular definition or method of calcula tion. A survey [8, p. 67] of such agencies reports a sample frequency of use of different benefit values:

	Used	Not Used
NHTSA Tables	5	35
National Safety Council	25	15
NCHRP Research Tables	6	34
In-house accident cost studies	15	25

This survey indicates that the NSC accident cost values, which are t second type of accident cost described above, are the most frequentl used (e.g., 84, 101, 102, 103]. The direct-costs-only calculation second most popular, used by many state highway departments [e.g., 105, 106, 107, 108, 109; see also 8, p. 6, Table 2]. The third meth accident cost calculation, represented by the NHTSA values [18, p. 9 110], is used comparatively infrequently; this may be because the NH gives accident cost values for three degrees of severity of injury [114]. Some agencies used other accident costs, such as NSC, simply calculations are easier with one value than with three [8, p. 79].

Suggested Accident Cost Values

The current status of the use of accident costs in evaluations of highway and safety alternatives is indicated by two recent publications, the revised Red Book [13], which presents the latest state of the art with respect to benefit-cost analysis of major highway alternatives, and NCHRP Report 162 [8], which is a recent, comprehensive presentation of information for evaluating highway safety programs. Each of these studies presents average accident costs derived in previous studies. Although these values for fatal accidents range from less than $20,000 to over $300,000 (in 1975 prices), users are advised that they are "free to choose" any of these values.

The studies summarized in the revised Red Book [13, p. 64] and NCHRP Report 162 [8, p. 6] can be divided into three types:

1. Statewide studies, such as those for Massachusetts, Utah, Illinois, California, New Mexico, and Ohio, that estimated only the *direct costs* of fatalities and injuries. After updating to 1975 prices and adjusting for unreported accidents, these studies give approximately $20,000 per fatal accident and $5,000 per injury accident.

2. Studies by the National Safety Council, Arthur D. Little, Wilbur Smith and Associates, and the Texas Transportation Institute that estimate direct costs plus some indirect costs. Included in indirect costs is the *net* value of lost future production (gross future production less expected future consumption of the deceased) for deceased and injured victims. The most widely used of these studies is that by the National Safety Council [84], which gives updated (to 1975) costs of accidents as follows [13, p. 64]:

Fatal	$113,500
Injury	6,200
PDO	570

3. Studies by the U.S. Department of Transportation that include in accident costs not only the direct costs and the net value of future lost production but also the value of the individual's future earnings that he himself consumes, as a partial indication of the amount the individual is willing to pay to avoid death. This study gives 1975 values as follows [13, p. 64]:

Fatal	$307,210
Injury	14,600
PDO	650

Although neither the revised Red Book nor NCHRP Report 162 gives recommendations on which accident costs to use, their discussions and examples seem to indicate preferred values. The revised Red Book gives extensive tables based on California accident rates together with CALTRANS accident costs; these accident costs in turn are based on the Wilbur Smith study of accident costs in the Washington, D.C. area. The Wilbur Smith values are updated and adjusted for unreported accidents to give average statewide accident costs per accident: fatal, $130,000; injury, $4,000; property-damage-only, $1,100. The Wilbur Smith study used net future earnings, much like the National Safety Council, to value deaths and injuries. In its "Users' Guide" (Appendix Q), NCHRP Report 162 gives accident costs from the National Safety Council and the DOT study. To the extent that a judgment can be made, it is presumed that there are the recommended values. Thus, to the extent that there are any, recommended accident-cost values are based on two concepts: (1) discounted future earnings less future consumption, and (2) discounted gross future earnings. Finally, some of the shortcomings of various cost-estimation studies should be noted:

1. Many summaries of the statewide accident studies, such as those of Massachusetts and Utah, have confused costs per accident with costs per involvement. NCHRP Report 162 and Fleischer [20, p. 53] are examples of this.
2. The influence of unreported accidents on overall accident costs is substantial, as demonstrated by numbers given in the revised Red Book. This adjustment should be made, but it undoubtedly is difficult to estimate in many states.
3. Some direct costs of accidents, such as traffic delay and inconvenience, are not included in many studies.

It is interesting to note, as pointed out by Brown [85, p. 54], that only the relative values of fatal, injury, and PDO accident costs are important in any given analysis. For example, the same set of projects will be chosen whether values of, say, $37,000/fatal accident, $2,200/injury accident, and $360/PDO accident or any scalar multiples of these values are used, such as $370,000, $22,000, and $3,600, or $3,700, $220, and $36. This implies that the results of the analysis are both less susceptible to error and more widely applicable. While this interesting arithmetical property of the accident cost values does not shed any light on which values should be used in the first place, it does suggest that, for example, National

Safety Council values place a greater value on PDO accidents relative to fatal and injury accidents than do, say, NHTSA values (see [51, p. 100] for these accident cost values). Some agencies, such as the highway department of the State of Delaware [16, p. 78], are reluctant (perhaps for reasons of moral overtones, etc.) to explicitly assign a dollar value to a life or injury; instead of accident costs they use relative weights for accidents, similar to what Brown describes. Delaware assigns the proportions 1:6:111 for PDO, injury, and fatal accidents, respectively. Brown's statement regarding relative accident costs applies to analyses where only safety benefits are being considered, and is not applicable if there are significant benefits other than safety. In addition, the absolute magnitude of accident costs is important if the cut-off level for spending on countermeasures is affected.

Cost of Fatalities

The principal methodological difficulty in evaluating accident costs is associated with evaluating fatalities and disabling injuries. In a paper published in 1963, Ackoff [111, p. 106] listed seven methods that may be used to make an economic evaluation of a human life: (1) the cost of saving a life, (2) the amount the community is willing to pay to save a life, (3) the cash award or compensatory pension to close relatives of a deceased person, (4) the aggregate expenditure for consumption, investment, and public services devoted to one person, (5) the value of a person's production as measured by his contribution to Gross National Product, (6) the economic loss that a person's death imposes on a community, and (7) the monetary value that an individual places on his own life as revealed by his risk-taking. Each of these methods is discussed below. After comments on the individual methods, some interrelationships among the methods are discussed.

The cost of saving a life is not, in general, an accurate measure of the value of a life. It is important that the cost of saving a life be known because this amount, for different situations, is necessary for determining the expenditure which should be made to save a life. That is, expenditures for saving lives should be made up to the level at which the cost of saving a life is equal to the value of a life. Thus, we should like to know the marginal cost of saving a life, but only if we already are spending the optimal (marginal cost equals marginal benefit of saving lives) amount on life saving does this cost approximate the value of a life. It is probable that, for many life-saving measures, the cost of saving a life is much less than the value of a life. It should be noted that, in this discussion, the cost of saving lives is made in reference to public expenditures to save lives; the amount of private cost which individuals are willing to incur to reduce their own risk of accidental death is discussed in connection with the last method.

The amount a community is willing to pay to save a life depends on whose life is being saved and on the circumstances under which the community is considering the saving of one or more lives. In this connection, Winch has this to say [112, p. 87]:

> The actual value which society puts on human life varies widely and depends mainly on the amount of sentiment aroused by the way it is lost. If a child is missing no expense is spared in the effort to find him and save his life, but if the same amount of money spent on road improvements would improve an accident black spot so as to save two unknown childrens' lives each year it is begrudged. If one person is killed in an air crash it is the object of a full inquiry; if a thousand are killed on the roads it is a matter of course.

Winch concludes that decisions involving highway improvements which are expected to reduce deaths must be made by "...the ministers politically responsible for expressing the opinions of society in this field..." [112, p. 88]. He notes that the American Association of State Highway Officials did this when they adopted the values for a life calculated by the National Safety Council. Essentially, it is difficult to determine the amount the community is willing to pay to save a life, for the same reason people do not accurately reveal preferences regarding any public good.

The cash award or compensatory pension paid to close relatives of a deceased person is usually only a partial amount of the economic loss brought about by death. Conard and others [113] made a comprehensive study of reparation systems and concluded that, with the exception of awards made under the tort liability and certain employers' liability systems having many of the characteristics of tort actions, the amounts paid to close relatives are, in general, very low: "...the amount of insurance carried by most people is inadequate to provide even subsistence, and merely provides a slender supplement to social security or public assistance" [113, p. 85]. The reparation systems other than tort liability and certain employers' liability systems, such as workmen's compensation, life insurance, health insurance, and social security, are intended only to lessen the burden of injury or death, not to provide full economic reparation. But awards made under tort liability often include not only awards for full economic loss to survivors but also awards for psychic loss, pain, and suffering. With the exception of the methods based on the community's or individual's willingness to pay to avoid risk, awards made under tort liability are perhaps the only indicator of losses other than direct economic losses. There are certain shortcomings in using these cash awards as an indicator of the amount people would be willing to pay to avoid the loss which they experience. First, an award may include punitive damages meant to punish the person who caused the loss or to deter this person from negligence. Second, the award often will be higher if the defendant's ability to pay is higher. It may be relatively low if the injured party is in immediate need of money; in such cases, plaintiffs often agree to a smaller payment so they will not have to wait as long for the case to be settled. The size of the award also depends on the skills of the plaintiff's representative, as well as on how good the case of fault against the negligent person is and also on the way in which he was negligent, even though the actual amount of loss may be unrelated to certain aspects of the negligence. Even though these awards are imperfect indicators of losses associated with pain and suffering, they are still indicators and as such are interesting to the economist.

The aggregate expenditure for consumption, investment, and public services devoted to a person is an imperfect indicator of the value of the person's life since it excludes certain important items. If the person is the income earner for others, then his dependents suffer a loss of this income when he dies. Also, most individuals pay taxes which are used for public roads; thus, by the nature of public goods, the person contributes more than he consumes, since his consumption takes nothing from others but his taxes add to the total available for all. Such an estimate also ignores the external effects on others, in the form of pain and suffering and loss of utility through lost future association with the deceased. Finally, such an estimate ignores the surplus of utility which the individual has over and above the market value of expenditures on him. It might be noted that, because of the nature of expenditures for investment and public services (i.e., people *jointly* consume public goods and services), it is very difficult, if not impossible, to calculate the actual amount of such expenditures devoted to one person. The amount of social investment and public services devoted to an individual can be estimated by dividing the total expenditures on investment and services by the total number of individuals. But it should be recognized that, because of certain characteristics of these expenditures, such estimates are not very meaningful.

The value of a person's production as measured by his contribution to Gross National Product is a fairly good measure of the direct economic loss due to his death. If the value of the person's production equals his income, then this method has the advantage of ease of calculation, although there is uncertainty with respect to expected future income streams. It should be noted that a person's income will not, in general, equal the value of his production. There are two reasons for this: (1) incomes of some people are wholly or partially derived from wealth, which is the result of past production by them or others, and (2) the income of some people does not equal the value of their marginal physical product. The principal shortcoming of this method is that it excludes certain losses brought about by a death, including psychic losses, pain and suffering, and the loss of enjoyment which the deceased would have had. Such losses have a value not reflected in the market for consumption goods and services. In general, the economic loss that a person's death imposes on a community is equal to the first valuation discussed, that is, the amount the community is willing to pay to save a life, if "community" is defined consistently and if "economic loss" is interpreted as the money value of all losses.

The monetary value that an individual places on his own life, as revealed by his risk-taking, is essentially a market-revealed value. The relation that this value bears to the previously discussed values depends on what the individual considers in determining what he is willing to pay to avoid risky situations. If the gets pleasure from gambling with his own life, then he may pay to increase his risk; it is reasonable to assume that this is not generally the case. Then what does the typical individual consider in determining what he will pay to reduce his risk of death? Is this amount only equal to the value that he places on his discounted future enjoyment of living, or does it also include consideration of the losses to others which may result from his death? It can be argued that it includes at least the former but may also include the latter. If an individual's willingness to pay to reduce his risk of death can be measured, it can be assumed that this value represents that market value he places on his own life, not including the value to others. To this value can be added the loss to others brought about by the individual's death to obtain a total value for the individual's life. Possible ways of calculating the amount an individual is willing to pay to avoid risk are more fully discussed below, but first some interrelations among the seven methods of evaluation are discussed.

Many economists suggest that the value of a life which should be used in calculating the benefits of public expenditures should be the amount the community is willing to pay to save a life (method 2). Using the same definition of community and interpreting economic loss broadly as the money value of all losses, the economic loss that a person's death imposes on the community (method 6) will be equal to the amount the community is willing to pay to save a life, for the marginal life saved; it is argued that this value will equal the marginal cost of saving a life (method 1) if the optimal amount is spent to save lives. The first method cannot be used to calculate the value of a life, of course, but the cost of saving a life is an input needed to determine the amount which should be spent to save lives. The amount the community is willing to pay to save a life cannot be calculated in any direct way because there is no way to induce people to reveal their preferences for public expenditures; but, since there are conditions under which this amount equals the economic loss (broadly defined) to the community which results from a death, it may be possible to divide this loss into components which can be estimated. Thus, is economic loss is defined broadly and if the community is defined consistently, and if the community is spending the optimum amount to save lives, methods 1, 2, and 6 give the same value for the marginal life saved.

But how are these three evaluations related to the other four evaluations described?

Ackoff contends that the amount the community is willing to pay to save a life (method 2) must on the average be less than the difference between the value of the person's production as measured by his contribution to Gross National Product (method 5) and the aggregate expenditure for consumption, investment and public services which are devoted to the person (method 4) [111, p. 106]. He does not discuss why he believes this is so and does not give any definition for the community. He evidently is using a narrow definition of community, one which excludes the person whose life is being evaluated. Weisbrod used a similar concept for the value of a life, i.e., "...the economic value of a person ... measured by the value of his future earnings, *net* of consumption" [114, p. 35]. Actually, Ackoff's value is smaller than Weisbrod's, since Ackoff's value is net of not only the individual's consumption but also the expenditures for investment and public services which are devoted to the individual. Weisbrod explains that his value for a life uses a definition which excludes from the community (society) the life being saved, but he notes that the concept of the gross value of a producer also could be used [114, pp. 35-36]:

> The choice between the two measures of the economic value of a person--present value of gross or net future earnings--rests upon the viewpoint taken. While we are concerned in this study with the economic value of a person to society, we have failed to define "society" precisely. If society is defined to include everyone, including the individual whose value is being considered, then his contribution to the group is the total value of his *gross* future earnings. But if society is so defined as to exclude the individual whose life is being valued (for example, as all those who would be left were he to die), then his contribution to "society" consists only of any excess of what he adds to total output over what he subtracts from it, his consumption; and his economic worth is the present value of his *net* future earnings.

Weisbrod also mentions an even narrower definition of society, one which defines society as excluding not only the individual whose life is being valued but also all of the individual's dependents: "Under this definition, the value of a person would be the present value of the difference between his future earnings and the consumption expenditures of all members of his family who are dependent upon him" [113, pp. 35-36]. Weisbrod also explains that [114, pp. 35-36]:

> Under either of the narrow definitions of "society", in which the individual whose life is being valued is excluded, and perhaps his dependents also, the value of many persons is negative. This is to say that people such as those retired have no earned income and no expected future earnings, yet they do continue to consume. They are an economic liability, rather than an asset, to "society."
>
> On the other hand, under the broad definition, which includes in society the person whose life is being valued, no one can be an economic liability. At worst, one may be contributing nothing to the sum total of wealth.

Thus, both Weisbrod and Ackoff use a definition of society which excludes the person whose life is being saved. Ackoff, moreover, maintains that the value of a life calculated using this definition is on the average more than the value the community is willing to pay to save the person's life. It seems unusual that these authors, especially Weisbrod who considers the problem in depth, would define society as excluding the person whose life is being valued. For most proposed public expenditures, the lives which are considered are ones which can be saved from within the community. It would seem that the definition of society used by Ackoff and Weisbrod would, in general, apply only if society were considering bringing back from the dead one who had already died , or some such other unusual consideration.

Both Weisbrod and Ackoff indicate that it would be desirable to use some market value which an individual places on his own life (method 7). Weisbrod says that life insurance might be useful as a measuring rod of the value of a life (method 3), but he lists several reasons why this indicator is unsatisfactory: (1) life insurance is purchased to provide for one's family, and some people have no family and hence no motive for carrying insurance, (2) life insurance carried on many persons, especially housewives, is certainly below the value of their lives, (3) many people are either ignorant or irrational with respect to life insurance purchases, (4) many people, even those who are fully informed, do not insure even at fair odds, and especially not at unfair odds such as offered by life insurance whose costs includes considerable overhead expenses, and (5) a person's ability to pay insurance premiums is mainly a function of his past and present earnings, not of his future earnings which are a better indicator of his value [114, pp. 36-38]. Ackoff mentions that, "...unfortunately, there has been little study of how much monetary value an individual places on his own life [11, p. 107], and then proceeds to discuss how the value that an individual places on his own life may be revealed by his behavior toward risk [111, p. 107]:

> Assume two services alike in all respects except the probability of surviving them. Then, the difference between the maximum amounts that the individual is willing to pay for these two services divided by the increased probability of survival is his monetary evaluation of his life, assuming he knows the relevant probabilities. For example, if the increase in probability of survival is .001 and he is willing to pay $100 for this, he places a value of $100/.001, or $100,000 on his life. Once we know the dollar-value that a person places on his life we can determine the monetary value of the risk to life by multiplying the dollar-value by the probability of survival [not surviving?]. Similar computations can be made for other types of harm. The total cost of risk of safety per trip ... would be the sum of these values.

It should be added that the value of a life determined by the above approach probably is different for different probabilities of survival. That is, a person who is willing to pay $100 to increase his probability of survival by .001 might well be willing to pay an amount other than $50,000 to increase his probability of survival by .5. Thus, if a public expenditure which will increase people's probabilities of survival is contemplated, it is correct to use their willingness to pay associated with the particular probabilities for that expenditure, not other probabilities. Since all the changes in probabilities associated with particular road improvements probably are small, however, it may be that the willingness to pay per (small) unit of increase in probability of survival is relatively constant over the ranges considered in road improvement studies.

It is crucial, in conducting experiments such as the one described by Ackoff, that an approximation be made of the willingness to pay, and the experimenter should be careful in using cost of a service as an indicator of willingness to pay. For example, if there are two alternatives which are alike except that one has a .001 higher probability of survival and costs $10 more, then use of the $10 as an indicator of the willingness to pay gives an estimate of the value of life of $10,000. The superior interpretation is that only the marginal users or non-users have such a value. It can be presumed that most of the users of the more expensive alternative have a value of life, at that particular probability difference, above $10,000. By considering the proportion of persons using each of the alternatives for several different pairs of alternatives, each pair having the same probability differences but different costs, it might be possible to determine the cumulative density function describing the proportion of people willing to pay an amount equal to or greater than a given amount, to increase their probability of survival by that particular amount.

Presuming that the value the individual places on his own life can be calculated, what does this value include and in what way is it related to the community's willingness to pay to save a life? It can be assumed that the individual's willingness to pay indicates only the value of his life to himself. To this value must be added: (1) economic value of his production which supports others, i.e., the present value of his future gross production net of his own consumption, and (2) the cost of pain or suffering to the community as a result of a premature death (perhaps adjusted to account for the fact that at least part of this pain and suffering would have occurred at some time in the future when the individual died of some other cause); this can perhaps be estimated from court awards.

McFarland [115, p. 117] argues that:

> The sum of two of the components of the value of a life given above, i.e., the market value of the life, to the individual whose life it is, plus the present value of the individual's future gross production net of his own consumption, should exceed the present value of the individual's future gross production. That is, an individual should be willing to pay to save his life more than the present value of his future consumption expenditures since he would normally have much "consumer's surplus" from life.

He argues that calculations giving values indicating otherwise probably are wrong in some way and that present value of future consumption expenditures should be used in place of the market value in such cases. This conclusion also is supported by rigorous theoretical models developed by Conley [97, p. 45] which indicate that, "...for income above some undetermined but presumably low levels, the value of life is greater than discounted earnings ..."

It can thus be argued that:

1. Values of life based on present value of future production net of consumption are based on the implicit assumption that the individual whose life is being saved is *not* a "member of society." Thus, it is a fallacious concept to use in benefit-cost studies.
2. Although the present value of total future production is a fairly good measure to use in benefit-cost studies, it is only a minimum value.
3. Both of the above give very imperfect measures when applied to housewives, children, the elderly, and the unemployed.
4. The preferred method of calculation would be a market-oriented method, if experiments could be developed to calculate values using such a method.

Several recent studies have attempted to estimate the value of a human life. These estimates, in 1975 dollars, are:

1. Carlson [92]—compensation to pilots for risky flying: $200,000 to $1,000,000.
2. Thaler and Rosen [96]—risk premium for working in risky occupations: about $260,000.
3. Ghosh, Lees and Seal [95]—speed of travel on British motorways, assuming value of time equals the wage rate: about $260,000.
4. Blomquist [99]—in the study previously discussed on use of seat belts: $257,000.
5. Jones-Lee [98]—from questionnaires on airline choice: about $6,000,000.

Thus, it can be seen that values of life based on willingness-to-pay methods usually exceed $257,000 per life in 1975 dollars ($300,700 in 1978 dollars), which is greater than the present value of predicted future earnings. It is recommended that a value of this magnitude be used in benefit-cost studies. Other lower values can be used, however, in methods that use *numbers* of fatalities as *separate* measures of effectiveness, if the user clearly understands what is to be "weighted" in the separate measure.

This willingness-to-pay value is a measure of the person's life to himself. To it must be added other accident costs, including the cost of the fatality to people other than the deceased (more precise guidelines better identifying these costs need to be developed). In any case, there seems to be no reason whatsoever to "exclude from society" the individual whose life is to be saved. Therefore, if a decision-maker does not believe there are enough research results using the willingness-to-pay method, he should at least recognize that the DOT method using gross earnings is preferable to the net earnings methods used by the National Safety Council and implied in the revised Red Book tables.

Major Future Sources of Accident Cost Values

Perhaps the two most important sources of appropriate accident cost values to use in future highway improvement analyses are the NCHRP Report 162 [8] and the revised Red Book [13]. Neither source recommends one specific set of values to use for fatal, injury, and PDO accidents; as mentioned above, they both present several currently-used values and essentially leave it to the reader to decide which values to use. NCHRP Report 162 [8, pp. 6-7], more useful in analyses of nonmajor, spot improvements, presents values used in several state studies, along with NSC and NHTSA values (both of which are used in accident cost calculations in the "Users' Guide," Appendix Q, pp. 113-114), then points out difficulties of assigning pecuniary values to injuries and fatalities. It identifies cost factors incorporated into each accident cost value, allowing the reader to choose that value which includes those cost factors he considers relevant and/or available in his data. It is recommended that both a positive interest rate, to reflect the time value of money, and a factor to account for inflation be used in any analysis involving future costs and benefits. The revised Red Book [13, pp. 63-65], geared more toward major highway designs and changes rather than nonmajor spot improvements, presents several accident cost values including NSC and NHTSA values, and leaves the reader free to choose from among these values or to assign his own accident costs based on such factors as regional variations in wage rates, costs of medical care, and costs of automobile servicing. The accident cost values presented in the revised Red Book are adjusted upward (injury accident costs by seven percent, PDO by 90 percent) to account for unreported accidents. An alternative to choosing one set of accident costs is to use a range of values to see whether different values affect the decision in question. At any rate, the accident costs that are used should be acceptable to the decision-maker who will be using the results of the economic analysis. It is recommended that the reader provide his own accident rate data, estimated on a before-after basis, whenever possible. This takes into account regional differences in vehicle mix, driver behavior, weather, and roadway characteristics. But if local accident rate estimates are unavailable, then the reader should use the estimated rates for selected highway types from the State of California statistics [102], based chiefly on the Wilbur Smith study of the Washington area [101], which uses an accident cost concept similar to that of the National Safety Council (see [8, p. 6, Table 2]). The apparent preference of the revised Red Book for the CALTRANS values is evidenced by their use as examples in certain tables [13, pp. 66-67].

Other Measures of Highway User Benefits

Besides reducing accident costs, many highway safety projects render other benefits as well. There are two basic categories of highway improvement projects, different with respect to their objectives. While most types of improvements have aspects that fit into both categories simultaneously, the first category includes improvement projects aimed primarily at objectives other than simply accident reduction. The Red Book lists the benefits of highway projects, in addition to accident cost reduction, as [12, p. 10]:

1. Reduced vehicles operating costs,
2. Saving of travel time, and
3. Increased motorist comfort and convenience.

In particular, the Red Book [12] analyzes these three factors, as well as accident costs; values for motorist comfort and convenience are arbitrarily assigned and included in vehicle operating costs for analytical purposes [12, p. 77]. Several studies have used these as measures of road user benefits from highway improvements. Winfrey [15] discusses vehicle operating costs, value of travel time, and motorist comfort and convenience in addition to accident costs. NCHRP 111 [70] deals with updated vehicle operating costs, under various road conditions and speeds. NCHRP 133 [14] considers vehicle operating costs and travel time as well as air pollution, noise effects, and accident costs. NCHRP 146 [18] includes highway travel time and accident costs in a comparative analysis of transportation systems.

Buffington and McFarland [116] include value of travel time, vehicle operating costs, and accident costs in their highway benefit-cost analysis. The revised Red Book [13] covers travel time and vehicle operating costs as well as accident costs.

In the past, agencies have typically followed the Red Book, using either its original unit values or updated versions of these [66, p. 23]; as a consequence, accident costs have not been widely used as a measure of project benefit [66, p. 24]. One reason that accident costs have not been extensively used in the past is that, while the Red Book gives accident cost values and accident rates [12, pp. 140-143], it does not clearly specify which accident rate to apply to each accident cost value. A second reason is that accident cost values suggested by the Red Book are a relatively small portion of total benefits of any particular project [12, pp. 129-136]. The revised Red Book is considerably more clear as to what accident rate to employ [13, p. 65]; given the past popularity of the Red Book [66, p. 23], this revision will no doubt have widespread influence on future road user benefit analyses.

The second category of highway improvement projects includes improvements directed primarily toward increasing motorist safety, i.e., reducing accident rates. Although accident costs historically have seldom been used in project evaluations, increased attention is being paid to them as a measure of project benefit. Surveys of highway and safety agencies, taken in 1962 [64], 1966 [65], and 1974 [66, pp. 20-25], indicate a significant increase in the inclusion of accident costs in economic analyses of roadway safety improvements [66, p. 24]. One reason for this increased interest in accident costs is that agencies are realizing that costs of accidents are higher than suggested by the Red Book [12, p. 100]. In addition, the increasing amounts of highway improvement funds, made available by recent Federal-Aid Highway Safety Acts and earmarked specifically for roadway safety projects, have increased the need for analyses that consider accident costs and reductions in accident rates.

Needed Improvements

In spite of the vast amount of accident cost studies and other research that has been done, there are three basic areas of needed improvements in highway improvements analyses. The first area for improvement concerns highway project benefits that are recognized but are generally ignored in economic analyses because of difficulties of measurement and quantification in dollar terms (relative weighting). These motorist comfort factors include [6]:

1. Reduction of traffic conflicts at intersections,
2. Reduction of passing and meeting other vehicles on undivided roadways,
3. Reduction of rough or patched pavements,
4. Better roadway delineation.

Omission of these benefits in analyses results in underevaluation of projects. Ways of accurately measuring, quantifying, and weighting these factors are needed in order to more fully account for benefits of highway improvements. One possible way to weight these benefits would be to assign subjective weights to each and use them with a hierarchical additive weighting method for either independent [117] or nonindependent [118] improvement alternatives.

A second category of needed improvement concerns vehicle operating costs and value of travel time. While thorough research [13, 14] has identified and and quantified these costs, the developed techniques for analyzing them are geared primarily toward comparisons of major highway designs and improvements rather than comparisons of nonmajor spot safety improvements, including those concerned with intersections, rail-highway crossings, and pedestrians. The need for improvement, then, lies in the treatment of vehicle operating costs and value to travel as related to spot safety improvements.

The third and largest area of needed improvement concerns accident costs. One major criticism of the accident cost values that are currently being used in economic analyses is that most of these values fail to capture significant benefits of projects. As pointed out above, accident costs comprised of only direct costs or direct costs plus net expected future production are simply inadequate. Accident costs comprised of direct costs plus gross or total expected future production are the best available, given the current state of the art, but even this calculation of accident costs does not capture the full value of a lost life. Probably the best way to calculate accident costs would be to use the direct cost plus gross production calculation, e.g., NHTSA values, in conjunction with the willingness to pay concept. The former would account for injury and property damage losses, while the latter would account for all fatality losses. Of course, the willingness to pay concept must be developed into an easily quantifiable and applicable calculation technique. If accident cost values other than the NHTSA/willingness to pay type are used, it should at least be recognized that these values fail to account fully for accident losses.

A second criticism of current applications of accident costs in economic studies is that generally no distinction is made among different types of accidents when accident rates are multiplied by costs per accident to calculate total accident costs (although several studies [e.g., 101, 106, 107, 108, 109] break down accident costs into categories by accident type, severity, and location, i.e., rural/urban; they do not predict reductions in accident rates by these categories, only reductions in the overall accident rate. Hence, accident cost reductions cannot be analyzed according to category). For example, a certain countermeasure may reduce, say, fatal head-on accidents proportionately more than, say, fatal ran-off-road accidents. If the same accident cost value is assigned to both types of fatal accidents, and if a fatal head-on accident os, on the average, more costly than a fatal ran-off-road accident, then this countermeasure will be undervalued with respect to its benefits in terms of reduced accident losses. If greater delineation according to accident type were made in analyses, then presumably greater accuracy in computing costs per accident (and hence expected benefits of projects) would be achievable. Whether or not this increase in accuracy would be sufficiently useful in choosing improvement alternatives to warrant the increased computational difficulties is still open to question, but preliminary calculations made in this study suggest that use of more detailed categories probably is justified (see Chapter XII). In addition, it is uncertain, a *priori*, how accurately rates of different accident types could be estimated. If there were only, say, two fatal head-on accidents during a given year at a particular location, statistical inferences would be, at best, extremely unreliable--the problem of inference from small samples. In such cases, statistical tests should be employed as outlined in Chapter XII of this report.

In summary, there are three measures of highway improvement benefits currently used in economic analyses: vehicle operating costs, value of travel time, and accident costs. Accident costs have become increasingly important in analyses, both because accident costs are now generally recognized as being greater than was generally supposed and because more funds for highway improvements have become available through recent Federal-Aid Highway Safety Acts. There are four types or definitions of accident costs; it is recommended that the NHTSA calculation, comprised of direct accident costs and gross expected future production of an accident victim, be used in conjunction with a willingness to pay measure of the value of an individual's life as an accident cost value. Until the willingness to pay concept is developed into an operationally viable technique, however, the NHTSA-type accident cost values should be used in accident cost studies. Improvements are needed in the three areas of motorist comfort and convenience, vehicle operating costs and travel time costs, and especially accident costs. Until further research provides these needed refinements, economic analyses will continue to undervalue the benefits of highway improvement projects.

Costs of Countermeasures

Before analyses can be performed to choose alternative countermeasures for implementation, the cost of each countermeasure must be determined. Not only are there several components of initial investment cost, there are future costs associated with each project as well.

Current Practices

Methods of Project Cost Calculation

There are two ways currently used by various highway and safety agencies for calculating the cost of a proposed highway safety or improvement project. One way is to consider only initial investment costs. The revised Red Book enumerates these costs [13, p. 62]:

1. Advance planning costs,
2. Preliminary engineering costs,
3. Final design costs,

4. Right-of-way acquisition and preparation costs, and
5. Construction costs.

Alabama [51] calculates maintenance costs as well as initial costs but uses only initial costs as the cost input for its dynamic programming project selection procedure.

The second method of project cost calculation includes future annual costs in addition to initial costs. A preference for this method over the first has been expressed by several sources [12, pp. 26-27; 118, p. 218; 15, pp. 55-56; 119, p. 67; 18, pp. 11-12; 116, p. 51; 13, p. 62]. A 1962 survey [64, p. 130] indicates that most agencies that use economic analysis in their highway improvement decisions do include maintenance costs. More recent examples are Kentucky [52] and Texas [73].

Estimation of Project Cost

There are three methods that agencies in charge of highway improvement implementation use to determine project cost, according to a 1973 survey [8, p. 67]. The most frequently used method, "design quantities estimate," involves estimating costs on a project-specific basis, where the unit cost or "average bid price" of each type of material--guardrail, pavement, delineators, etc.--includes not only the cost of the material itself but the costs of labor, equipment, overhead, and contractor's profit as well. The unit material costs are based on previous costs; an engineering field study determines the quantity of each type of material needed to implement a particular highway project. Estimates of unit costs and quantities of materials give the agency undertaking the project a "bid estimate" or estimated project cost. Both Texas [73] and Alabama [120] use this method.

The second most frequently used method, according to the survey, is to make a rough cost estimate based on a "cursory review" of the proposed project location. Such an estimate is made on the basis of the engineer's knowledge of the cost of similar projects previously implemented.

The third most popular method of cost estimation uses average cost tables. These tables contain an average cost value for each *type* of countermeasure, to provide state and local agencies with predetermined values to assign to prospective projects. A recent national highway safety needs study provides an example of such cost tables [61, p. V-25; 62, pp. D/45-D/52].

In practice, annual costs are estimated for only a few representative years of a particular project's expected service life. Annual costs for the remaining years are then obtained via extrapolation or interpolation [13, pp. 34, 49]. Examples of this practice are studies by the highway departments of Alabama [51, pp. 20-37] and Kentucky [52, p. 48].

Interest Rates and Future Project Costs

There is substantial opinion in favor of using a positive interest rate when calculating the present value of recurring costs associated with a particular project, e.g., maintenance and operating costs. The Red Book provides for the inclusion of an interest rate in its formula for total annual highway cost calculation [12, p. 26] while making no specific suggestion as to what an appropriate discount rate might be; the Jorgensen-Westat study [118, pp. 65, 218-219] does likewise. Winfrey [15, pp. 124-125] suggests using two or more discount rates rather than attempting to estimate a cost of capital or a minimum attractive rate of return. Constantly changing economic conditions cause the cost of capital to fluctuate, while a minimum attractive rate of return is determined subjectively, often for a particular application. By performing analyses with multiple rates, "[m]anagement then has a basis of judging the sensitivity of the results with respect to the factor of rate of probable return, and then is in a position to make a more enlightened decision." NCHRP Report 162 [8, p. 7] and NCHRP Report 96 [119, pp. 73-75] cite several reasons for using a positive interest rate rather than a simple linear aggregation of costs over time; these include the value of time preference, the opportunity cost of resources, the cost of borrowing funds, and uncertainty about the future. NCHRP Report 146 [18, pp. 15-17] discusses the problem of how to determine the appropriate interest rate for transportation projects. The higher the rate, the fewer the projects that can be undertaken with a given budget. The opportunity cost of capital is reflected in the recommended eight percent "social rate of discount." Buffington and McFarland [116, p. 52] also recommend an eight percent discount rate; they decided on this value because it represents a compromise between the six and ten percent extremes recommended for public works projects [14]. The revised Red Book [13, pp. 24-26] distinguishes between costs calculated in constant dollars and those calculated in current dollars. If costs are expressed in constant dollars, then a discount rate of four to five percent appropriately reflects taxpayers' opportunity cost of capital used in public projects of average risk; if costs are in current dollar terms, then "...the average anticipated rate of inflation should be added to the constant dollar discount rate."

A wide range of interest or discount rates are used in economic analyses of highway projects. A 1962 survey [64, p. 130] indicates the following percentage distribution of interest rates used by 64 agencies:

Interest Rate (%)	Agencies Using (%)
0.0	20
0.1 - 3.9	22
4.0 - 5.9	45
6.0 - 7.0	13
above 7.0	0

Another survey [8, p. 68], taken in 1973, corroborates the earlier survey; the range of rates used by highway and safety agencies is from zero to ten percent, with most agencies using rates between five and seven percent. A 1974 survey [66, p. 22, Table 3] finds the median discount rate or cost of capital to be seven percent, although many planners commonly use an interest rate of ten percent to reflect the opportunity cost of capital for highway improvements [18, p. 15]. More specific examples include a 1976 government study of highway safety needs [61, p. V-25], which uses a ten percent rate; Kentucky [52, p. 48] likewise uses a ten percent rate to discount future maintenance costs of spot highway improvements. Alabama [51, pp. 20-51] uses a zero percent rate for discounting maintenance costs, while Texas [121, p. 2/6] uses an eight percent capital recovery factor.

Service Lives of Projects

Sources are fairly consistent in their suggestions regarding appropriate service lives of spot improvement projects, i.e., the period of time that a project is expected to affect accident rates. In accordance with Winfrey [15, p. 242], NCHRP Report 162 [8, p. 8] indicates that the analysis period should not extend beyond the period of reliable forecast; hence, the estimated service life of a project should not exceed the length of time that estimated accident reduction can reasonably be expected, given traffic diversion, vehicle design, and other parameters that affect the performance of a given improvement project. Because traffic projections are not ordinarily made for periods exceeding twenty-five years, primarily because of the many uncertainties about the relatively distant future, the revised Red Book [13, p. 33] suggests an analysis period and service life of fifteen to twenty-five years for highway improvement projects. Another source [18, p. 18] recommends a twenty-five year service life for highway construction projects; although the physical lives of such transportation facilities are generally much longer than twenty-five years, this time limit reflects technological advances that make existing facilities comparatively inefficient. As before, this argument for a twenty-five year limit rests on uncertainty about future conditions.

In recent years, agencies undertaking highway improvements have begun to follow these suggestions. A 1962 survey [64, pp. 125-126] shows that in the past, many agencies did not use a study period, while others simply used service lives between twenty and forty years for pavement improvements and between twenty and seventy-five years for major and minor structures. More recently, a 1969 study of California highways [75, p. 33] recommends and uses a maximum service life of twenty years, on grounds that uncertainties about the future make predictions too unreliable after that length of time. The highway departments of Kentucky [52] and Alabama [51] use a maximum service life of twenty years in their highway spot improvement programs.

Inflation and Future Project Costs

Because economic analysis of highway improvements involves future costs (and benefits), it is relevant to consider the effects of inflation. The consensus appears to be that inflation should not be included in present value calculations. Lee and Grant [122] conclude that inflation should not be considered when forecasting future costs and benefits and that current prices should be used except in those cases "...when there is overwhelming evidence that certain inputs or outputs, such as for land, are expected to experience significant price changes relative to the general price level." Winfrey concurs, stating that [15, p. 248]:

> Within the economy of highway transportation, the inclusion of an inflationary factor in the future highway costs of construction and maintenance would call for similar consideration of inflation in the road-user costs for motor vehicle operation and in the value of travel time. Thus, both costs and benefits would be inflated, so their relative magnitude may be the same with or without the factor of inflation.

NCHRP Report 162 [8, p. 7] also agrees with Lee and Grant, emphasizing the difficulty of predicting future inflation rates and hence the undesirability of including an inflation factor in present value calculations of highway project costs (and benefits). The revised Red Book [13, p. 25] recommends using constant dollars rather than inflated or current dollars in economic analysis, "...since it avoids the need for speculation about future inflation in arriving at the economic merit of the project."

In practice, most agencies follow these guidelines and do not use any sort of inflation factor in their economic analyses of highway improvement projects. The 1973 survey mentioned above [8, p. 68] indicates that agencies typically use no inflation rate; a very few use rates ranging from five percent to slightly over seven percent. Alabama [51, pp. 20-37] uses no inflation rate in its CORRECT program for highway safety improvements, although Kentucky [52, p. 48] implicitly includes inflation by using an interest rate of ten percent in its present value calculations of costs and benefits (the revised Red Book [13, pp. 24-26] recommends an interest rate of four to five percent for the real cost of capital; any interest rate higher than this includes an inflation rate). The recent national highway safety needs study mentioned above [61, p. V-24] makes all cost estimates in constant 1974 dollars, thereby excluding inflation from its calculations.

Needed Improvements

There are two suggestions regarding future economic analysis of highway improvement projects. The first is that both a positive discount rate of about four to five percent and future maintenance costs should always be included when calculating the present value of the total cost of a particular project. Calculations should be made in constant dollar terms, with no inflation factor.

The second suggestion regards initial construction costs. Although it might be difficult to include this consideration in an economic analysis, it should at least be recognized that there may exist economies of scale in implementing projects geographically close together, i.e., the initial cost of implementing two projects near each other may be less than the sum of their independent initial costs. For example, the equipment and crews used on one project could, upon completion, be transferred directly to the second project, thereby saving the costs of transporting them into the field a second time.

PART FOUR: COUNTERMEASURE EFFECTIVENESS AND REVIEW OF SELECTED COUNTERMEASURES

VIII. METHODS OF DETERMINING COUNTERMEASURE EFFECTIVENESS

Since the turn of the century, thousands of attempts have been made to calibrate the effectiveness of different highway accident countermeasures in reducing deaths, injuries, and property damage. Crash cushions, guardrails, median barriers, intersection lighting, edge striping, pedestrian crosswalks, paved shoulders, active protection at railroad-highway grade crossings, and hundreds of other highway safety designs and devices have been subjected to evaluation. Some of these evaluations have constituted rigorous, well-documented research, while others have been little more than the capricious whims of advocates of a given design or device.

Types of Studies

At a rudimentary level, the various attempts to evaluate highway accident countermeasures can be divided into four types: naturalistic studies, artificial studies, system models, and subjective assessment. Each of these four major types can be subdivided to produce a broad spectrum of evaluation philosophies and methodologies. The balance of this section will be devoted to describing the various ways and means by which highway accident countermeasures have been evaluated.

Naturalistic Studies

Naturalistic studies of countermeasure effectiveness have used a variety of measures to determine effectiveness. Fatality rates, injury rates, property damage only rates, vehicle speeds and variances at a given point along a highway, conflicts at intersections, lateral placement of a vehicle within a lane, and skid marks all constitute dependent variables which may be used to evaluate the effectiveness of different countermeasures in the highway environment.

The hallmark of naturalistic studies of highway accident countermeasures is that they are part of an ongoing process; they are not simulated, i.e., artificially arranged. Naturalistic evaluations of highway safety systems and devices attempt to measure the effectiveness of those systems and devices in the real-world environment of highway traffic.

Naturalistic evaluations of highway accident countermeasures can be divided into two groups according to the type of dependent variable chosen for a given evaluation. The two types of dependent variables used in naturalistic studies are accident variables and proxy variables.

Accident Variables

The goal of highway safety is simple and straightforward. It is to reduce death, injury, and property damage on the nation's roads and highways. From this it follows that accident rates, fatality rates, injury rates, and property damage only rates are the purest and most direct measures of effectiveness of various countermeasures.

Proxy Variables

Unfortunately, fatality, injury, and PDO accident rates are very insensitive variables by which to measure the effectiveness of a program or device. This is because accidents are very low probability events (approximately twelve accidents per million vehicle miles) and are caused by a multitude of factors acting singly and in concert.

Most highway accident countermeasures which are implemented in the name of safety are thought to produce only modest returns in terms of lives saved, injuries prevented, and accidents avoided. Therefore, if these modest countermeasures are to be demonstrated to be effective in achieving their goals, either the countermeasure in question must be deployed at a large number of locations, or the countermeasures must be evaluated over a protracted period of time, or both.

To circumvent the problem of using accident data to evaluate countermeasures, it has become more common to measure the effectiveness of safety designs and devices with proxy variables. Proxy variables are measures which are assumed to covary with accident rates but which are more sensitive to imposed countermeasures than are the death rate, injury rate, and PDO rate.

Examples of proxy measures which have been used to evaluate accident countermeasures include speed, speed variance, lateral placement of the vehicle in the lane, skid marks, and conflicts at intersections.

Evaluation Designs

In order to evaluate the effectiveness of accident countermeasures in the field, two basic types of designs have been used: experimental designs and quasi-experimental designs.

Experimental Design

Assume that we are interested in determining the effectiveness of automatic gates at railroad-highway grade crossings. To conduct this evaluation, we would begin, ideally, by randomly selecting a large number (e.g., 1000) of passively protected railroad-highway grade crossings and save the remaining, unaltered crossings as a control group. After a suitable period of time, the number of accidents sustained at the gated crossings would be compared with the number at the ungated crossings. The difference in accident rates between the two groups would constitute our measure of effectiveness.

This hypothetical study of automatic gates is called a "naturalistic, experimental study." The term "experimental" implies that the assignment of treatments, e.g., the determination of which crossings will receive automatic gates, is randomly determined and that a random control group is defined against which the effects of the treatment can be measured.

Quasi-Experimental Design

While naturalistic, experimental studies of the effectiveness of highway accident countermeasures have been few in number, "naturalistic, quasi-experimental studies" of safety designs and devices have been fairly common. Quasi-experimental studies differ from experimental studies in that treatments (countermeasures) are not randomly assigned among potential treatment sites, and no randomly defined control group exists against which to compare the efficacy of the imposed treatment (countermeasure).

The most common naturalistic, quasi-experimental design which has been used to evaluate highway accident countermeasures is the simple before-and-after design. By the tenets of this design, a location with a known accident history is treated with a given countermeasure. Then, accident data are collected at the location for a suitable period of time after the countermeasure has been deployed. The difference in accident rates before and after imposition of the treatment constitutes a measure of effectiveness of this program. While other naturalistic, quasi-experimental designs, such as time series designs, multiple time series, and ex post facto analysis, have been used to evaluate highway accident countermeasures, they are sufficiently uncommon as to be omitted from this discussion.

Artificial Studies

Artificial studies of the effectiveness of highway accident countermeasures are conducted in laboratory settings. Performance tests of bridge rails, guardrails, and median barriers are, in effect, evaluations of the benefits which might be attributable to such devices deployed in real-world settings. Human factors studies of lighting, warning devices, and the conspicuousness of signs are, in fact, attempts to determine the value of different visual cues in reducing accidents. Behavioral studies of driver braking and steering are often aimed at calculating the amount of friction required by drivers in emergency situations. Indirectly, such studies estimate the accident avoidance potential of increasing the available friction on road surfaces having low skid numbers.

Artificial studies of the effectiveness of highway accident countermeasures can be divided into two categories: physical performance tests and behavioral performance tests.

Physical Performance Tests

Full scale crash tests of median barriers, guardrails, bridge rails, break-away poles, crash cushions, etc. are the most obvious and most dramatic attempt to assess the real-world capabilities of crash-phase safety devices under controlled laboratory conditions. The amount of crash sustained by a vehicle, the lateral and longitudinal forces recorded on the vehicle during the crash, and the degree to which the vehicle is redirected by a guard rail are the dependent variables of full scale crash testing.

Physical performance measures are also applicable to the evaluation of accident avoidance safety devices such as street and highway lighting. Different luminary systems can be judged in terms of the amount of light reflected off the pavement at fixed distances from the source, of the size of the light field cast by a given bulb and reflector system, etc. Again, these dependent measures of the worth of a system or device are physical in nature. Each can be calibrated along a physical dimension with the aid of appropriate instrumentation.

Behavioral Performance Tests

As the phrase implies, behavioral performance tests require the mediation of a human operator. The dependent variables of behavioral performance tests are the verbal and motor responses of human subjects.

If we assume that misperceived sign messages cause accidents, then we might conduct a human factors study to determine how sign messages should be structured so as to promote rapid reading, and hence, reduced accidents. If obstructions placed near the right edge of the highway cause drivers to move toward the center line and, hence, increase accident probability, behavioral research might indicate the degree to which existing obstacles should be set back from the roadway. In short, if driving simulations of potentially hazardous conditions can be arranged, then information on the degree of hazard inherent in those conditions and on the effect of ameliorating those conditions can be estimated.

Systems Models

Systems models of traffic accidents assume that the precursors to a crash, or the consequences of a crash, can be specified to such a degree that it is possible to predict, in a statistical sense, either where a crash will occur or what the consequences of a crash will be if it occurs at a particular location. Systems models that predict crash locations are referred to as accident probability models, while systems that predict consequences of crashes are referred to as crash simulation models.

Accident Probability Models

While it is important to recognize that accidents are low-probability events, it is also important to recognize that accidents are not random events. Accident probability can be shown to vary as a function of a number of variables, such as average daily traffic, relative frequence of adjoining streets, roadway geometry, and number and locations of roadside obstacles. Models which attempt to predict where accidents will occur use the information provided by covariates, such as those listed above in determining where countermeasures should be implemented and what benefits those countermeasures might produce. For example, if we possess an accident probability model which validly forecasts where "ran-off-road/hit-fixed-object" crashes will occur, we should also be able to estimate the benefits which would accrue to a roadside clearance project implemented on the basis of our model. If we possess a model which validly predicts where head-on crashes will occur, then we know where to install median barriers and what benefits those barriers will produce.

Crash Simulation Models

If a vehicle strikes a naked bridge abutment at an extremely high rate of speed, the inevitable result for the driver is death. On the other hand, if the abutment is struck at a trivially low rate of speed, the result will be that the driver escapes injury. Between these two extremes, the probability of driver fatality ranges from one to zero. If a crash cushion is placed in front of a bridge abutment, the probability of fatality to the driver from striking the device is lower than the probability of fatality from striking the abutment (note that the amount of benefit derived from the crash cushion is dependent upon speed at impact and the angle at which the device is struck).

A crash simulation model of an energy absorbing cushion placed in front of a bridge abutment might include the following inputs: traffic volume, speed distribution of vehicles at the bridge, makeup of the vehicle mix, i.e., percent cars and percent trucks, and angles at which the crash cushion might be struck. The input data would be passed against the performance characteristics of the cushion under study, and a distribution of crash consequences, e.g., decelerative forces and injury levels, would be ouput. Similarly, the crash consequences of striking an unforgiving bridge abutment could be derived. The difference in the distribution of crash consequences for the protected and unprotected abutments would constitute the effectiveness of the countermeasure.

Subjective Assessment

Subjective assessment is the most common method of evaluating the effectiveness of accident countermeasures. Sometimes these estimates are performed by one man who is presumably familiar with the countermeasure which he is evaluating and with the location(s) where it will be deployed. Such one-man evaluations are often referred to as "engineering judgments." On occasion, a team of individuals with different educational or experience backgrounds is assembled to estimate the worth of a program or a countermeasure. Their collective engineering judgment is referred to as a "multidisciplinary approach" to the problem. If they employ some stylized method of rank ordering the effectiveness of various competing countermeasures, it is said that they have employed a variation of the "Delphi technique" in reaching their conclusions.

Subjective assessments of countermeasure effectiveness are so numerous and so varied that it is difficult to clearly subdivide this type of evaluation into clear, mutually exclusive categories. However, most subjective evaluations of the effectiveness of accident countermeasures can be viewed as accident specific, location specific, or countermeasure specific.

Accident Specific

To apply this method of evaluation, one or more individuals examine a set of accident narratives and estimate the degree to which the presence of a countermeasure reduced the consequences of a crash, or conversely, the degree to which the absence of a countermeasure caused or aggravated an accident.

Location Specific

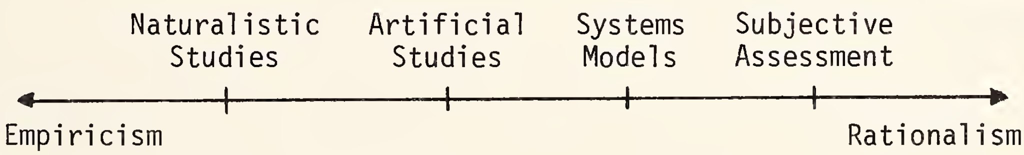
Certain locations which have sustained an unusually large number of accidents may be evaluated to determine which of several remedial treatments might produce the greatest accident reduction or amelioration. For example, a given horizontal curve which has been the scene of numerous ran-off-road accidents might be favorably treated with edge stripes, guardrails, greater super elevation, better transition prior to the curve, or a roadside clearance program. These treatments have different costs, but each produces a unique benefit in terms of accidents avoided and deaths or injuries reduced.

Countermeasure Specific

The potential of a specific countermeasure in reducing deaths, injuries, or property damage can be assessed through engineering studies of safety devices. Certain such devices, particularly crash phase safety devices, are subjected to a wide range of test conditions that simulate engineers' subjective estimation of real-world conditions under which the devices will operate. On the basis of countermeasure performance data obtained under the test conditions of expected real-world circumstances surrounding the types of accidents relevant to the engineering study, the potential of the proposed countermeasure is estimated.

Shortcomings of the Four Basic Methods of Evaluating Highway Accident Countermeasures

The four basic methods of evaluating the effectiveness of highway accident countermeasures can be thought of as falling along a philosophical scale extending from *empiricism* at one extreme to *rationalism* at the other. "Empiricism" is defined in Webster's as "the practice of relying upon observation and experiment especially in the natural sciences." "Rationalism" is defined as "a theory that reason is in itself a source of knowledge superior to and independent of sense perception." With an empiricism/rationalism scale, the four methods of effectiveness evaluation can be ordered as shown in the following figure:



Naturalistic studies lie at the empiricism end of the scale. Naturalistic studies, it is recalled, are characterized by observations and measurements made in the real-world environment of highway traffic and highway accidents. Experimental and quasi-experimental procedures provide the method by which the value of a countermeasure is determined.

Artificial studies of the effectiveness of highway accident countermeasures are typically experimental but are one step removed from the reality of highway traffic and highway accidents. Artificial studies of the effectiveness of accident countermeasures are conducted in staged, laboratory settings. Results garnered through laboratory studies can be extrapolated to the highway environment only through logical inference or empirical validation.

Systems models of accident probability and crash simulation are posited at a higher level of abstraction than are naturalistic and artificial evaluations. The input data for systems models may be empirical or conjectural in nature, but the operations on those inputs are basically rational in flavor. The output of systems models, like the output of artificial studies, can be extrapolated to the real-world highway environment only through logical inference or empirical validation.

Subjective assessments of countermeasure effectiveness come straight out of the rationalist school of philosophy. Advocates of this type of evaluation feel that empirical attempts to determine countermeasure effectiveness are insensitive to the idiosyncracies of specific locations where countermeasures might be deployed. They argue that the effectiveness of countermeasures in reducing fatalities, injuries, and property damage is highly dependent upon the locations and conditions under which those countermeasures are implemented. Human reasoning, they feel, is the only means of accounting for the specificity of given locations and is thus the only means of accurately estimating the effectiveness of countermeasures at those locations.

Specific Shortcomings

Naturalistic Studies

(a) Inadequate data - To evaluate the effectiveness of many highway accident countermeasures, suitable collections of accident data simply are not available. Accident data sets based on police reports are available in most states, but these data sets are often of such poor quality that they cannot be used for evaluation purposes. Accident data sets generated from the reports of specially trained personnel (e.g., the Multi-Disciplinary Accident Investigation Reports produced by various contractors for NHTSA) are more detailed than police data, but they are smaller in size and are generally nonrepresentative of the overall population of accidents occurring in the nation.

(b) Costly, time consuming - The collection of accident data is obviously a costly and time-consuming process. The effectiveness of a countermeasure deployed today cannot be calibrated in terms of accidents eliminated until several months or years of accident data have been accumulated.

(c) Proxy variables - Because accident data must be collected for long periods of time before the effectiveness of a countermeasure can be substantiated, proxy measures are used to provide short range calibration of the effectiveness of safety programs and devices. Unfortunately, some of the proxy measures which have been used to calibrate countermeasure effectiveness bear little correlation to accident rates; in other words, the fact that a countermeasure produces a lowered reading on proxy measure is no guarantee that the accident rate will be similarly affected. In other cases, a positive relationship does exist between proxy measures and the accident rate, but the degree of relationship between the two is unknown. Thus, if a given countermeasure reduces a proxy measure by one-half, it should be predicted that the accident rate is reduced, but not necessarily by one-half. In short, the proxy variables which have been used in safety evaluations may not be valid reflections of the basic aims of highway safety, namely, the reduction of death, injury, and property damage.

Artificial Studies

(a) Proxy variables - It has just been stated that proxy variables used in naturalistic evaluations are of questionable validity in predicting accident rates. The same thing can be said about all variables used to measure effectiveness in artificial studies. All variables used in artificial evaluations are proxies for fatal, injury, and PDO accident rates. Deformations of sheet method, "g's", trauma sustained by cadavers, lambers, and verbal responses by human subjects are all dependent variables thought to be proxies of real-world accident rates. However, as was the case with naturalistic proxy variables, the validity of artificial proxy measures is open to debate.

(b) Laboratory setting vs. real-world setting - Laboratory evaluations of accident countermeasures have the advantage that they can be closely monitored and carefully measured. And, to the extent that laboratory conditions mimic real-world conditions in all important aspects, the findings of a laboratory may be validly extrapolated to a real-world setting. However, the disparity between real-world settings and laboratory settings is often so great that it is difficult to extrapolate from one setting to the other. The fact that a given device performs well under test conditions is no guarantee that it will perform as well when deployed.

Systems Models

Systems models attempt to predict where accidents will occur or how severe those accidents will be on the basis of a prescribed set of input data. By adding additional inputs, e.g., the installation of a given countermeasure, reductions in accidents or accident severity can be predicted.

The major flaw of most systems models is that they have not been validated to determine the accuracy of their predictions. It should be remembered that systems models operate on specified inputs according to certain inferencial assumptions. If these assumptions are sound, the model may well predict countermeasure effectiveness. However, the only way to ensure the adequacy of a model is through empirical verification.

Subjective Assessment

The same shortcoming of systems models also applies to subjective evaluations of accident countermeasures. If a subjective evaluation indicates that a given safety device will reduce accidents by ten percent, the only means of accepting or rejecting this claim is by empirical verification. Unfortunately, the empirical validation of subjective assessments is rarely carried out.

Variability of Countermeasure Effectiveness

In discussing the effectiveness of countermeasures, it is easy to assume that the level of effectiveness is the same for each accident countermeasure in all circumstances, but this is not the case. The effectiveness of an accident countermeasure is a function of several variables. These include the location where the device is deployed, the presence or absence of other countermeasures, and the influence of traffic and vehicle characteristics.

Location

The effectiveness of various accident countermeasures is highly site-specific. For example, guardrails are probably more effective, reduce more fatalities, on curves than on tangents. Automatic gates at railroad/highway grade crossings are, of course, more beneficial at some crossings that at others. Paved shoulders may be more effective on two lane highways with ten-foot main lanes than on similar highways with twelve-foot main lanes.

How effective, then, are guardrails, automatic gates, and paved shoulders? Any single answer to this is an oversimplification. The effectiveness of a countermeasure covaries with a host of other variables. For practical purposes, the most we can hope to achieve in defining countermeasure effectiveness is to specify a range of effectiveness for a given countermeasure and to indicate which covariates will influence the effectiveness of a countermeasure.

Interaction Among Countermeasures

If countermeasure A reduces accidents by X, and countermeasure B reduces accidents by Y, it does not follow that the simultaneous deployment of A and B at a given location will reduce accidents by X plus Y. In fact, the simultaneous deployment of A and B may produce results less than, equal to, or greater than X plus Y.

Assume that a given curve has an unusually high fatality rate. To correct the situation, we groove the pavement, paint stripes along the roadway edge, add raised reflectors to the edge line, and install better guardrails. If these four countermeasures are imposed and the fatality rate is subsequently reduced, we will have no means of determining the contribution of each countermeasure to the overall effectiveness achieved. One or more of the treatments may be totally ineffective; perhaps all of the reduced fatality rate is due to one treatment. There are undoubtedly some interactions among the treatments, producing an effect which is not equal to the sum of the effects of the individual treatments. In any event, it seems unlikely that the overall effectiveness of our intervention is simply the sum of the individual effects of four countermeasures.

Traffic and Vehicle Characteristics

Assume that a crash cushion at a given location is known to have reduced fatalities by 80 percent in 1976. From this it does not follow that the device will reduce fatalities by 80 percent in the future. As stated before, the effectiveness of countermeasures depends upon a number of variables. If our crash cushion is located on a section of highway which will see increasing truck traffic in future years, the efficacy of the crash cushion may decline. On the other hand, ten years from now the motor vehicle fleet may contain a higher percentage of compact and subcompact cars. Under these circumstances, the efficacy of our crash cushion may rise, even though no physical modifications to the cushion are made. Thus, it should be clear that the effectiveness of a specific countermeasure, deployed at a specific location, will change as changes take place in traffic and vehicle characteristics.

IX. GENERAL REVIEW OF ESTIMATES OF COUNTERMEASURE EFFECTIVENESS

The idealized allocation system shown in Figure 9 assumes that the overall process of rationally distributing highway safety funds is a two-step process:

1. First, a set of potential safety projects within a state, a municipality, or a district is defined, and then
2. Those projects are submitted to a cost-effectiveness algorithm which selects the "best" combination of projects for a specified budget.

It could be argued that both of these steps should be joined together to form a larger, generic cost-effectiveness model capable of carrying out both functions. While such a conceptualization is tenable, it is at the same time a conceptualization which goes beyond the minimal definition of a cost-effectiveness model. For our purposes, and for purposes of insuring compatibility with existing efforts by the states to perform cost-effectiveness analyses, we will assume that the process of rationally allocating safety funds involves two separate and independent models: a *project-definition model* and a *cost-effectiveness model*. The project-definition model specifies or defines a set of safety projects worthy of consideration for funding; the cost-effectiveness model selects from the set of proposed projects that subset with the highest yield for a stated investment.

The balance of this section will be devoted to considering (in general terms) the degree to which the states, and the various highway districts and municipalities within the states can adequately define sets of potential safety projects within their jurisdictions. The accuracy and the availability of the basic input data needed by the states, districts, and municipalities to adequately define a set of potential safety projects will be discussed. In particular, the accuracy and the availability of the following data (and data sets) will be discussed:

1. Accident data
2. Countermeasure effectiveness data
3. Countermeasure cost and service life data
4. Highway, traffic, and environmental data.

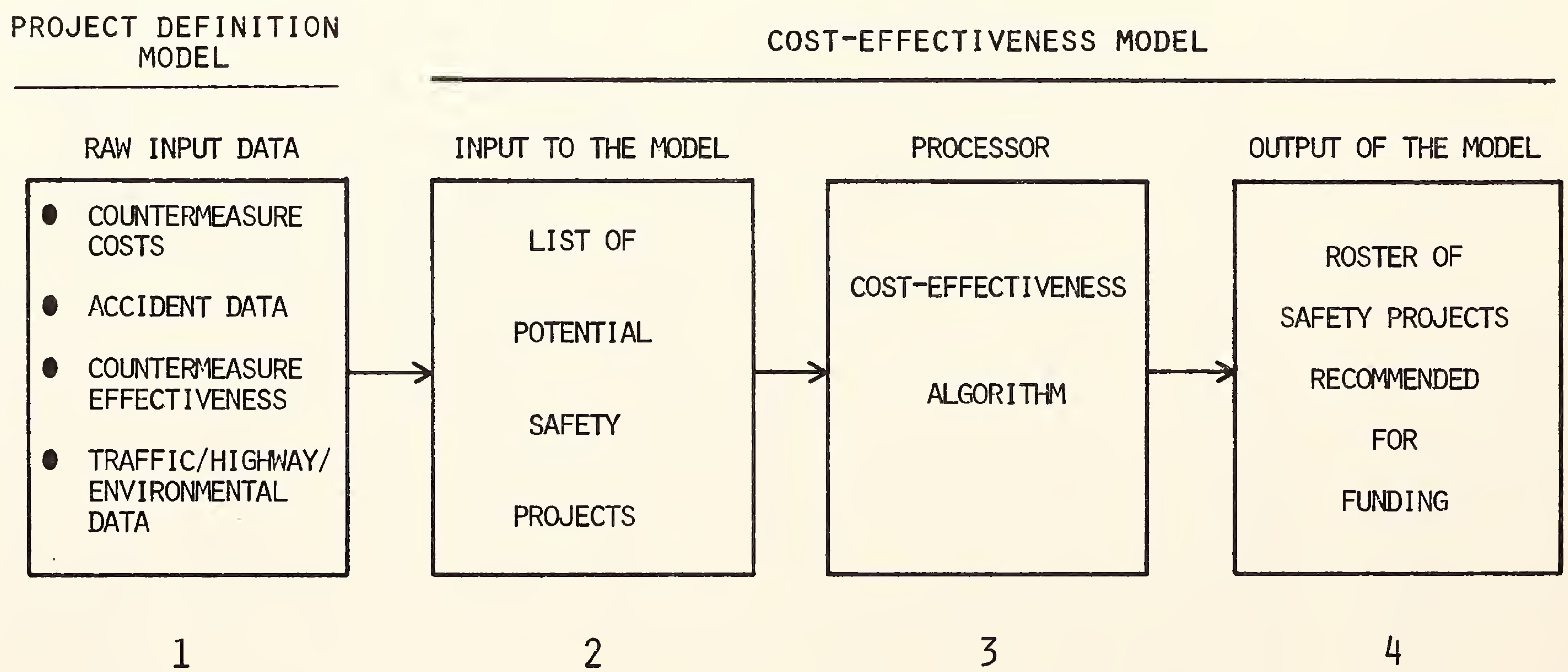


Figure 9. Idealized Allocation System for the Deployment of Highway Safety Funds

Accident Data

> [T]he fact is that in this country we do not have suitable statistics to provide us with the information needed to combat the problem of accidents, injuries, and deaths ... We do not have information that would permit us to assess adequately road environment factors in the production of accidents. This is partly because existing statistical systems do not even allow pinpointing the accident with suitable precision. Obviously, if one wishes to study accidents in terms of road factors, it is at least necessary to know where the accident occurred, and the physical characteristics of that exact spot [123, p. 9].

In the eleven years since B.J. Campbell made this statement, much effort and progress have been made in improving the quality of traffic records systems within the states. Today most states are able to pinpoint where their traffic accidents are occurring, and many states are able to specify the physical characteristics, e.g., lane width and skid number, at and near high accident locations.

In the late 1960's, Kihlberg and Tharp [124] sent questionnaires to all state highway organizations and asked each state to provide some basic information about their highway/traffic record and retrieval systems and their accident record and retrieval systems. Results from three items contained in those questionnaires are:

1. Does your state highway organization maintain records of highway features and traffic volumes listed by roadway sections?

   Yes - 44 No - 5 No response - 1

2. Does your state highway organization maintain, possess, or have access to data on highway accidents?

   Yes - 47 No - 2 No response - 1

The majority of the states indicated that their highway data and accident data are recorded so that they can be retrieved via automated means.

3. Does your record system provide for locating the site of a particular accident within the roadway section where the accident occurred and thus permit the data covered in question 1 to be matched with the data in question 2?

Yes - 40		No - 10
Manually	19	
Automated	9	
Manually or automated	12	

(Adapted from [124, pp. 8-9])

While the results of the survey by Kihlberg and Tharp indicated that the states were, by and large, actively engaged in collecting accident data, it was also clear at this time that more work was needed. Some states needed to automate their accident record systems. Other states needed to specify more precisely where accidents were occurring within the highway environment. And all states needed better means of comparing accident locations with highway features and traffic conditions at those locations.

Recognizing the inadequacy of accident records systems as they existed in most states in the late '60s and early '70s, the Federal Highway Administration (FHWA) in 1972 designated Highway Safety Standard Nine a priority emphasis area. FHWA directed, in effect, that all states should upgrade the quality of their accident data bases so that by December 31, 1975 [55, p. 48]:

> All states should be able to accurately identify accident locations to within one-tenth of a mile in rural areas and to within 100 feet in urban areas on their federal-aid and state highway systems. The reference system and accident reference file should be defined and maintained to permit rapid entry and retrieval of data in a form usable by engineers and others in the development of appropriate countermeasures and be compatible with other information in the statewide traffic records systems. This same accuracy should be obtained for all public roads within each state.

Michigan has improved its ability to accurately locate accidents on its streets and highways with a system known as MALI -- Michigan Accident Location Index [125]. With the aid of this system, begun in 1970, the accident location specified by a police officer is compared to a street index stored in a computer. By means of this comparison, a mile point number can then be automatically assigned to each accident. The main advantage of this system is that descriptions of accident locations provided by the police officers can be transcribed by machine to produce a numerical, i.e., mile point, description of the accident locations. By eliminating the human operator formerly necessary to transcribe the accident data to the mile point reference system, it can be shown that the accident location is more accurately specified.

Arizona is in the process of upgrading its accident location capabilities with the aid of a program known as ALISS -- Arizona Location Identification and Surveillance System [126]. The fundamental principal of this system is that the whole of the State of Arizona can be divided into a grid system which can be used to locate accidents at specified distances from stated coordinates [126, pp. 51-52]:

> The Location File of the ALISS System is made up of a digital model of the entire road and street network of the state. (W)orking from new aerial photography (ortho photos) obtained from NASA through special agreements using U-2 high-flight aerial photography ... maps are prepared ... Each jurisdiction in the state has then inspected the line maps for its own political boundaries and has indicated which roadways it feels significant enough to include.
>
> For each road and street in the state, a set of state plane coordinates is digitized, or calculated, which defines the linear features of that road. Each road is then defined by a series of component pieces, called links. A link consists of either road intersection (a point link) or a road section (a length link). A road section consists of a stretch of road from one digitized point (a node) to the next successive node along that road.
>
> All node points describing links of roads and streets are combined in the LINK Data Base, which is the Location System File.
>
> [E]ach accident record is tied to the LINK in which it occurred in the LINK data base, representing the location of that accident. This allows the accident road logical data base to indicate the location of an accident and the road link logical data base to indicate where accidents have occurred on a road.

In a clear departure from past efforts at locating traffic accidents within a highway system, the State of New York has studied the feasibility of using LORAN-C for purposes of locating accidents [127, 128]. "LORAN-C is a radio-navigational system ... which is presently operated and maintained by the U.S. Coast Guard" [127, p. 3]. At this time LORAN-C transmitters are positioned in the Eastern half of the United States. With the aid of a LORAN-C receiver, an operator (e.g., a police officer) is able to calculate his exact position with regard to three reference transmitters from which he is receiving signals [127, p. 4]:

> A LORAN-C receiver measures the difference in the time of arrival of signals from the LORAN-C transmitting stations to the receiver. These time differences are proportionate to the difference in the distance between the receiver and the transmitters. A LORAN-C

receiver will determine two or more sets of time difference values, which describe two lines of position (LOP). At the intersection of these two lines is a position which is identical to that of the receiver. This provides the receiver with his exact location.

If a LORAN-C receiver were located in every police car, the investigating police officer at the scene of an accident could directly determine his exact location, with the aid of his receiver. Rather than locating his position with regard to proximal highway features, the officer would determine the geographic coordinates of his position from the receiver, and then enter those coordinates on the accident report form. Any intermediate coding by clerks would be obviated and accuracy would thereby be enhanced.

While the use of LORAN-C to locate accidents is still in its infancy, the New York State Department of Motor Vehicles has concluded that "... LORAN-C can technically, operationally, and economically satisfy the precise position identification requirements for selected applications in New York State" [127, p. 59].

The Division of Highways of the State of California began operating a computer-assisted accident surveillance system in 1965. In 1970, the design work began on a new system known as TASAS -- the Traffic Accident Surveillance and Analysis System [129]. The data contained in the TASAS system provide information on accidents (approximately 130,000) which occur on the state highway system and information on the state highways themselves: location (route, county, postmile identification), highway group (divided, undivided, independent alignment), ADT, and federal-aid systems identification.

On the basis of the accident data yielded by the TASAS system, a quarterly report (known as a Table C report) of high accident locations is sent to each of California's eleven highway districts to aid in the identification of roadway sections and locations in need of alteration or treatment [129, pp. 100-112]:

> Table C reports list high accident concentration locations. It counts the total number of accidents for 3, 6, 12, 24, and 36-month periods and shows the significance. It also calculates the Actual Rate and shows Expected Rate. This report does have the option to consider highway segment lengths of up to 0.5 miles.

In addition to the quarterly report of locations having accident rates significantly greater than should be expected, the TASAS system can be used to generate accident reports for specific subclasses of accidents. For example, if a highway district within the state wanted a printout of those locations which had wet weather accident rates in excess of expectations, such a printout could be produced. Similarly, bridge accidents, nighttime accidents, ramp accidents, etc. could be printed out upon the request of state highway personnel.

The accident surveillance system operated by the State of Oregon is somewhat similar to the system employed in California [130]. The Oregon study instituted in the mid-1960's was built upon a milepost location system which had been in operation for many years. With the aid of the automated system implemented in the mid-60's, the state began providing periodic printouts of high accident locations to districts at six-month intervals. High accident "locations" are 0.2 mile lengths of urban roadway and one mile lengths of rural roadway. The output of hazardous locations is ranked according to accident rates (accidents/million vehicle miles). With the aid of these printouts, the district engineers have the ability to identify hazardous locations within their jurisdictions and, hopefully, to prescribe treatments or countermeasures which will reduce the hazards at the indicated locations.

Limitations of Accident Data

> [P]olice level data are not recorded in detail. Levels of vehicle damage and occupant injury are evaluated by an officer who may be trying simultaneously to summon medical aid, direct traffic, and determine whether or not a law has been broken. Under these circumstances, the data yielded by these investigators is very good, but necessarily the collection of data should not be considered the officer's area of expertise or his major area of responsibility [131, p. 39].

Scarcity of Environmental (Highway) Questions on Accident Report Forms

It is customary in traffic safety to discuss traffic accidents in terms of three factors: the vehicle(s), the driver(s), and the environment. On the basis of these three factors or some combination thereof, the "cause" of the accident is defined. The driver was intoxicated, the brakes failed, the tires were bald and the road was wet, the sign post which the vehicle struck was not breakaway -- these are reasons offered to explain why accidents occur or why accidents are more severe than they might have been.

In looking over numerous accident report forms used by the various states, it can be seen that most of the information collected by the police officers on state forms pertains to the drivers and/or pedestrians involved in the crash. For example, driver age, sex, race, sobriety, seat belt use, physical condition, and driving maneuvers are all contained on many state accident report forms. Vehicle information, e.g., vehicle make, model, and year, defects, tire condition, and vehicle color, and environmental (highway) information, e.g., horizontal curvature, vertical curvature, highway class, and object struck, are also collected, but to a lesser degree.

Council and Hunter have commented upon this void in accident information [89, p. 183]:

> Even with what is felt to be a good system (the North Carolina system), there are problems resulting from the fact that the report form used is oriented toward the legal consequences of an accident (i.e., a resulting charge or court case) and the collection of driver-oriented data and less toward roadway-oriented questions. For example, economic analysis of median barriers in the current study was made impossible by the lack of information on whether medians existed at accident sites. In a similar manner, it would be impossible to analyze accidents occurring on freeway ramps without specific information on this roadway segment which had been carefully collected and recorded by the investigaing officer.

Accuracy of Police-Compiled Data

The Federal Highway Administration specified in 1972 that all states should be able to locate urban accidents to the nearest hundred feet, and rural accidents to the nearest tenth of a mile. The previous section briefly discussed systems being developed by Michigan and Arizona to comply with this requirement. However, it should immediately be recognized that regardless of the sophistication of the data retrieval system employed by a state, the output of that system is no better than the data originally collected on the accident report form. If an investigating officer records the location of an accident as 0.2 miles (.33 km) north of a given intersection instead of 0.2 miles (.33 km) south of that intersection (where it in fact occurred), there are few if any edits in most traffic records systems which would correct this error. If an officer estimates the distance from an accident site to a reference intersection instead of measuring the distance from the accident to the intersection, the accuracy of this datum will generally be reduced, since human estimates of distance are notoriously inaccurate.

The degree of inaccuracy inherent in police-generated accident report forms is, at this time, unknown. The frequency with which police reports contain inaccurate directions and distances is unknown. The prevalence of miscoded highway types, roadway features, highway surfaces, and vertical and horizontal curvature is unknown. And finally, the effects of inaccurate accident information on subsequent attempts to discover high accident locations and to prescribe treatments for those locations are unknown.

Unreported Traffic Accidents

Each state defines a minimum level of property damage and/or personal injury which must be sustained in an accident before that accident should be reported. In some states the dollar threshold for reporting is as low as 25 dollars; in other states the threshold is several hundred dollars. With such definitions of reportable accidents, it is obvious that many minor accidents go unreported. Even more unfortunate is the fact that many accidents which legally should have been reported are not reported. The degree to which reportable accidents do not enter the data base is not well known. One study by McGuire [132] indicates that the nonreporting of accidents) may be a significant problem. Another study by House, et al. [133] indicates that the problem of nonreported accidents may not be too severe, at least in the North Carolina traffic records system.

Complicating the problem of inaccurate accident data and the nonreporting of accidents is the practice in many states of allowing the accident participants to fill out their own accident report forms, i.e., in many states the drivers of crash involved vehicles rather than police officers fill out accident report forms. The reduction in accuracy which results from the practice, and the increase in nonreported accidents which results from this practice is unknown. It seems reasonable to expect that the participants in a traffic accident have a perception of the events which surrounded that accident which frequently would be at odds with the perceptions of a neutral third party, e.g., a uniformed police officer. It also seems reasonable to speculate that many minor traffic accidents which legally should be reported in fact go unreported when the accident participants can informally come to some amicable accomodation among themselves. As stated before, the amount of bias due to inaccuracy and nonreporting which results when crash participants report their own accidents is unknown.

Synopsis

While many problems still exist in state accident data bases (e.g., inaccurate locations for accident scenes, miscoded information, too few questions pertaining to the highway environment on the accident report forms, unreported accidents), these problems should not be overemphasized. At this time, most states do have adequate accident data to identify high accident locations and to describe the kinds or types of accidents, e.g., wet weather accidents or nighttime accidents, which are occurring at those locations. Efforts should be continued to improve the quality and completeness of accident data. In the interim, however, the data bases which are now in existence should be put to greater use in defining potential safety projects.

Countermeasure Effectiveness Data

The second major ingredient needed to define a traffic safety project is an estimate of the effectiveness of the proposed treatment. If, for example, a particular bridge is sustaining two accidents per million vehicle crossings, how much would the accident rate be reduced if the bridge were widened two feet? Four feet? Would widening the bridge reduce all accidents (fatal, injury, and PDO) by the same amount or would one accident type be more affected than another? Without answers to questions such as these, the expected benefits to be realized from the imposition of a specific countermeasure cannot be calculated. Without answers to questions such as these, safety projects cannot be adequately defined and thus cannot serve as adequate input data to any cost-effectiveness model.

Of the several ingredients needed to adequately define a potential traffic safety project (e.g., accident rates by type before treatment, cost of the proposed treatment, service life of the treatment), the ingredient most difficult to obtain is the effectiveness of the proposed countermeasure in reducing deaths, injuries, and property damage. Frequently, effectiveness data for specific countermeasures are not available in the literature. Even more disturbing is the fact that when the same countermeasure is evaluated by different authors, the resultant estimates of effectiveness may differ sharply.

Table 7, taken from five different sources [68, 89, 118, 134, 135], predicts estimates of effectiveness for 19 classes of accident countermeasures. It should be noted that most of the 19 categories of accident countermeasures are further subdivided into more specific countermeasures. Countermeasure effectiveness is shown as "percent accident reduction," i.e., percent reductions in fatal, injury, fatal plus injury, property damage only, and total accidents. Every effort was made to retain the language and the intent of the sources from which the data were taken. While some of the sources expressed the degree of confidence they had in their estimates, or provided significance tests with their estimates, these statements have been omitted. Finally, in reading Table 7 it should be understood that the negative table entries represent percentage increases in the accident rate attributable to the countermeasure.

In looking through Table 7, vast differences in countermeasure effectiveness can be seen. For example, source [60] indicates that automatic protective devices at railroad grade crossings will reduce total accident rate by 28.4 percent. Source [118] indicates that upgrading railroad-highway grade crossings from passive to active status will reduce accidents by 12 percent in urban areas and 20 percent in rural areas. Source [135] attributes a 30 percent reduction in the accident rate to reflectorized guide markers at horizontal curves; Source [89] states that delineation on curves produces a 16 percent reduction in the accident rate.

In the Task B report of this project [135], quotes from Solomon, et al. [30] and Council and Hunter [89] stressed the point that many accident countermeasures have not been evaluated or have been only poorly evaluated. This lack of adequate evaluations for the different accident countermeasures

Table 7. Estimates of Countermeasure Effectiveness

COUNTERMEASURE	PERCENT ACCIDENT REDUCTION Fatal	Inj	PDO	Total	SOURCE
Utility poles and trees:					
a. Make utility poles breakaway.	30.0	-1.0	0		[18]
b. Relocate utility poles 30 ft from edge of pavement.	32.0	-1.7	0		[18]
c. Remove utility poles.	38.0	-1.5	0		[15, 18]
d. Remove trees.	50.0	25.0	-20.0		[18]
Automatic protective devices at railroad grade crossings.	No Change	-16.3		28.4	[19]
Railroad highway grade crossings upgraded from passive to active status:					
a. Urban				12.0	[15]
b. Rural				20.0	
Pavement anti-skid treatment.	-8.0	15.7		20.6	[19]
Resurfacing sections of highway:					
a. Urban, more than 2 lanes	(46)			42.0	[20]
b. Rural, 2 lanes	(21)			12.0	[20]
c. Rural, more than 2 lanes	(59)			44.0	[20]
Pavement widening (with or without added lanes) without new median, and shoulder widening or improvement.	-13.3	31.8		28.0	[19]
Widen the travel way (no dimensions) on rural 2 lane sections of highway.	(30)			38.0	[20]

Table 7. Estimates of Countermeasure Effectiveness (continued)

COUNTERMEASURE	PERCENT ACCIDENT REDUCTION				SOURCE
	Fatal	Inj	PDO	Total	
Installing or upgrading of traffic signs.	-15.4	29.2		4.8	[19]
Install/improve warning signs along section of highway:					
a. Urban, 2 lane roads		(14)		14.0	[20]
b. Urban, more than 2 lane roads		(26)		20.0	[20]
c. Rural, 2 lane roads		(32)		36.0	[20]
d. Rural, more than 2 lane roads		(3)		18.0	[20]
Install/improve warning signs on rural curves:					
a. 2 lane		(71)	23.0	57.0	[20]
b. more than 2 lanes		(40)		52.0	[20]
Signing: curve warning arrows.				20.0	[21]
Installation of striping and/or delineators	100.0	39.2		18.9	[19]
Install/improve edge marking on 2 lane sections of rural highway.		(17)		14.0	[20]
Right edge lines				2.0	[21]
Install delineators on rural curves:					
a. 2 lanes		(16)		2.0	[20]
b. more than 2 lanes		(-10)	61.0	46.0	[20]
Refelectorized guide markers at horizontal curves				30.0	[21]
Delineation on curves	16.0	16.0	16.0	16.0	[15]

Table 7. Estimates of Countermeasure Effectiveness (continued)

COUNTERMEASURE	PERCENT ACCIDENT REDUCTION Fatal	Inj	PDO	Total	SOURCE
Add transition guardrail to exposed bridge rail ends.	55.0	20.0	-50.0		[18]
Protective guardrail at bridge rail ends.				50.0	[21]
Improve substandard bridge rail.	15.0	5.0	-3.0		[18]
Attenuators at underpass or bridge piers.	75.0	60.0	-300.0		[18]
Impact attenuators.	50.0	50.0	-20.0		[15]
Make signs breakaway:					
a. Small signs	70.0	25.0	-12.0		[18]
b. Large metal supports	60.0	20.0	-20.0		[18]
c. All supports combined	68.0	24.0	-14.0		[18]
Improve guardrail ends, i.e., breakaway cable terminal or turned down ends.	55.0	25.0	-15.0		[18]
Installation of flashing beacons.	93.8	59.3		37.3	[19]
Flashing beacons at intersections:					
a. 4 leg, red-yellow				50.0	[21]
b. 3 leg, red-yellow				50.0	[21]
c. 4 way red				75.0	[21]
d. railroad crossing				80.0	[21]

Table 7. Estimates of Countermeasure Effectiveness (continued)

COUNTERMEASURE	PERCENT ACCIDENT REDUCTION				SOURCE
	Fatal	Inj	PDO	Total	
Concrete median barrier:					
a. median width 1-12 feet	90.0	10.0	-10.0		[18]
b. median width 13-30 feet	85.0	5.0	-25.0		[18]
Installation or improvement of median barrier.	17.5	-8.5		-35.6	[19]
Install median barriers on highways with more than 2 lanes:					
a. Cable type	(4)			-33.9	[20]
b. Beam type	(-22)			-20.0	[20]
Channelization including left turn bays.	42.3	51.5		32.4	[19]
Add left turn lane without signal:					
a. Urban, 2 lane roads	(80)			19.0	[20]
b. Urban, more than 2 lane roads	(54)		18.0	6.0	[20]
c. Rural, more than 2 lane roads	(-1)			-6.0	[20]
Add left turn lane and signal:					
a. Urban, more than 2 lane roads	(1)		-7.0	27.0	[20]
b. Rural, more than 2 lane roads	(58)			43.0	[20]
Add left turn channelization at non-signalized intersections:					
a. Curbs and/or raised bars, urban area.				70.0	[21]
b. Curbs and/or raised bars, suburban area				65.0	[21]
c. Curbs and/or raised bars, rural area				60.0	[21]
d. Painted channelization, urban area				15.0	[21]

Table 7. Estimates of Countermeasure Effectiveness (continued)

COUNTERMEASURE	PERCENT ACCIDENT REDUCTION Fatal	Inj	PDO	Total	SOURCE
(continued)					
e. Painted channelization, sururban area				30.0	[21]
f. Painted channelization, rural area				50.0	[21]
Add left turn channelization at signalized intersections:					
a. left turn phase				36.0	[21]
b. no left turn phase				15.0	[21]
Traffic signals, installed or improved.	17.3	30.2		6.0	[19]
Install new traffic signals.	(50)			29.0	[20]
New signals (with or without channelization and/or lighting)				27.0	[21]
Widen existing bridge or other major structure.	50.0	61.9		43.8	[19]
Replacement of bridge or other major structure.	100.0	65.9		61.5	[19]
Horizontal alignment changes.	Increase	55.8		39.9	[19]
Reconstruct curves on 2 lane rural highway		(89)	96.0	88.0	[20]

Table 7. Estimates of Countermeasure Effectiveness (continued)

COUNTERMEASURE	PERCENT ACCIDENT REDUCTION Fatal	Inj	PDO	Total	SOURCE
New safety lighting:					
a. at intersections	*Percent of Night Accidents			75.0*	[21]
b. railroad crossing				60.0*	[21]
c. bridge approach				50.0*	[21]
d. underpass				10.0*	[21]
Lighting:					
a. Urban freeways	50.0	20.0	14.0		[15]
b. Urban interstate interchanges and rural primary intersections	50.0	50.0	50.0	50.0	[15]

is reemphasized here. Today, the worth of many countermeasures which are routinely being employed is unknown. For other countermeasures, estimates of effectiveness are seriously in error. Until such time as this deficiency in the estimation of countermeasure effectiveness is dealt with and handled, any and all cost-effectiveness models will yield results of questionable validity. That is to say, if the input data to a cost-effectiveness model are spurious, then the results yielded by that model will also be spurious.

From the previous paragraph, it should not be concluded that all efforts at establishing cost-effectiveness models for the allocation of highway safety funds should be abandoned. On the contrary, these efforts should be increased. But, at the same time, it should be understood that parallel efforts to better calibrate the effectiveness of standard countermeasures (and countermeasures now under development) must also be increased. To develop cost-effectiveness models without redressing deficient inputs to those models is to insure that the models themselves will always be deficient.

Countermeasure Cost and Service Life Data

The quality and quantity of data available for estimating the initial cost of most safety improvement projects is adequate for cost-effectiveness analysis. There is a lack of good data on maintenance costs for many alternatives. For most alternatives, however, this does not appear to be a major problem since such costs often are negligible for safety projects. Nevertheless, there is considerable room for improvement in estimating maintenance costs and including these costs in analyses.

There has been little study of the effective service life of most safety alternatives, and it appears that this item could easily contain an error of fifty percent or more, which could significantly affect the ranking of projects. For example, service lives as low as ten years have been observed for tree removal, when it seems clear that this countermeasure would be effective as long as the roadway is used. If major reconstruction of the roadway is planned in the foreseeable future, the expected time until reconstruction would be appropriate to use as the life for this countermeasure. If major reconstruction is not planned, it would seem reasonable to use, say, thirty years or greater for tree removal.

Assuming correct discounting procedures are used, and a positive discount rate is used to discount future benefits and costs to present-value terms, errors in estimating service lives are generally more significant for short-lived alternatives. For example, using a twenty-five year service life when thirty years should be used generally would not affect an outcome nearly as much as using five years when ten years should be used. Thus, there is a need to develop better estimates of service lives, especially for short-lived alternatives.

Highway, Traffic, and Environmental Data

After a state, district, or municipality has identified a series of high accident frequency locations within its jurisdiction, the accident rates at those locations can be determined if the traffic volumes at those locations can be specified. And if the physical, i.e., highway and environmental, characteristics at those locations are known, reasonable hypotheses about the causes of accidents at those locations, as well as potential treatments at those locations, can be entertained.

States have adequate highway, traffic, and environmental data files which can be used in defining potential safety projects. All states collect and maintain a variety of highway, traffic, and environmental data. Among the data bases routinely collected by various states are the following:

1. Traffic volumes (ADT counts)
2. Roadway alignment files (vertical and horizontal curvature)
3. Roadway logs (number of lanes, lane widths, shoulder width)
4. Photo logs (sequential film footage of the highway environment)
5. Bridge inventories (bridge width, approach characteristics, etc.)
6. Skid number inventories
7. Rainfall data (available through U.S. National Oceanic and Atmospheric Administration)

While all states collect and maintain some (if not most) of the data bases listed above, the form in which those data are recorded and stored varies greatly. For example, some states have their skid number inventories stored on magnetic tape while other states have this information stored on data sheets. Some states have their roadway logs computerized; others rely on hard-copy storage. The form in which highway and traffic data are stored, e.g., detailed drawings, paper data sheets, magnetic tape or disk, and film, affects the retrievability of the data and, ultimately, the usefulness of the data in defining potential traffic safety projects.

A recent study by Wright and Robertson [137], conducted in Georgia, indicates that fatal, ran-off-road, single-vehicle crashes occur disproportionately at sharp, horizontal curves following steep downhill grades. Some 26 percent of the fatal accidents which were investigated during the study occurred at or near horizontal curves of greater than six degrees preceded by grades of minus two percent or less. By investigating the roadway environments at one-mile distances from the accident scenes, the authors were able to estimate that only about eight percent of the roadway environment in Georgia is composed of horizontal curves of more than six degrees preceded by a downhill grade less than or equal to minus two percent. Or, in other words, the authors identified a highway/environmental characteristic associated with a threefold representation ($26/8 \approx 3$) in fatal, ran-off-road, single-vehicle accidents. The authors concluded that roadway locations exhibiting the horizontal and vertical characteristics just discussed should be identified and considered for priority treatment.

For any state maintaining a computerized inventory of roadway alignment, the problem of identifying all horizontal curves greater than six degrees preceded by a gradient less than or equal to minus two percent would be relatively simple. But, for any state maintaining its roadway alignment file in the form of hard copy, the task of identifying all locations on the highway system that exhibit the physical characteristics just discussed would be laborious -- and the final product would, no doubt, be replete with errors.

One of the deficiencies in state highway/traffic data systems, then, is the lack of automation of some data files. Most, if not all, states have hard-copy information available for use in defining a particular accident site or high accident locations, but many states do not have their data stored in a fashion which will allow a district engineer or a state safety administrator to define all locations exhibiting a given characteristic within their jurisdictions.

A second major shortcoming faced by the states in using their highway/traffic data files is the difficulty involved in merging information from two or more independent files. If, for example, a state were interested in identifying all federal-aid system locations with horizontal curves greater than three degrees and with skid numbers below 30, in most states it would be necessary to merge information from two separate and independent files -- a roadway alignment file and a skid number file. The difficulties inherent in merging two or more files containing data collected by different groups of individuals, in different years, working perhaps with different reference systems, seem considerable. And if the problems inherent in merging two or more highway data files are great, the problems inherent in merging highway/traffic data files with accident data files are even more so.

Conclusions

The highway, traffic, and environmental data available to state safety personnel are fairly good. If efforts are extended to improve these data systems, it is suggested that two endeavors are worthy of serious consideration:

1. More highway, traffic, and environmental data should be automated to insure ease of data retrieval and to provide a greater potential in identifying hazardous locations on the basis of physical (highway, traffic, and environmental) characteristics.
2. Attempts should be made to increase the compatibility among existing and future highway data files and between existing and future highway data files and accident data files.

While more effort at improving data files discussed above is desirable, it is felt that the highway, traffic, and environmental data files currently in existence are adequate for defining potential safety projects. These data files do not constitute an impediment to the deployment of cost-effectiveness models in the state.

X. DETAILED REVIEW OF SELECTED COUNTERMEASURES

The previous section was concerned with the general quality and availability of input data, i.e., cost data and effectiveness data, needed to define potential traffic safety projects. This section documents the costs and accident reduction effectiveness of seven specific countermeasures:

1. Adding shoulders to two-lane highways
2. Resurfacing pavements having inadequate friction
3. Installing signals at a stop-controlled, simple intersection on a moderate volume highway
4. Installing flashing lights at railroad-highway grade crossings
5. Installing delineators on horizontal curves
6. Installing impact attenuators at raised gore areas
7. Widening bridges

In reviewing the literature concerning these seven countermeasures, it became clear that the costs associated with the different treatments vary considerably. For example, the recently published AASHTO *Guide for Selecting, Locating, and Designing Traffic Barriers* [138] provides initial costs and repair costs for three types of crash cushions or impact attenuators (see Table 8). If these values are taken at face value,it can be seen that the ratio of the highest estimated initial cost to the lowest estimated initial cost is 11.6; the ratio of the highest estimated repair cost to the lowest estimated repair cost is 14.6. The initial cost ratios (highest initial cost/lowest initial cost) and repair cost ratios (highest repair cost/lowest repair cost) for the three impact attenuation systems shown in Table 8 are, respectively: 1.9, 3.8; 4.3, 4.4; 3.86, 4.2.

The literature also indicates that the accident reduction effectiveness estimates of the seven countermeasures discussed here are highly variable. The literature on highway shoulders provides an example of this. A recent study conducted in North Carolina [139] found a positive safety benefit to highway shoulders, while earlier studies in California and Oregon found no correlation or negative correlation between shoulder width and accident rate [140, 141, 142]. A study from Great Britain [143] showed a 47.3 percent reduction in wet-road, intersection accidents after resurfacing; a study conducted by Midwest Research Institute [144] found no

Table 8. Initial Costs and Repair Costs of Three Impact Attenuation Systems

IMPACT ATTENUATION SYSTEM	PUBLICATION DATE FOR SOURCE FROM WHICH COST DATA WERE EXTRACTED	AVERAGE INITIAL COST	AVERAGE REPAIR COST PER HIT
Steel Drums	1973	$5,323	$ 295
	1974	8-10,000	750
	1975	5,800	1,110
	1975	5,600	
	1973	7,500	400
	1974		666
	1974		421
Hi-Dro Cell Sandwich	1973	4,941	221
	1974	14-21,000	237
	1975	15,700	103
	1970		452
	1974		395
	1974	12,500	113
	1973	10,500	260
	1974		257
	1974		221
	1973	6,188	112
Fitch Inertial	1973	2,557	966
	1974	3-7,000	730
	1975	5,550	484
	1974		356
	1974	3,000	850
	1974		938
	1973	2,500	1,500
	1976	1,812	667
	1974		408

(Adapted from Table A-3, [138, pp. 193-194]).

reduction in wet-road accident rates for 142 sections of highway (located in 16 different states) after resurfacing.

For some of the seven countermeasures (e.g., bridge widening), few, if any, rigorous estimates of effectiveness are available. In these cases, we have attempted to adapt existing accident data found in the literature to provide our own estimates of countermeasure effectiveness. In each instance where we provide these estimates, both the assumptions upon which those estimates are based and the source of the accident data used for calculating effectiveness are clearly cited.

Adding Shoulders to Two-Lane Highways

> A shoulder is the portion of the roadway contiguous with the traveled way for accommodation of stopped vehicles, for emergency use, and for lateral support of base and surface courses. It varies in width from two feet or so on minor rural roads, where there is no surfacing or the surfacing is applied over the entire roadbed, to about twelve feet on major roads, where the entire shoulder may be stabilized or have an all-weather surface treatment.
>
> The shoulder on minor rural roads with low traffic volume serves essentially as structural lateral support for the surfacing and as an additional width for the narrow traveled way. It permits drivers meeting or passing other vehicles to drive on the very edge of the roadway without leaving the surfacing thus making use of the shoulder itself. Such operation is undesirable and is fitting only where traffic volume is so small that meetings and passings are infrequent. Where there is appreciable traffic volume, roads with narrow surfacing and narrow shoulders give poor service, have a high accident experience and require frequent and costly maintenance.
>
> Desirably, a vehicle stopped on the shoulder should clear the pavement edge by at least a foot. If working space is needed, as for tire change, a two-foot space is none too large. Thus a usable shoulder width of nine to ten feet is desirable for passenger vehicles and eleven to twelve feet for trucks or buses. This has led to the adoption of ten feet as the compromise shoulder width that should be provided along high type facilities. In difficult terrain and on low volume highways usable shoulders of this width may not be feasible, but in general ten feet is recognized as the desirable minimum. A minimum shoulder width of four feet should be considered for the lowest type highway, and preferably a six-or eight-foot width. Heavily traveled and high speed highways should have usable shoulders at least ten feet and preferably twelve feet wide [42, pp. 234, 235].

Table 9. Injury Accident Rates Associated With Different Shoulder Widths

Shoulder Width (ft)*	Accidents per MVM	(# Acc.)
1	0.52	(4)
2	0.77	(43)
3	0.42	(53)
4	0.70	(86)
5	0.50	(47)
6	0.60	(205)
7	0.67	(81)
8	0.67	(240)
9	0.29	(3)
10	0.67	(9)
TOTAL		771
Mean Accidents/MVM	0.62	

*One foot equals .3 meters.

(Adapted from Table 1 [140]).

The first study to compare the accident rate (injury accident rate, in this case) and shoulder width was conducted by Belmont [140] in the early 1950's using accident data collected in California in 1951 and 1952. The 1.122 one-mile (1.67 km) tangent sections of highway investigated during the study were all located along two-lane highways with paved shoulders. Table 9 presents an overall summary of the data contained in the report. The general conclusions drawn by the author was that for those sections of highway with ADT greater than 2,000, the injury accident rate increases as the shoulder width is increased.

In 1956, Head and Kaestner [141] presented a study which compared traffic accident rates in the State of Oregon to the width of the gravel shoulders along the highways on which those accidents occurred. Accident data were collected from 1952-54 on rural, two-lane primary highways in Oregon. Highway data were collected via a special survey which tabulated lane width, shoulder width, sight restriction, and terrain description. ADT information was available through the Oregon State Highway Department.

One mile sections of highway meeting the following criteria were chosen:

1. Gravel shoulders
2. Sight restriction < 30 percent
3. Lanes > 10 feet (3 m)
4. No speed zones
5. All sections straight and level

Some 344 one-mile (1.67 km) sections were included in the study.

They found that [141, p. 568]:

1. There is no relationship between accident frequency and shoulder width on two-lane tangents of less than 3600 ADT.
2. In the two highest ADT ranges, 3600-5500 and 5600-7500, the frequency of all types of accidents decreases as shoulder width increases.
3. The only statistically reliable trends in the study are that total accidents and PDO accidents decrease as shoulder width increases, in the 3600-5500 ADT range.

A 1956 study by Billion and Stohner [145] compared accident rates (injury plus fatal accident rates) to shoulder width and roadway alignment. The accidents reported in the study occurred between 1947 and 1955 on two-lane, rural roads twenty feet (6 m) in width. The composition of the shoulders along roadways where the accidents occurred was as follows (cell entries indicate the percentage of accidents which occurred along roadways with a given shoulder width and a given shoulder composition):

Composition of Shoulder	Shoulder Width (ft)* 3-4	5-7	8&over	TOTAL
Earth and/or grass	8.48	28.38	5.84	42.70
Gravel and/or Macadam	7.43	30.77	9.68	47.88
Unclassified	1.06	5.57	2.79	9.42
TOTAL	16.97	64.72	18.31	100.00

*One foot equals .3 meters.

(Adapted from Table 2 [145]; N = 754 accidents)

The findings from this study are shown in Table 10. For level tangents it can be seen that the shoulder width has little effect on the accident rate. For highway locations with grades greater than five percent or curves greater than five degrees, the accident rate seems to decrease with increasing shoulder width. Finally, for highway locations with grades greater than five percent and curves greater than five degrees, the accident rate declines as shoulder width increases.

Table 10. Injury and Fatal Accidents Per MVM as a Function of Alignment and Shoulder Width

Alignment	Shoulder Width (ft)* 3 - 4	5 - 7	8 & over	TOTAL
Level Tangent	2.55 (58)	2.09 (287)	3.38 (107)	2.36 (452)
Grade > 5%	8.55 (13)	5.92 (59)	3.54 (8)	5.82 (80)
Curve > 5°	19.71 (41)	14.75 (113)	10.56 (19)	14.99 (173)
Grade > 5% & Curve > 5°	66.67 (16)	16.86 (29)	19.05 (4)	22.58 (49)
TOTAL	4.82 (128)	3.11 (488)	3.84 (138)	3.44 (754)

*One foot equals .3 meters.

(Adapted from Table 3, [43]).

In 1960 Blensly and Head [142] published a study comparing accident rates and paved shoulder width. Some 298 sample elements were used in this study. A sample element consisted of a one-mile (1.67 km) section of rural, two-lane, level, and tangent highway with paved shoulders and with accompanying accident data. ADT's ranged from 1000 to 5600.

Accident data were collected during the late 1950's. All accidents throughout the study sections, not just injury-producing accidents, were considered.

They summarized their findings as [142, p. 9]:

> Through the use of partial correlation techniques, it was established that when the effects of other roadway elements were eliminated, and the study sections grouped in various ADT ranges, no significant relationship between accident frequency and paved shoulder width emerged except in the 2,000-2,999 ADT range. In that area, property damage and total accidents showed a significant tendency to increase in frequency as paved shoulder width increased. No relationship appeared between frequency of personal injury accidents and width of paved shoulders in the 1,000-5,600 ADT range.
>
> Through use of the analysis of covariance procedure, it was found that when the effect of ADT was controlled, there was a significantly higher mean number of property damage and total accidents on sections with wide paved shoulders than there was on sections with narrow paved shoulders in the 1,000-5,600 ADT range.

Finally, in 1974, Heimbach, Hunter, and Chao [139] published a report which compared accident rates on North Carolina highways with and without paved shoulders. Accident data were collected over a four-year period (1966-1969). Highways included two-, four-, and six-lane roadways with ADT's from 2,000 to 10,000. Very rigorous matching procedures were used to insure that study sections were comparable, except for the presence or absence of paved shoulders. The study indicated that the presence of paved shoulders did reduce accident rates. Table 11 indicates the percent reduction in accidents (fatal, injury, and PDO accidents) which might be attributed to paved shoulders.

Table 11. Accident Reduction Effectiveness (%) by Accident Type

Accident Type	Accident Reduction (%)
Fatal Accidents	12.3
Injury Accidents	12.5
PDO Accidents	19.9
TOTAL Accidents	17.3

(Adapated from Table 4, [36]).

Countermeasure Costs

The initial cost of adding paved shoulders to an existing roadway varies considerably from location to location depending on: (1) the shoulder design, (2) the existing roadway cross-section, (3) the length of roadway, and (4) the local cost of materials. If the roadway cross-section is adequate for adding shoulders, and bridges on the roadway are of adequate width, the cost of adding paved shoulders can be as low as $2.00 to $5.00 per square yard of surface. If the existing cross-section is inadequate, the roadway may have to be reconstructed and costs can be considerably higher.

The service life of paved shoulders normally would be considered the same as the improved highway, which usually would be twenty years or greater.

Resurfacing Pavement with Inadequate Friction

> From the standpoint of safety, the friction level of pavement surfaces cannot be high enough. The author counted 157 clearly distinguishable skid marks made under dry conditions on a 4-mile (6.67 km) section of a main rural highway passing through a small town. Based on the observation that the skid marks are erased by traffic after about five weeks and an assumed average daily traffic of about 8,000 vehicles over the observed distance, it is found that in one case out of 1,800, drivers were confronted with an emergency situation which caused them to lock their wheels [146, p. 36].
>
> A skid number of 37 is recommended as the tentative minimum requirement for pavement friction on main rural highways [146, p. 1].

> The most common *average* relationship between skid number and wet weather accidents is one trending from values long recognized as being unsafe in the 10 to 20 SN range through intermediate values to values above 40 which have almost invariably been recognized as quite sufficient. The debate has long wandered over this intermediate ground fixing first at one point and then at another "level of safe skid resistance" or "level of demand for skid resistance." Always, the final number to be advocated is a product of the vagaries of the data resources of the moment and/or the assumptions made in analytical treatments ... It may seem likely that since there are so many answers to the question, the question is not formulated to allow a unique solution. The position taken here is that there perhaps is not, but more importantly need not be, a unique answer to the question of an appropriate level of skid resistance in order for skid number determinations to be used in the optimum way for the public good [147, p. 1].

Countermeasure Effectiveness

Data provided by Hatherly and Young [143] indicate that resurfacing at high-accident intersections may be effective in reducing accident rates. In their study, some 37 urban intersections were selected on the basis of accident history. Twenty-three of these sites received a surface treatment (eposy resin/calcined bauxite material), and fourteen were saved as controls. The accident experience of the 37 sites was:

All Accidents	12 months before	12 months after
Treated Intersections (N=23)	269	152
Control Intersections (N=14)	179	147

This table indicates that the treatment is associated with 31.2 percent reduction in total accidents [143, p. 25].

Wet Road Accidents	12 months before	12 months after
Treated Intersections (N=23)	109	33
Control Intersections (N=14)	73	42

This table indicates that the treatment is associated with a 47.3 percent reduction in wet road accidents [143, p. 25].

Using a simple before-after design, Trietsch [148] provides data showing the effect of seal coat overlays on accident frequency at three different highway locations. In August and September of 1973, three segments of interstate highway in Fort Worth, Texas received seal coats. The length and the associated ADT of each segment was:

I-30	Eastbound 6000 ft (1800 m)	ADT 68,000
	Westbound 2000 ft (600 m)	ADT 68,000
I-820 - I-20	Both Directions 5700 ft (1710 m)	ADT 38,000
I-35 W	Both Directions 5400 ft (1620 m)	ADT 68,000

Accident data were collected for comparable six-month periods* before and after the seal coats were laid. The results were:

Highway		Accidents		Percent Change in Accident Frequency	
		EB/NB	WB/SB	EB/NB	WB/SB
I-820 - I-20	Before	9	5	-33	-60
	After	6	2		
I-30	Before	19	10	+74	-50
	After	33	5		
I-35 W	Before	26	25	-12	-68
	After	23	8		
TOTAL	Before	54	40	+15	-63
	After	62	15		

In all, 99 accidents occurred along the test sections during the before period. A total of 77 accidents occurred during a comparable time period after the treatments were imposed, i.e., accident frequency went down 22.2 percent.

The most comprehensive study to date on the effects of skid number and resurfacing on accident rates is provided by Harwood, Blackburn, St. John, and Sharp [144]. Some 428 highway sections in sixteen states were considered during the course of this study. These highway sections were

*Five-month periods in the case of I-820 - I-20 composed of two-lane highways, multilane controlled and uncontrolled highways, and urban/rural highways. A variety of ADT's were associated with each highway section classification.

One hundred forty-two sections were resurfaced during the course of the study. A matched control group consisting of 142 sections which did not undergo resurfacing were saved for purposes of comparison. Also, 144 other randomly chosen sections which did not undergo resurfacing were saved for purposes of analysis.

Accident data collected before and after resurfacing yielded the following outcome:

	Wet Pavement Accident Rate (Accidents/MVM)	
	Before	After
Treated Sections (N=142)	3.39	3.06
Control Sections (N=142)	3.00	2.97

On the basis of these data there is no reason to believe, statistically, that resurfacing had any effect on wet pavement accident rates.

The authors did note, however, that [144, p. 146]:

> In interpreting the matched-pair analysis results, it should be kept in mind that *there was virtually no change in the mean skid number* for test sections from the before to the after period; i.e., on the average the skid number of test sections was not improved by resurfacing. Thus it cannot be determined from the matched-pair before-after analysis whether or not there is a significant relationship between wet pavement accident rate and skid number, because there was no change in the mean skid number brought about through resurfacing.

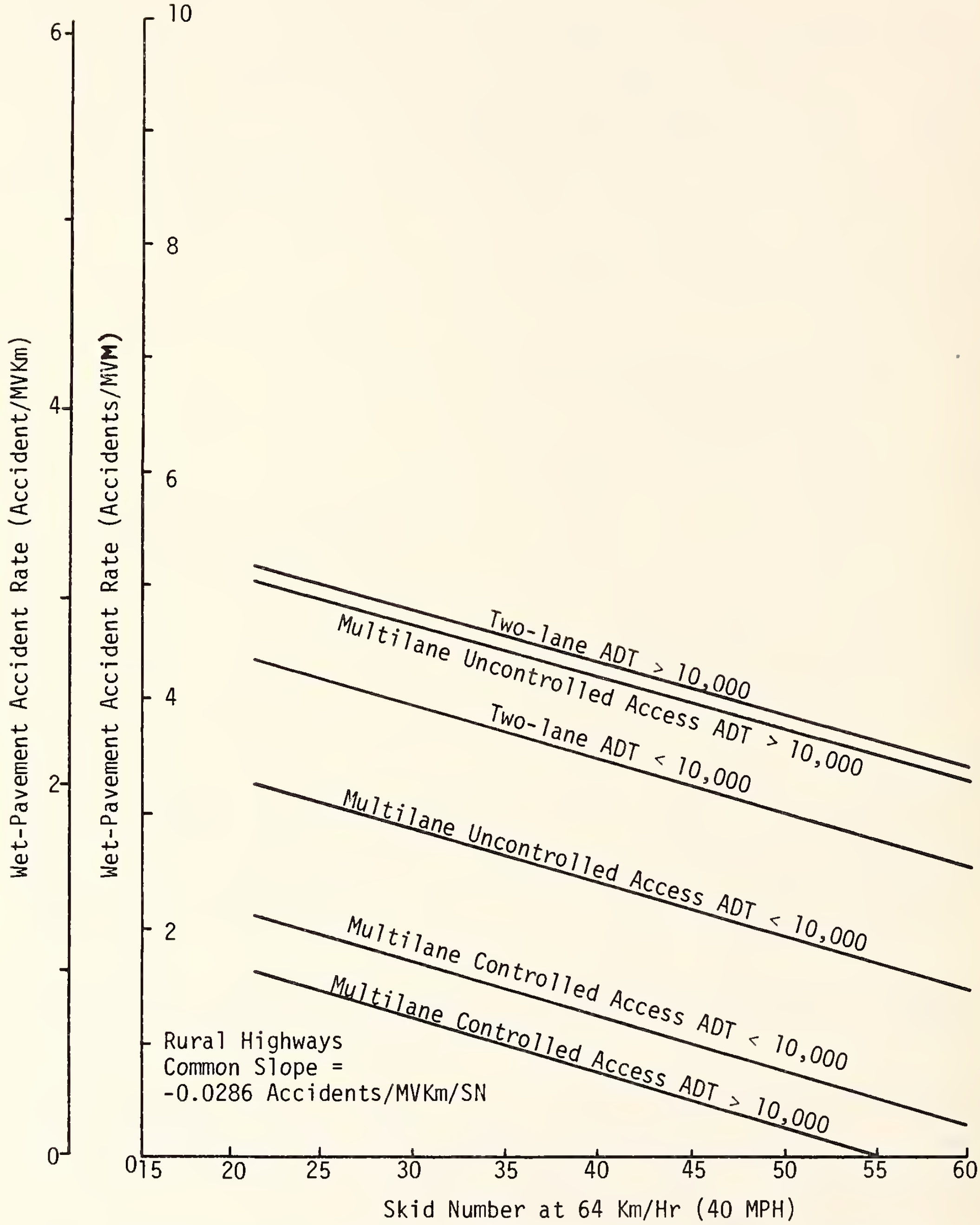
Combining all accident data, i.e., treatment sections, matched control sections and unmatched control sections, the authors regressed wet pavement accident rates on skid numbers (SN 40) for twelve different classifications of highway type (3), traffic volume (2), and urban/rural environment (2). The results are shown in Figure 10. Since none of the twelve linear regression coefficients differed significantly from any other, a common slope of -0.046 (accidents/MVM) was used for each.

On the basis of the regression lines shown in Figure 10, it is possible to calculate benefits which might be obtained due to resurfacing if the skid number on a given section of highway could be increased to a larger value. For example, if a given urban, two-lane highway with ADT less than 10,000 has a skid number of 10, it should be predicted that the accident rate in that section will be 4.94 accidents/MVM. However, if the skid number is 60, the predicted accident rate will be 2.64. On the average then, if the skid number of the section in question is raised from 10 to 60, accident rate might be expected to drop from 4.94 to 2.64, a reduction of 46.56 percent in the accident rate.

Based on the logic used in the previous example, Figures 11 through 13 depict the effectiveness which might be achieved if resurfacing does, in fact, increase skid number from a given value to a higher value. Figure 11 depicts accident reduction effectiveness for urban, two-lane highways with ADT less than 10,000. Figure 12 depicts accident reduction effectiveness for rural, multilaned, controlled access highways with ADT greater than 10,000. Figure 13 depicts accident reduction effectiveness generally, without regard to highway type, urban/rural environment, or traffic volume. Note that the regression equations from which these "effectiveness functions" were derived all have the same slope. The variation in the effectiveness functions shown in Figures 11 through 13 is due solely to differences in base accident rates for the highway conditions specified. Note also that the effectiveness functions are based upon regression equations which have very low predictive ability, i.e., low R^2 values. As the authors point out [41, p. 147]:

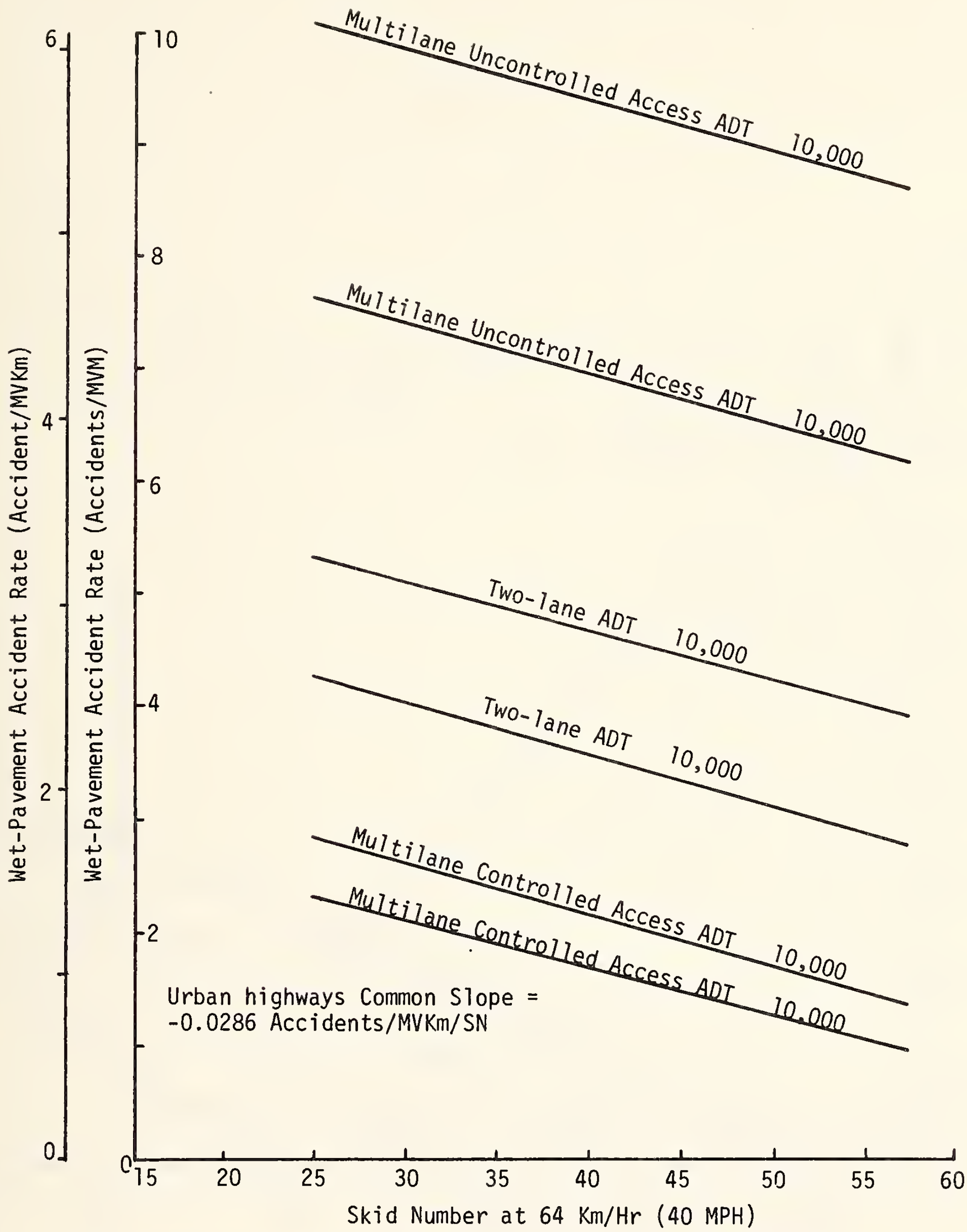
> [T]he usefulness of these relationships for predicting the effect of skid number on accident rate of a given highway in a given year is limited by the low correlation coefficents found in this analysis. The relationships do give an accurate estimate of the long-term *expected value* of accident rate, however. The predictive ability of the relationship can be improved by employing them to predict accident rates for multi-year periods or for groups of similar highway sections.

In 1973, Rizenbergs, Burchett, and Napier [149] published a study showing wet-accident rates along rural interstate and parkway roads in Kentucky as a function of skid number (SN 70). In this study 110 test sections of rural interstate and parkway roads were investigated. Appendix



Relationship between wet-pavement accident rate and skid number at 40 mph (64 km/hr) for rural highways.

Figure 10. Wet Pavement Accident Rate as a Function of Skid Number of Twelve Classes of Highway



Relationship Between wet-pavement accident rate and skid number at 40 mph (64 km/hr) urban highways.

Figure 10. Wet Pavement Accident Rate as a Function of Skid Number of Twelve Classes of Highway (continued)

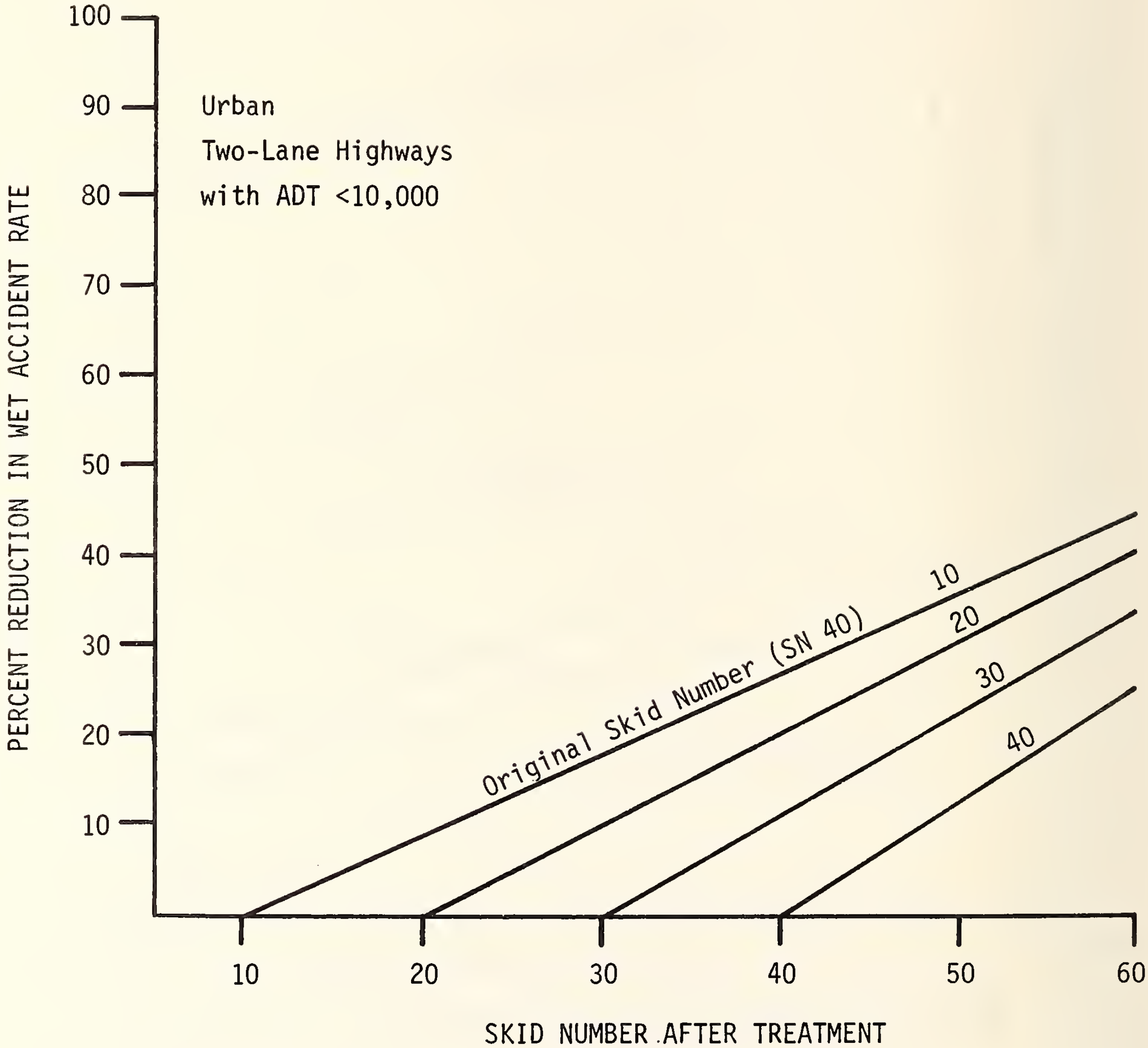


Figure 11. Percent Reduction in Wet Accident Rate Due to Increase in Skid Number on Urban, Two-Lane Highways with ADT < 10,000

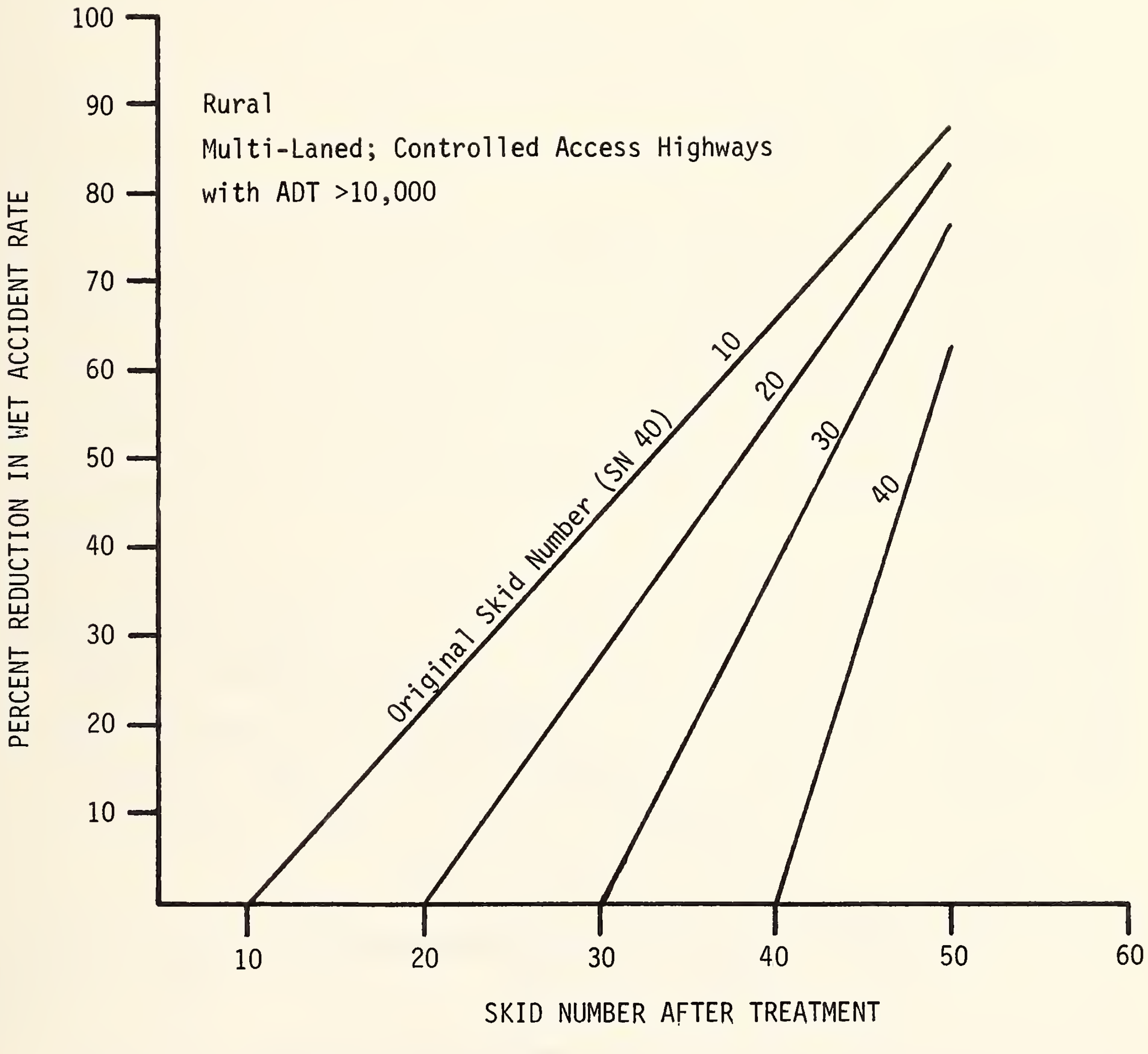


Figure 12. Percent Reduction in Wet Accident Rate Due to Increases on Skid Number on Rural, Multi-Laned Controlled, Access Highways with ADT > 10,000

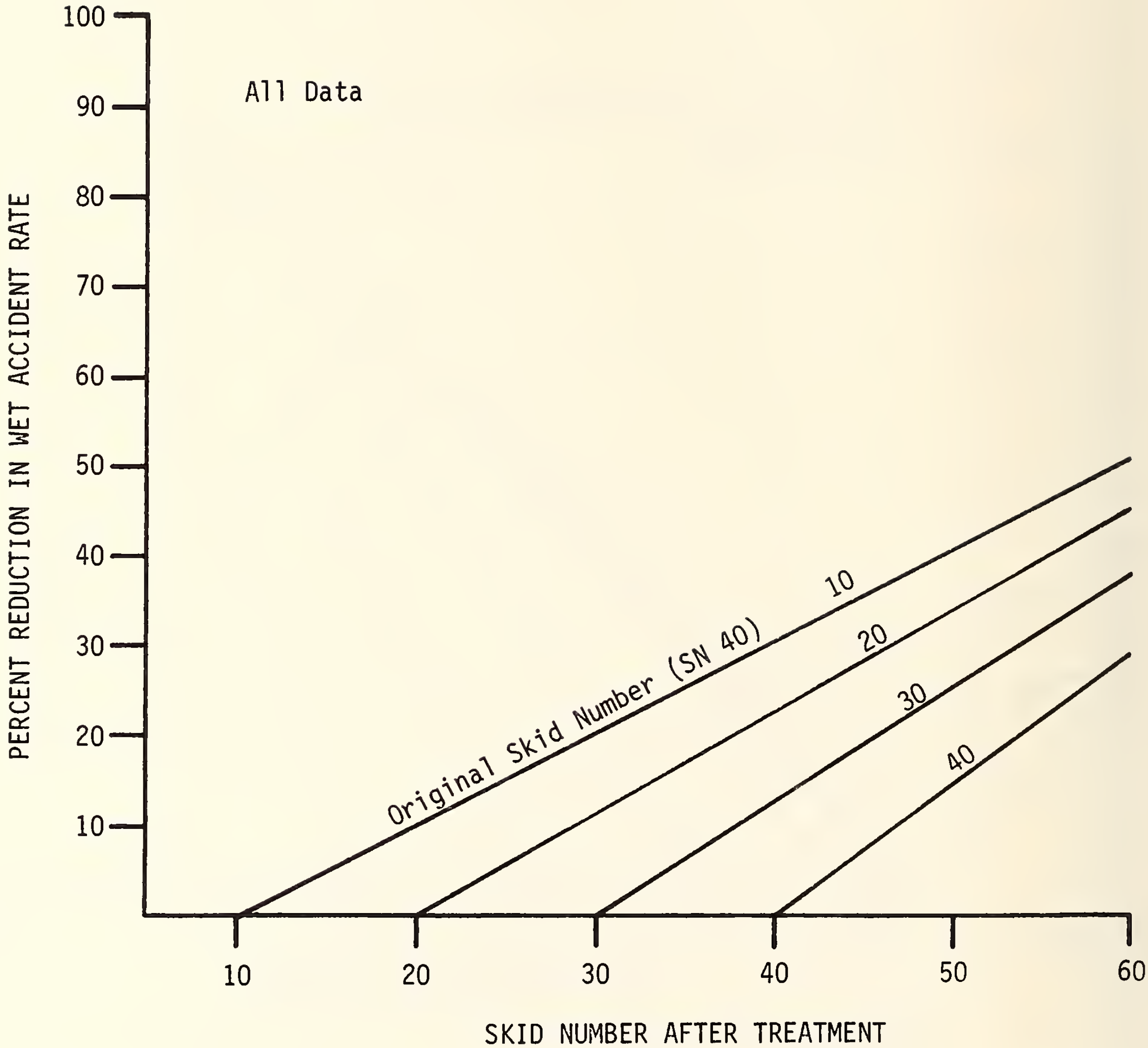


Figure 13. Percent Reduction in Wet Accident as a Function of Increases in Skid Number

B to the report provides raw data on all test sections. Among those variables recorded by test section are the average skid number (SN 70) and the wet accident rate for calendar years 1970-72*. On the basis of the data provided in this appendix, a simple linear least squares regression of the wet accident rate on skid number was carried out at the Texas Transportation Institute (TTI). The resulting linear equation was:

$$AR = 31.80 - 0.55\ SN$$

where AR = wet accident rate

SN = skid number (SN 70)

It should be noted that the skid number accounted for only 8.7 percent of the variance in the wet accident rate. However, on the basis of this linear relationship, calculations were made to determine the effect which increasing the skid number would have in reducing the wet accident rate. The results of these calculations are plotted in Figure 14 along with the corresponding calculations from the Harwood, et al. study, Figure 12. The results from both studies, Rizenbergs, et al., and Harwood, et al., are very similar.

A second study by Rizenbergs, et al. collected accident and friction data at 230 test sites on rural, two-lane roads in the state of Kentucky [150]. The skid numbers (SN 40) and wet accident rates associated with these 230 sites are provided in Appendix A of their report. Again, a simple least squares regression of the wet accident rate on skid number was carried out at TTI. The resulting equation was:

$$AR = 101.58 - 1.51\ SN$$

where AR = wet accident rate

SN = skid number (SN 40)

Skid number accounts for 9.6 percent of the variance in wet accident rate.*

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*Wet accident rate is calculated as wet accidents divided by 100 million vehicle miles (i.e., no distinction is made between miles accrued on wet pavement and dry pavement).

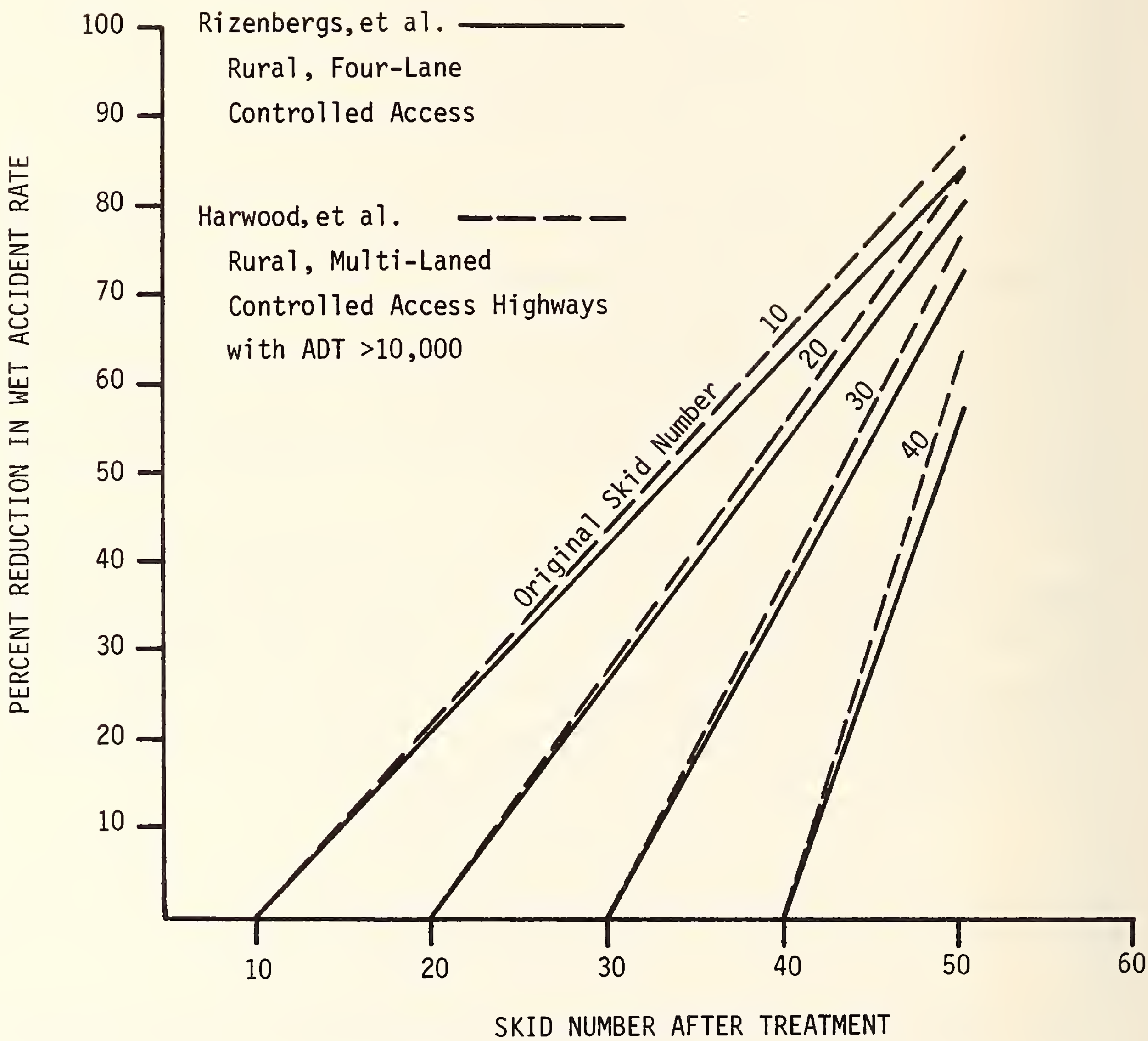

Figure 14. Percent Reduction in Accident Rate as a Function of Increases in Skid Number. (Data from Two Studies are Plotted).

On the basis of this linear equation, the reductions in the wet accident rate which would be predicted from increases in the skid number were calculated. Similar calculations were made based on the data provided by Harwood, et al. for rural, two-lane highways with ADT's less than 10,000.* The results of these calculations are shown in Figure 15. Clearly, the predicted benefits which would result from an increased skid number are vastly different for the two sets of data.

A paper by Runkle and Mahone [151] suggests, quite correctly, that any treatment imposed to reduce wet weather accidents will not be 100 percent effective. Some wet weather accidents will still occur. The authors estimate that the imposition of countermeasures (e.g., resurfacing) at locations sustaining high wet weather accident rates will result in a lowered wet-accident rate at the treated locations, a rate more in keeping with statewide or district-wide averages [151, p. 95]:

> The estimated reduction in wet accidents is computed by assuming that after the reduction, wet pavement accidents should account for approximately 20% of the combined total of wet and dry accidents ... The 20% value for wet accidents was determined to be a reasonable general value in a previous study conducted by the authors. This value is substantiated by the data shown in Table 9, in which the percentages of wet accidents for the interstate, arterial and primary, and secondary systems for the years 1965 through 1974 are presented. In the future, in order to compensate for possible weather influences, the basic value (now 20%) will probably be based on the year for the accident data under investigation. Furthermore, separate values may be utilized for each of the highway districts in the state.

If the statements of Runkle and Mahone are taken at face value, then it follows that the potential effectiveness of a countermeasure designed to reduce wet accidents can be expressed as a function of the relative percentage of wet accidents which occur along a given highway section. For example, assume that 20% of the accidents within a highway district occur on wet roads. Further assume that a given section of slick highway sustains 30% wet accidents. Presumably the highway section in question could be treated (e.g., resurfaced) to reduce wet accident frequencies to

*Note that all 230 test sections in the Rizenbergs, et al. study had ADT's less than 10,000.

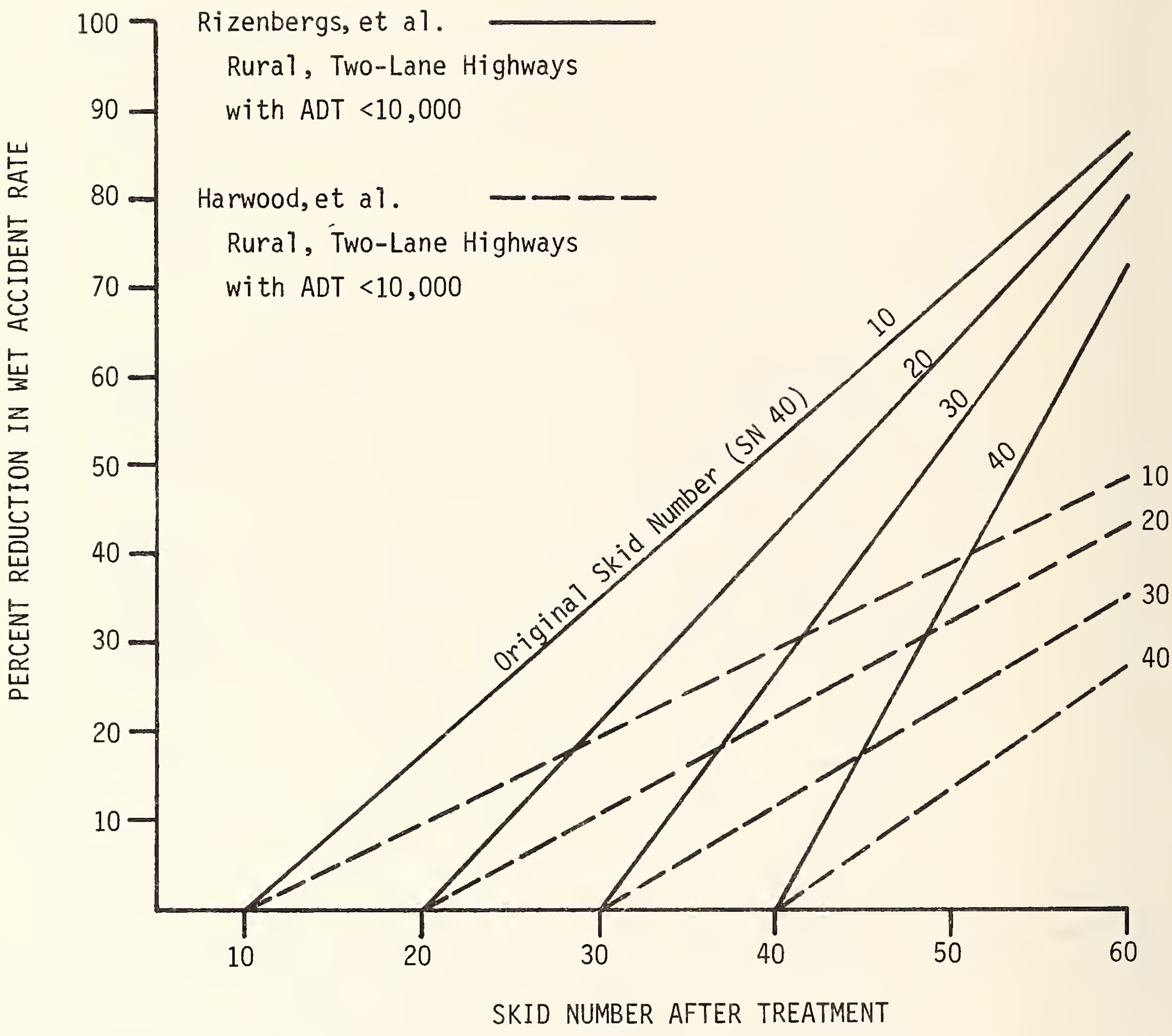

Figure 15. Percent Reduction in Wet Accident Rate Due to Increases In Skid Number for Rural, Two-Lane Highways with ADT < 10,000. (Data from two studies are plotted).

a level commensurate with other highways in the area. Thus, if 30 wet accidents (out of 100 total accidents) per year occurred along the section before treatment, it would be predicted that only 17.5 wet pavement accidents would occur per year after treatment.

$$\frac{WA - N}{TA - N} = .20 = \text{Base rate of wet pavement accidents in the vicinity.}$$

$$\frac{WA - .20TA}{.80} = N$$

$$WA - N = \text{wet accidents after treatment}$$

where: WA is wet accidents before treatment
TA is total accidents before treatment
N is wet accidents avoided following treatment

(Note: It is assumed that the treatment in question reduces wet accidents but has no effect on dry accidents).

To calculate the effectiveness of a given countermeasure in reducing wet accidents, the following formula is appropriate:

$$\text{Percent Reduction in Wet Accidents} = \left(\frac{N}{WA}\right) \times 100$$

It should be noted that this measure of effectiveness represents the *maximum* amount of benefit which might be derived from the placement of a perfect wet pavement countermeasure at a given location. In actual practice, the benefits derived from the deployment of a given countermeasure might fall short of the benefits anticipated.

The following figure (Figure 16) shows the maximum benefit which might be derived from the deployment of wet accident countermeasures (e.g., resurfacing) as a function of the percentage of wet accidents at a location prior to treatment, and as a function of three base rates for wet pavement accidents. Generally, these functions were derived by TTI, based on the assumptions made by Runkle and Mahone.

The State of California [135] estimates the effectiveness of wet accident countermeasures with a procedure similar to the one employed by Runkle and Mahone. From past experience, California officials have estimated that wet accident countermeasures reduce wet accident rates (WAR) at

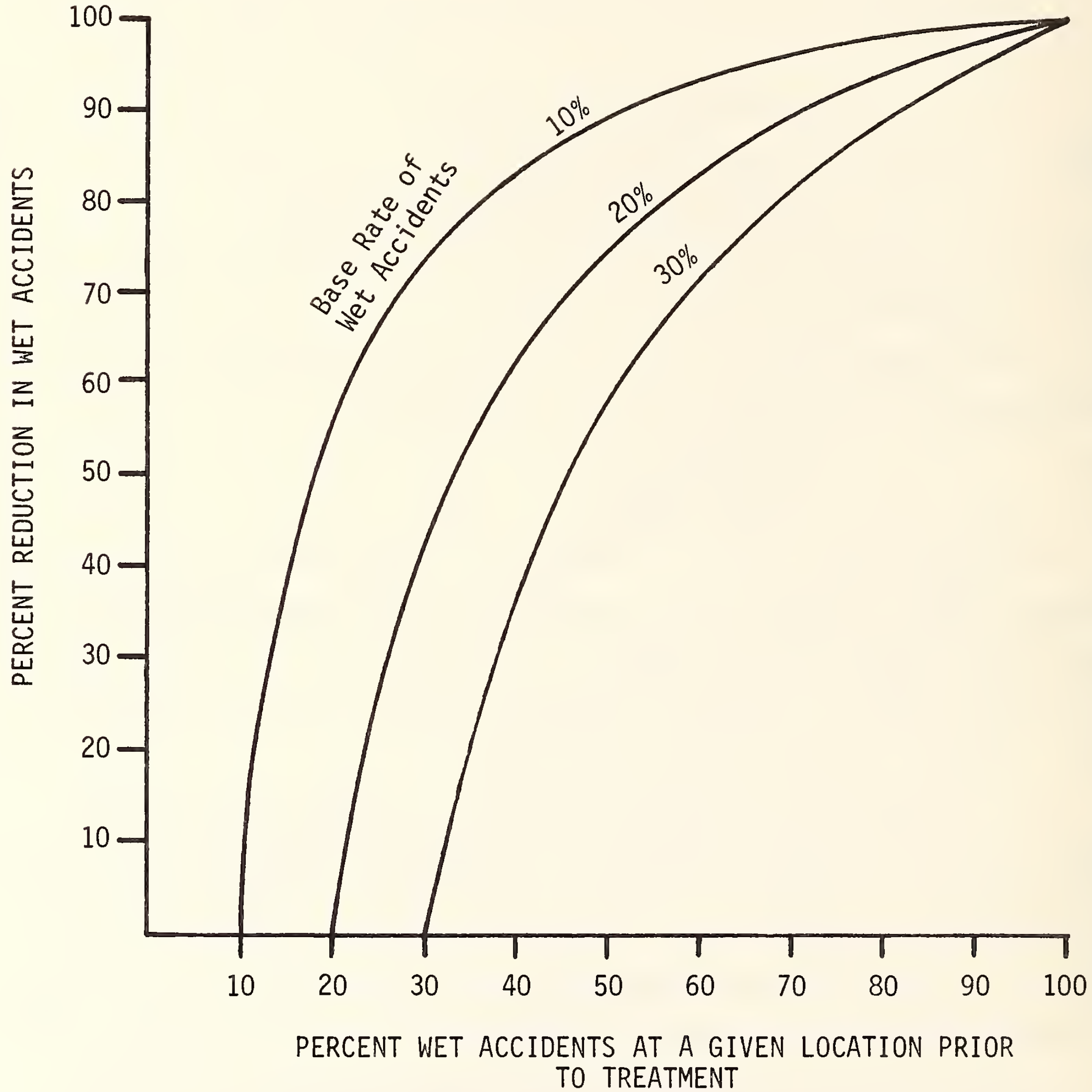

Figure 16. Percent Reduction in Wet Accident Rate as a Function of Wet Accident Rate in Vicinity and at a Given Location

given locations down to a value equal to three times the dry accident rate (DAR) at the same location, plus 1.3 (when the accident rate is expressed as accidents per million vehicle miles). Thus, if the wet accident rate at a given location is twenty accidents/MVM, and the dry accident rate at the same location is three accidents/MVM, under California's assumptions, a wet accident countermeasure imposed at this location would reduce the wet accident rate down to 10.3 accidents/MVM.

On the basis of the assumptions provided by the State of California, it is possible to calculate the effectiveness of wet accident countermeasures for a variety of locations differing in terms of wet accident rates and dry accident rates. The results of such calculations are shown in Table 12 and Figure 17.

Countermeasure Costs

There are several methods that can be used to increase the skid resistance of pavements. The wide range of techniques for restoring skid resistance for Portland cement concrete pavements and bituminous surface pavements is shown in Tables 13 and 14. These tables show estimated costs and expected service lives for Texas for 1975. It should also be emphasized that the "Recommendation" is for Texas and may be different for other states.

Resurfacing either cement or bituminous pavements with hot-mix asphaltic concrete is shown in Table 13 as costing about $1.50 per square yard for a minimum-thickness overlay in Texas. If the pavement is uneven, thus requiring a level-up course, this cost would at least double. The service life of a hot-mix asphaltic concrete overlay is estimated to average fifteen years, but this life can vary considerably, say from five years to twenty-five years, depending upon traffic, environmental conditions, and quality of the overlay.

The service life of pavement resurfacing is somewhat different from that of other accident countermeasures in that the quality declines over time. Skid resistance of a newly overlaid pavement is high immediately after resurfacing but declines as traffic passes over the roadway. This decline in effectiveness usually is not considered in safety evaluations of resurfacing, which is perhaps one of the more important shortcomings in

Table 12. Percent Reduction in Wet Accident Rate.

Wet Accident Rate (WAR) Before Treatment (Acc/MVM)	Dry Accident Rate (DAR) (Acc/MVM)						
	1	2	3	4	5	6	7
5	14.0	--	--	--	--	--	--
6	28.3	--	--	--	--	--	--
7	38.6	--	--	--	--	--	--
8	46.3	8.8	--	--	--	--	--
9	52.2	18.9	--	--	--	--	--
10	57.0	27.0	--	--	--	--	--
11	60.9	33.6	6.4	--	--	--	--
12	64.2	39.2	14.2	--	--	--	--
13	66.9	43.8	20.8	--	--	--	--
14	69.3	47.9	26.4	5.0	--	--	--
15	71.3	51.3	31.1	11.3	--	--	--
16	73.1	54.3	35.6	16.9	--	--	--
17	74.7	57.1	39.4	21.8	4.1	--	--
18	76.1	59.4	42.8	26.1	9.4	--	--
19	77.4	61.6	45.8	30.0	14.2	--	--
20	78.5	63.5	48.5	33.5	18.5	3.5	--
21	79.5	65.2	51.0	36.7	22.4	8.1	--
22	80.5	66.8	53.2	39.5	25.9	12.3	--
23	81.3	68.3	55.2	42.2	29.1	16.1	3.0
24	82.1	69.6	57.1	44.6	32.1	19.6	7.1
25	82.8	70.8	58.8	46.8	34.8	22.8	10.8

$$\text{Percent Reduction in Wet Accident Rate} = \left(\frac{\text{WAR} - (1.3 + 3 \times \text{DAR})}{\text{WAR}}\right) \times 100$$

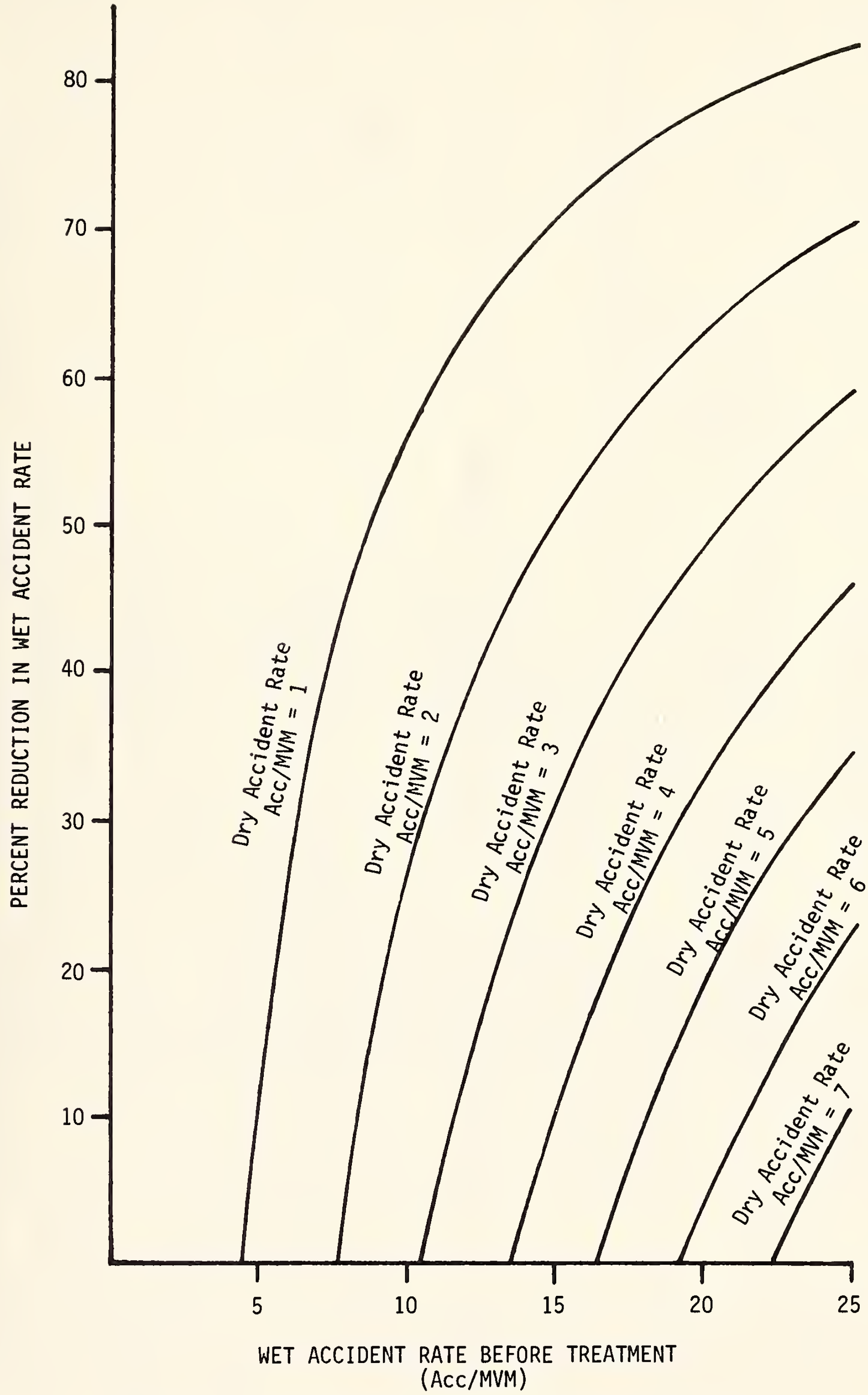

Figure 17. Percent Reduction in Wet Accident Rate

Table 13. Methods of Restoring Skid Resistance to Portland Cement Concrete Pavements

TREATMENT	BRIEF DESCRIPTION	RECOMMENDATION	ESTIMATED COST $/yd^2	EXPECTED LIFE YRS	ANNUAL/yd^2 COST @ 8%
NEW PAVEMENTS					
High Quality Mortar	Use Low W/C mixes with sharp siliceous fine aggregate textured by fluted cylinder or wire broom	All new Portland cement concrete surfaces	Incremental 0-0.50 (Depends on local availability of agg.)	20	0-0.05
TREAT EXISTING SURFACES					
Sandblast	Sandblast existing surface to remove polish	Not recommended Benefits minor & temporary	0.40	<1	0.40
Acid Etching	Remove polish by removal of aggregate by acid reaction	Not recommended Benefits minor & temporary	0.15	<1	0.15
Scabbling	Minor roughening of surface by impact tool	Not recommended Benefit minor	0.10	<1	0.10
Longitudinal Grooving	1/8" X 1/8" grooves 3/4" centers made by diamond or abrasive saws	Recommended for directional control	1.00	5	0.25
Transverse Grooving	1/8" X 1/8" transverse grooves at regular or random spacing	Recommended where cross drainage is poor and in braking areas	1.50	5	0.37
Diamond Grooving	3/8" X 3/8" grooves in two directions at 45° to centerline	Recommended for trial in sags and super-elevation run-off areas	2.00	5	0.50

Table 13. Methods of Restoring Skid Resistance to Portland Cement Concrete Pavements (continued)

TREATMENT	BRIEF DESCRIPTION	RECOMMENDATION	ESTIMATED COST $/yd^2	EXPECTED LIFE YRS	ANNUAL/yd^2 COST @ 8%
OVERLAY EXISTING SURFACES					
Portland Cement Concrete Overlay	Thin bonded patches or Thick structural course	Usually bridge decks only - Not recommended solely as anti-skid treatment	60.00	20	6.11
Chip Seal	Conventional Bituminous binder with anti-skid aggregate cover. Requires lane closings	Recommended only where Road life is limited. Low first cost. Marginal for very high vols.	0.35	5	0.09
Rubberized Asphalt Chip Seal	As above with rubberized asphalt	As above	0.50	7	0.10
Hot Mix Asphaltic Concrete	Asphaltic concrete with selected non-polishing coarse aggregate	Recommended long life treatment. Use where ride improvement needed	1.50 minimum thickness	15	0.17
Asphaltic Concrete with Precoated Chips	Sprinkle treatment--precoated anti-skid chips rolled into surface	Recommended for high speed high volume facilities	1.50	15	0.17
Open-Graded Plant Mix Friction Course	High void open graded mix with non-polishing aggregate	Recommended thin surface over smooth, pavements structurally sound	1.50	10	0.23
Epoxy Seal	Sprayed epoxy binder with special non-polish fine chip cover	Recommended for bridge decks	10.00	10	1.50
Epoxy-modified	Epoxy-modified binder for greater strength and durability	Recommended for trial on high volume freeway with nonpolishing aggregate	7.50	25	0.85

Table 14. Methods of Restoring Skid Resistance to Bituminous Surfaced Pavements

TREATMENT	BRIEF DESCRIPTION	RECOMMENDATION	ESTIMATED COST $/yd^2$	EXPECTED LIFE-YRS	ANNUAL/yd^2 COST @ 8%
TREAT EXISTING SURFACES					
Longitudinal or transverse grooving	1/8" X 1/8" grooves at 3/4"-1" centers sawn longitudinally or transversely	Recommended only in paved shoulders to aid lateral drainage	2.00	15	0.24
Heater-Planer	Remove excess asphalt from isolated fat spots by heating and scraping	Recommended for small areas. Preparatory treatment for overlay	0.40	5	0.10
Heater-with Chip Cover	Extended fat areas are heated and pre-coated chips spread and rolled in	Recommended for trial on low traffic volume roads	1.00	5	0.25
OVERLAY EXISTING SURFACES					
See Table 1 - Overlays for bituminous surfaces are similar.					
NEW PAVEMENTS					
Use non-polishing aggregate as for overlays.					

evaluating this countermeasure. A more accurate way of evaluating resurfacing probably would be to assume that this countermeasure declined in effectiveness to zero at the end of its service life. Thus, if the countermeasure reduces accidents by 30 percent in the first year after resurffacing and the service life is ten years, a first approximation to more accurately considering this countermeasure probably would be to assume that the effectiveness declines somewhat as follows:

Year	Percent Reduction in Accidents
1	30
2	27
3	24
4	21
5	18
6	15
7	12
8	9
9	6
10	3
11	0

Although this is clearly an oversimplification of the use of service life and effectiveness estimates, it may be more accurate than assuming that effectiveness remains constant over the entire service life, as is currently done in many evaluations. Survivorship curves for different pavement surfaces need to be developed showing skid resistance as related to traffic and other variables.

Installing Signals at a Stop-Controlled, Simple Intersection on a Moderate Volume Highway

Countermeasure Effectiveness

Although traffic signals are often warranted for reasons other than safety, improvements in safety may result from their installation. As with other types of countermeasures, the safety benefits of traffic signals are often disguised. Generally speaking, the installation of traffic signals may reduce the overall severity of the accident experience while increasing the total number of accidents.

One of the first studies of the effects of traffic signals was a study of 599 intersections, by Vey [152]. His study showed an approximate 20 percent overall reduction in accidents -- accidents involving vehicles traveling at right angles generally decreased, while accidents involving vehicles traveling on the same street increased. Signals installed (on other warrants) at locations with few previous accidents apparently contributed to accident increases.

Vey also developed a relationship between average daily traffic and accident experience before and after signalization (Figure 18). The general trends shown have since been confirmed by numerous studies.

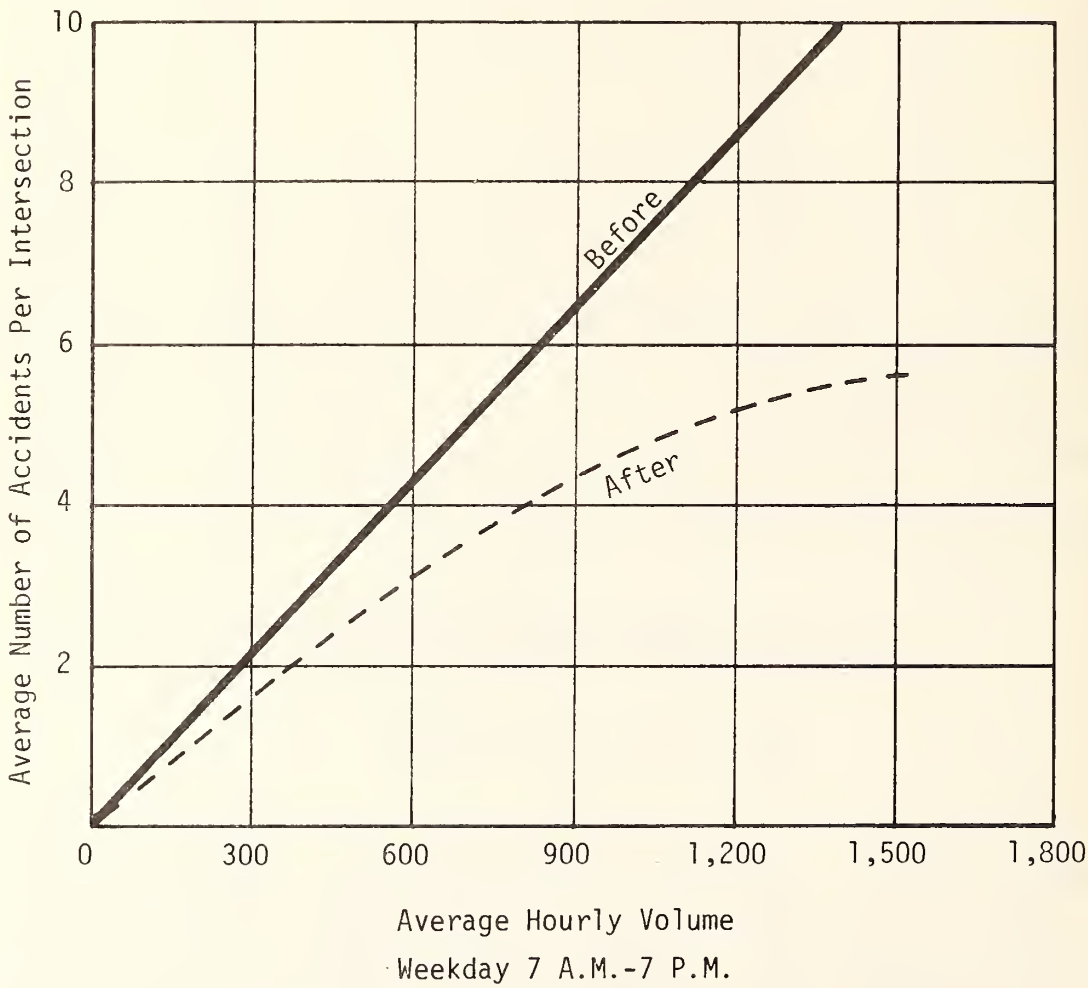

Figure 18. Accident Rates at Intersections Related to Traffic Volume Before and After Signal Installation

Syrek [153] compared accident rates for four-way stop and two-phase signalization for low and high volume intersections (Table 15). His results show that signalization offers overall improvement in the high volume situation, but not in the low volume case. Note that in both cases the rate of right angle accidents decreased, while the rate of left turn accidents increased. As these two types of accidents tend toward higher severity, the ramifications must be carefully weighed. Syrek also points out that what is good or bad on the average may be just the reverse for the individual situation.

Table 15. Low and High Volume Intersections

Low Voume Intersection

Major Street ADT--8,000; Minor Street ADT--7,000

	FOUR-WAY STOP Accidents per Million Vehicles (Vol. Group H)	SIGNAL Accidents per Million Vehicles (Vol. Group 0)
Right Angle	.35	.30
Rear End	.14	.19
Left Turn	.07	.17
TOTAL	.56	.66

High Volume Intersection

Major Street ADT--15,000; Minor Street ADT--7,000

	FOUR-WAY STOP Accidents per Million Vehicles (Vol. Group F)	SIGNAL Accidents per Million Vehicles (Vol. Group 0)
Right Angle	.44	.30
Rear End	.34	.19
Left Turn	.07	.17
TOTAL	.85	.66

Solomon [154] investigated accident experience before and after signalization at 39 intersections. He found that total numbers of accidents increased by nearly one-fourth. However, right angle and miscellaneous accidents were reduced overall; deaths were reduced about 50 percent and injuries by about 20 percent. Solomon's findings agreed with Vey's in that, while accidents increased at low volume, simple intersections, they decreased at high volume, complex intersections. Considerable variation in accident patterns is reflected in Table 16.

Table 16. Change in Accident Rate After Installation of Traffic Signals

Intersection Type	ADT Average	Change in Number of Accidents	Accident Rate Per Million Vehicles Entering Intersections: Before	Accident Rate Per Million Vehicles Entering Intersections: After	Net Change in Rate
T	11,800	+78%	1.7	3.0	+73%
Cross, undivided	20,000	+61	1.3	2.0	+53
Cross, divided	27,200	+ 4	1.3	1.1	-16
Multi-leg	16,900	-47	4.1	1.3	-69
Overall	20,200	+23%	1.5	1.8	+19%

A Michigan report [155] on before and after accident experience at 52 urban and suburban locations showed that the number of right angle accidents fell by 46 percent while the number of all other types rose, producing a total increase of about one-third.

An Ohio study [156] of 65 rural intersections showed an overall increase in accidents of 16 percent, no signficant change in injuries, and a 34 percent decrease in right angle accidents. When intersections were grouped by volume, the trend was the reverse of that reported by Vey [152] and Syrek [153] - 10 percent decreases at 36 below-average-volume locations, and 27 percent increases at 29 above-average-volume locations. The report concluded that traffic signals lose their ability to reduce accidents somewhere in the range of 9,600-11,000 ADT.

A study of 32 locations in California [157] showed an overall accident reduction of 39 percent. Half of the sites showed decreases of 50 percent or more, and 79 percent showed improvement. Another California study [158] of 125 intersections showed accident decreases at 61 percent of the locations.

Signalization of two-way stop controlled and four-way stop controlled intersections in Indiana [159] produced the results shown in Table 17. These data confirm that signalization may reduce accidents related to conflicting right-of-way, but will likely have little effect or will increase other types of accidents.

Table 17. Accident Effect Produced by Signalization of Two-Way and Four-Way Stop-Controlled Intersections

	Percent of Intersections by Accident Type			
	Right Angle	Rear-end	Other	OVERALL
Two-way Stop, 32 intersections				
Increase	3%	37%	19%	19%
No Significant Change	88	63	81	81
Decrease	9	0	0	0
TOTAL	100%			
Four-way Stop, 6 intersections				
Increase	0%	17%	17%	17%
No Significant Change	50	83	83	50
Decrease	50	0	0	33
TOTAL	100%			

A study by Dale [60] considered accident experience associated with traffic signals that were installed or improved. Unfortunately, the results are somewhat clouded, as no distinction is made between new installations and upgrading. The data showed that during one-year before and after periods, accidents decreased 6 percent (not significant), fatalities were reduced 17.3 percent (not significant), and injuries decreased 30.2

percent (significant at 0.05 level). When converted to accident rates for actual ADT's before and after, the accident rate was reduced 15 percent.

In an extensive study, Roy Jorgensen and Associates and Westat Research Analysts [20] noted the extremely varied and inconclusive results of previous reports. They developed a general relationship between percent reduction of accidents and the percent of total before accidents that were either right angle or left turn accidents (Figure 19). Their recommendation was that signals were warranted as a safety improvement only if 60 percent or more of the before accidents were right angle or left turn [20]:

> These studies also indicate that signalization is most effective when traffic volumes are high and relatively balanced between major and minor legs. Right angle accidents and left turning accidents are reduced with signalization, whereas rear-end accidents increase.

The Los Angeles County Road Department [160] developed a relationship between traffic volumes and accident rates after signalization (Figure 20). Other researchers evaluated that relationship as well [118]:

> The results of the Los Angeles County study indicated that predictions developed from the graph yielded a median error of less than plus or minus 2 accidents per year. The graph was used to predict number of accidents at 25 locations in several states (California, Connecticut, and Virginia). The median error was 3.48 accidents and the standard estimate of error was 4.55. Considering that the mean number of observed "after" accidents was 6.38 accidents, it would seem that this graph would be of little value for universal use. However, it is an approach to forecasting which may well be effective under controlled circumstances.

The final recommendation by Roy Jorgensen and Westat Research was that if the conditions specified were met, then installation of signals should result in a 29 percent decrease in accidents and a 50 percent reduction in injuries and fatalities.

It has been reported [8] that the California Division of Highways forecasts an average accident reduction of 27 percent with the installation of signals.*

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*They are now estimating twelve to fifteen percent [personal communication].

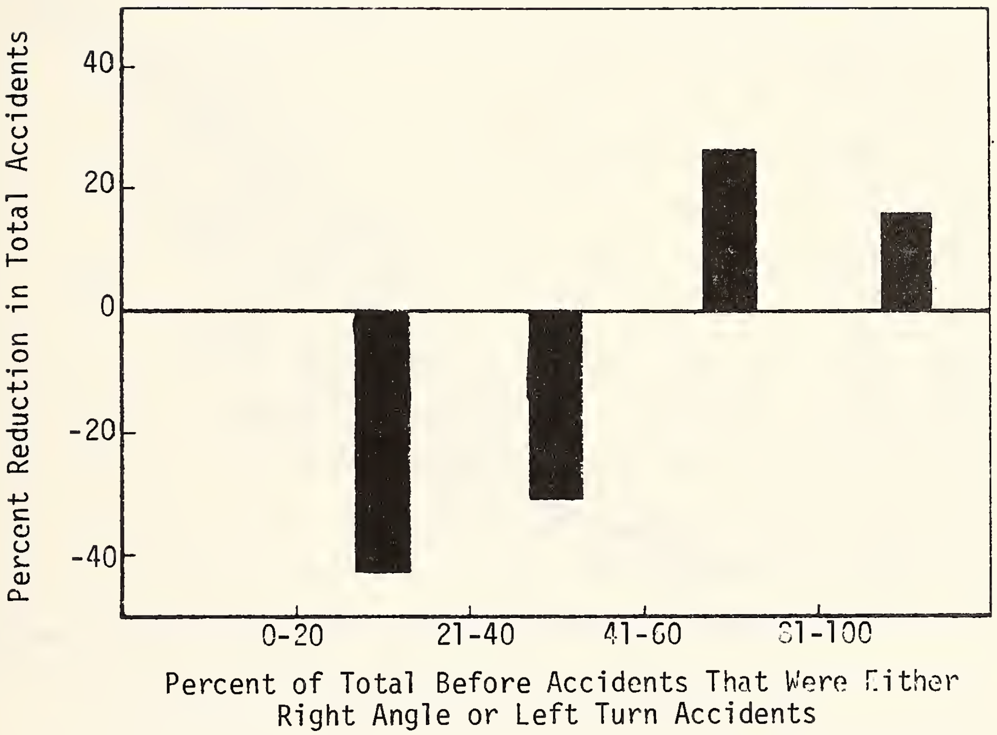

Figure 19. Relationship Between the Percent Reduction in Total Accidents and the Percent of Total Before Accidents that were Right Angle or Left Turn Accidents

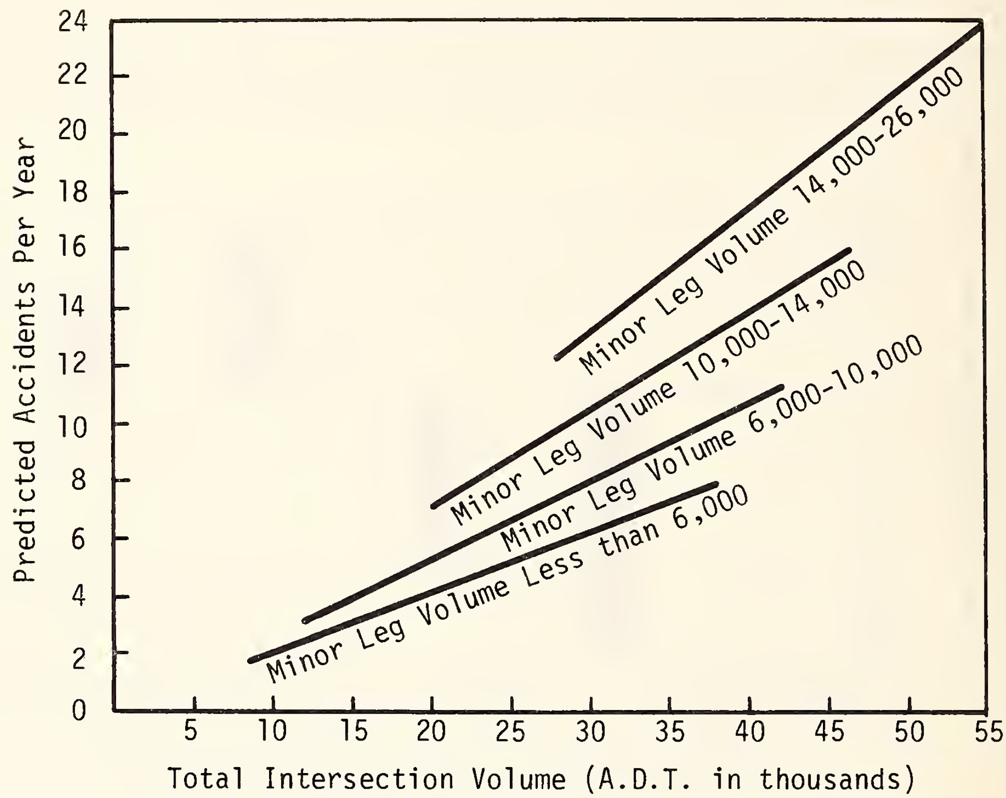

Figure 20. Relationship Between Predicted Accident Rate and Traffic Volume, After Signalization

Countermeasure Costs

A 1969 report by Fleischer [20] provides the following installation and maintenance costs for five alternative means of controlling intersection traffic (a service life of fifteen years is assumed for all alternatives):

Alternative	Installation	Maintenance
Four-Way Stop	$ 187	$ 364
Fixed-Time Signal	6,729	5,465
Semi-Actuated Signal	7,196	5,920
Fully-Actuated Signal	7,477	6,148
Fully-Actuated with left turn channelization	11,682	6,831

A 1971 report by Dale [59] provides cost figures for fifteen safety projects which installed or improved traffic signals. The overall cost for the fifteen projects was $64,015--an average of $4,268 per project.

In an update to his 1971 report, Dale [60] indicated that 79 safety projects (including fifteen previously mentioned) which installed or improved traffic signals cost a total of $455,617--an average of $5,767 per project.

The State of Alabama estimates the installation cost of traffic signals to be $9,000 [161]. For those signals, an annual maintenance cost of 30 dollars per year is assumed during the course of a 10 year service life.

The cost data in Table 18 are based on recent estimates used in nationwide traffic engineering instruction [162, p. V83].

Flashing Lights at Railroad Highway Grade Crossings

Railroad-highway grade crossings with a high accident potential or experience are generally prime candidates for the installation of flashing light signals. Although they may be accompanied by automatic gates to enhance their effectiveness, flashing light signals are the basic active grade crossing traffic control device. The effectiveness of flashing light signals relative to passive forms of warning (signs and pavement markings) has been the subject of numerous studies over the past several years.

Table 18. Costs of Traffic Signals

Signal Type	Initial Costs*: Material and Equipment	Initial Costs*: Labor and other	Initial Costs*: Total	Maintenance and Operating Costs per month
Fixed Time	$ 7000	$10 - 14000	$18 - 21000	$150 - 225
Fully Actuated	10000	14 - 19000	24 - 29000	300 - 480
5 - Phase	16000	23 - 31000	39 - 47000	300 - 480
6 - Phase	17000	24 - 32000	41 - 49000	300 - 480
8 - Phase	18000	26 - 35000	44 - 53000	300 - 480

*Mast arm mounted

Countermeasure Effectiveness

In 1970, there were 174,709 public railroad-highway grade crossings in the United States which were passively protected [163] (passive protection refers to crossbucks, stop signs, or no signs). In all, 7,255 train involved accidents occurred at these intersections, a ratio of 0.042 accidents per intersection (Table 19).

During the same year, 5,157 train-involved accidents occurred at some 48,673 actively protected railroad-highway grade crossings, a ratio of 0.0106 accidents per intersection (active protection refers to flashing lights, automatic gates, wigwags, bells, watchmen, and manual gates). Table 20 gives this data.

Table 19. Estimated Annual Train-Involved Accidents By Railroad Volume Class and Highway Volume Class

(DOT Table 6)

All Crossings with Passive Protection

Sequence of numbers in each volume class cell:
Number of grade crossings
Average number of accidents per crossing
Number of accidents

Railroad Volume Class	Highway 1	Highway 2	Highway 3	Highway 4	Highway 5	Highway 6
6	735 0.159 117	246 0.435 107	335 0.910 305	90 1.777 160	27 2.593 70	4 3.750 15
5	4,483 0.056 248	589 0.170 100	490 0.353 173	142 0.655 93	37 1.233 46	11 1.455 16
4	11,039 0.035 381	1,696 0.103 175	1,404 0.209 293	266 0.380 101	87 0.586 51	11 0.818 9
3	21,957 0.021 457	3,410 0.062 212	3,111 0.124 387	562 0.224 126	244 0.328 80	64 0.469 30
2	23,111 0.016 363	3,764 0.046 172	3,686 0.092 340	715 0.164 117	307 0.241 74	34 0.353 12
1	68,161 0.012 796	10,099 0.035 352	9,916 0.071 703	2,571 0.126 323	1,102 0.180 198	203 0.261 53
	1	2	3	4	5	6

Highway Volume Class

Note: The range of highway traffic and railroad traffic in each volume class is the same as used in previous tables.

Table 20. Estimated Annual Train-Involved Accidents By Railroad Volume Class and Highway Volume Class

(DOT Table 7)

All Crossings with Active Protection

Sequence of numbers in each volume class cell:
Number of grade crossings
Average number of accidents per crossing
Number of accidents

Railroad Volume Class	1	2	3	4	5	6
6	460 0.067 31	313 0.150 47	744 0.281 209	405 0.598 242	183 0.940 172	39 1.538 60
5	1,384 0.030 42	915 0.083 76	1,930 0.164 317	676 0.311 210	350 0.414 145	62 0.629 39
4	2,209 0.023 51	1.633 0.059 96	3,383 0.119 402	1,144 0.220 252	549 0.304 167	166 0.470 78
3	3,441 0.018 61	2,350 0.045 106	4,001 0.096 383	1,368 0.167 229	725 0.232 168	188 0.340 64
2	1,915 0.015 28	1,274 0.039 50	2,693 0.085 230	1,064 0.142 151	628 0.189 119	150 0.267 40
1	2,458 0.012 30	1,915 0.033 63	4,664 0.072 337	1,927 0.120 231	1,118 0.159 178	249 0.213 53

Highway Volume Class

Note: The range of highway traffic and railroad traffic in each volume class is the same as used in previous tables.

At first blush, actively protected crossings do not seem particularly advantageous--0.0106 accidents per active crossing versus 0.042 accidents per passive crossing. However, it is immediately recognized that active protection is not installed at crossings on a random basis, but, hopefully on the basis of hazard. If a particular grade crossing is unusually hazardous and active warning signals are installed, the crossing may still have a higher number of accidents than some other crossing selected at random, but it will have a lower accident rate than would be expected if it were passively protected.

Two variables which are known to correlate with the accident rate at crossings are railroad traffic volume and highway traffic volume. While these two variables do not fully predict the accident rate, they do partially explain the markedly different probabilities of accidents at different crossings.

The DOT report [163] divides railroad traffic volume and highway traffic volume into six different categories or classes:

Class	Trains (per day)	Highway Vehicles (per day)
1	0 - 2	0 - 500
2	3 - 5	501 - 1000
3	6 - 10	1001 - 5000
4	11 - 20	5001 - 10000
5	21 - 40	10001 - 20000
6	X1+	20001+

Generally speaking, the actively protected crossings are associated with heavy train and motor vehicle traffic while the passive crossings are associated with low train/motor vehicle volume (see Tables 19 and 20). In order to gain some overall measure of the effectiveness of active protection devices in reducing accidents, these associations must be taken into account.

Looking at Table 20, it can be seen that there were 460 railroad crossings in the United States in 1970 which were actively protected and which had a train volume of over 40 trains per day (railroad volume class 6) and a highway traffic volume of 500 or fewer motor vehicles per day (highway volume class 1). In spite of the active protection at these 460 crossings, 31 accidents still occurred--an average of 0.067 accidents per crossing.

During the same year, there were 735 passively protected crossings which serviced more than 40 trains per day (railroad volume class 6) and fewer than 501 motor vehicles per day (highway volume class 1). From the previous paragraph it was shown that for actively protected crossings experienced this level of traffic (railroad volume 6; highway volume 1) an average of 0.067 accidents occur per crossing. Applying this coefficient to the 735 similar but passively protected crossings, it is estimated that 49.25 accidents would have occurred at these crossings if they had been actively protected. In fact, 117 accidents occurred at these 735 passively protected intersections (Table 19).

In the same manner, the expected number of accidents at passive crossings (if they had been actively protected) was calculated for each combination of train volume and motor vehicle volume, some 36 combinations in all. These expectancies appear as the lower cell entires in Table 21. The upper cell entries represent the actual (observed) accidents at the various passively protected crossings.

From the data contained in Table 21, the percent effectiveness of active protection can be calculated according to the following formula:

$$\text{Effectiveness (\%)} = 100 \left(\frac{\text{Observed Accidents - Expected Accidents}}{\text{Observed Accidents}} \right)$$

For passive crossings associated with railroad traffic volume 6 and highway traffic volume 1, it is shown that installation of active protection would have reduced accidents by 57.91%:

$$100 \left(\frac{117 - 49.25}{117} \right) = 57.91\%$$

In the same manner, the effectiveness of active protection in reducing accidents can be calculated for each of the 36 combinations of train/motor vehicle traffic volume. The resulting calculations are shown as Table 22. The lower right cell in this table represents the overall effect active protection devices would have in reducing accidents if they were installed at all passive crossings - a 22.89 percent reduction in accidents.

Table 21. Actual and Expected Accidents At a Passive Crossing

Highway Volume Class

Railroad Volume Class	1	2	3	4	5	6	
6	117 49.25	107 36.90	305 94.14	160 53.82	70 25.39	15 6.15	774 265.65
5	248 134.49	100 48.89	173 80.36	93 44.16	46 15.32	16 6.92	676 330.14
4	381 253.90	175 100.06	293 167.08	101 58.52	51 26.45	9 5.17	1010 611.18
3	457 395.23	212 153.45	387 298.66	126 93.85	80 56.61	30 21.76	1292 1019.56
2	363 346.67	172 146.80	340 313.31	117 101.53	74 58.02	12 9.08	1078 975.41
1	796 817.93	352 333.27	703 713.95	323 308.52	198 175.22	53 43.24	2425 2392.13
	2362 1997.47	1118 819.37	2201 1667.50	920 660.40	519 357.01	135 92.32	7255 5594.07

Top number in each cell represents observed accidents at a passive crossing.

Bottom number in each cell represents expected accidents at a passive crossing, if it had been actively protected.

Table 22. Effectivess of Active Protection at Railroad-Highway Crossings

Railroad Volume Class	Highway Volume Class 1	2	3	4	5	6	
6	57.91	65.51	69.13	66.36	63.73	59.00	65.68
5	45.77	51.11	53.55	52.52	66.70	56.75	51.16
4	33.36	42.82	42.98	42.06	48.14	42.56	39.49
3	13.52	27.62	22.83	25.52	29.24	27.47	21.09
2	4.50	14.65	7.85	13.22	21.59	24.33	9.52
1	(2.76)*	5.32	(1.56)*	4.48	11.51	18.42	1.36
	15.43	26.71	24.24	28.22	31.21	31.61	22.89

Cell entries are calculated benefits attributable to active protection

*Calculations indicate a negative benefit attributable to active protection

In concluding this analysis, two obvious points should be made:

1. This whole analysis was done in a very gross fashion. All types of active and passive protection systems were simply dumped into one of two categories. The effectiveness of different active and passive protection systems is no doubt large.
2. For purposes of analysis, it was assumed that passive crossings having a specified train and motor vehicle volume were equivalent to active crossings having the same volumes of traffic.

The Oregon State Highway Department [164] examined over 400 crossings and developed the following accident prediction equation:

$$A = 0.25 + 8.03\,(10^{-5})\,[(v_1 t_1 p) + 1.4\,(v_2 t_2 p)] - 1.58\,(10^{-10})\,[v_1 t_1 p + 1.4\,(v_2 t_2 p)]^2$$

where: A = the number of accidents

v_1 = vehicle movements during the daylight hours (6:00 A.M. to 6:00 P.M.)

v_2 = vehicle movements during dark hours

t_1 = train movements during daylight hours

t_2 = train movements during dark hours

p = a protection factor: crossbuck = 1.0; wigwag = 0.8; flashers = 0.6; gates = 0.1.

The fifth and sixth columns of Table 23 show accident expectancies calculated with this equation for crossbucks and flashers for 81 different combinations of train and highway traffic. The seventh column gives the percent reduction in accidents estimated for installation of flashers. For the combinations of train and highway traffic chosen, it can be seen that flashing lights generally tend to reduce accidents by about 30 to 35 percent. The legend for Table 23 is as follows:

V_1 = vehicle movements during daylight hours (6:00 a.m. to 6:00 p.m.)

V_2 = vehicle movements during dark hours

t_1 = train movements during daylight hours

t_2 = train movements during dark hours

A_s = expected accidents at crossings with crossbucks

Table 23. Effectiveness of Flashing Light Signals at Railroad-Highway Grade Crossing as Indicated by a Formula Supplied by the State of Oregon.

V_1	V_2	t_1	t_2	A_s	A_f	Eff
10,000	5,000	20	20	9.3	10.1	-8.6
			10	10.4	9.1	12.5
			1	10.1	7.8	22.8
		10	20	10.4	8.5	18.3
			10	9.3	6.8	26.9
			1	7.0	4.8	31.4
		1	20	8.7	6.2	28.7
			10	5.7	3.7	35.1
			1	1.6	1.1	31.3
	1,000	20	20	10.3	8.3	19.4
			10	10.2	8.0	21.6
			1	10.0	7.6	24.0
		10	20	7.9	5.5	30.4
			10	7.4	5.0	32.4
			1	6.8	4.6	32.4
		1	20	3.1	2.0	35.5
			10	2.1	1.4	33.3
			1	1.1	0.8	27.3
	500	20	20	10.2	8.0	21.6
			10	10.1	7.8	22.8
			1	10.0	7.6	24.0
		10	20	7.4	5.0	32.4
			10	7.0	4.8	31.4
			1	6.7	4.5	32.8
		1	20	2.1	1.4	33.3
			10	1.6	1.1	31.3
			1	1.1	0.8	27.3
5,000	5,000	20	20	10.4	8.5	18.3
			10	9.3	6.8	26.9
			1	7.0	4.8	31.4
		10	20	9.8	7.4	24.5
			10	7.6	5.2	31.6
			1	4.3	2.8	34.9
		1	20	8.6	6.0	30.2
			10	5.4	3.5	35.2
			1	1.2	0.8	33.3
	1,000	20	20	7.9	5.5	30.4
			10	7.4	5.0	32.4
			1	6.8	4.6	32.4

Table 23. Effectiveness of Flashing Light Signals at Railroad-Highway Grade Crossing as Indicated by a Formula Supplied by the State of Oregon (Continued)

V_1	V_2	t_1	t_2	A_s	A_f	Eff
		10	20	5.6	3.7	33.9
			10	4.7	3.1	34.0
			1	4.0	2.6	35.0
		1	20	2.7	1.8	33.3
			10	1.7	1.1	35.3
			1	0.8	0.6	25.0
	500	20	20	7.4	5.0	32.4
			10	7.0	4.8	31.4
			1	6.7	4.5	32.8
		10	20	4.7	3.1	34.0
			10	4.3	2.8	34.9
			1	3.9	2.5	35.9
		1	20	1.7	1.1	35.3
			10	1.2	0.8	33.3
			1	0.7	0.5	28.6
1,000	5,000	20	20	9.1	6.5	28.6
			10	6.2	4.1	33.9
			1	2.3	1.5	34.8
		10	20	8.7	6.2	28.7
			10	5.7	3.7	35.1
			1	1.6	1.1	31.3
		1	20	8.4	5.9	29.8
			10	5.2	3.4	34.6
			1	0.9	0.6	33.3
	1,000	20	20	3.7	2.4	35.1
			10	2.8	1.8	35.7
			1	1.9	1.3	31.6
		10	20	3.1	2.0	35.5
			10	2.1	1.4	33.3
			1	1.1	0.8	27.3
		1	20	2.4	1.6	33.3
			10	1.4	1.0	28.6
			1	0.4	0.4	0.0
	500	20	20	2.8	1.8	35.7
			10	2.3	1.5	34.8
			1	1.8	1.2	33.3
		10	20	2.1	1.4	33.3
			10	1.6	1.1	31.3
			1	1.1	0.8	27.3
		1	20	1.4	1.0	28.6
			10	0.9	0.6	33.3
			1	0.4	0.3	25.0

A_f = expected accidents at crossings with flashing lights

Eff = percent reduction in accidents attributable to flashing lights.

Peabody and Dimmick [66] have developed an equation (similar in intent to the one developed by the State of Oregon) to predict accident frequency at railroad-highway grade crossings. Their equation is:

$$I = 1.28 \frac{H^{0.17}\ T^{0.151}}{P^{0.171}} + K$$

where:

I = probable accidents in a 5-year period

H = highway traffic -- average daily number of vehicles

T = train traffic -- trains per day

P = protection coefficient (signs = 19; flashing lights = 96)

K = a factor which must be calculated from special data presented in the report.

The Peabody-Dimmick equation was applied to 49 combinations of train and traffic volume, as shown in Table 24. Anticipated accidents over a five year period range from a low of 1.2 accidents (ADT = 100, trains/day = 1, flashing lights) to a high of 6.9 accidents (ADT = 20,000, trains/day = 40, signs). Table 25 shows that, for the combinations of ADT and trains per day chosen, flashing lights reduced accidents by about 25 percent.

A study conducted by McEachern [166] in Houston compared 114 crossings equipped with automatic signals with 65 crossings equipped with crossbucks. That comparison indicated more dramatic benefits for signals, as follows:

	Accidents per Exposure*		
	Crossbucks	Automatic Signals	Percent Reduction in Accidents
Single Track	.0145	.0041	72
Multiple Track	.0157	.0062	61
Total	.0148	.0054	64

*The values shown were derived from visual inspection of a figure provided in McEachern's report.

Table 24. Expected Accidents (during a Five-year period) as Predicted by the Peabody and Dimmick Formula.

	Trains Per Day													
	1		2		5		10		20		30		40	
ADT	Signs	Flashing Lights	Signs	Flashing Lights	Signs	Flashing Lights	Signs	Flashing Lights	Signs	Flashing Lights	Signs	Flashing Lights	Signs	Flashing Lights
100	1.6	1.2	1.8	1.3	2.1	1.5	2.3	1.7	2.5	1.9	2.6	2.0	2.8	2.1
500	2.1	1.6	2.3	1.8	2.6	2.1	3.0	2.3	3.3	2.5	3.5	2.6	3.7	2.7
1,000	2.3	1.8	2.6	2.0	3.0	2.3	3.3	2.5	3.7	2.8	3.9	3.0	4.1	3.1
2,000	2.6	2.0	2.9	2.3	3.4	2.5	3.8	2.8	4.1	3.2	4.3	3.4	4.6	3.5
5,000	3.1	2.3	3.5	2.6	3.9	3.0	4.4	3.3	4.9	3.7	5.2	3.9	5.4	4.1
10,000	3.5	2.6	3.9	2.9	4.3	3.4	4.9	3.8	5.5	4.1	5.9	4.4	6.1	4.6
20,000	3.9	3.0	4.3	3.3	5.0	3.8	5.6	4.2	6.1	4.7	6.6	5.0	6.9	5.2

Table 25. Accident Reduction Effectiveness of Flashing Light Signals as Predicted by the Peabody and Dimmick Formula

	Trains per Day						
ADT	1	2	5	10	20	30	40
100	25	28	29	26	24	23	25
500	24	22	19	23	24	26	27
1,000	22	23	23	24	24	23	24
2,000	23	21	26	26	22	21	24
5,000	26	26	23	25	24	25	24
10,000	26	26	21	22	25	25	25
20,000	23	23	24	25	23	24	25

The percent reduction in accidents attributable to automatic signals found by McEachern compares favorably with a California study. A study of 1552 crossings by the California Public Utilities Commission [167] showed that flashing light signals reduced accidents per crossing at all crossings by 63 percent from previous forms of control (including crossbucks). Also, casualties per accident were reportedly reduced by 40 percent. When comparing urban and rural crossings, the PUC found that the reduction in accidents at urban crossings was 57 percent, and at rural crossings, 67 percent. More importantly, casualties per accident at urban crossings were reduced only nine percent, but at rural crossings, 61 percent. In all cases, the greatest effectiveness was achieved when flashing light signals were used to upgrade crossbucks (64 percent reduction in accidents at all crossings, 57 percent at urban crossings, and 74 percent at rural crossings).

Further substantiating the findings of McEachern and the State of California are a report by Schoppert and Hoyt [168] indicating an 80 percent accident reduction due to flashing lights, and a report by Hopkins and Hazel [169] estimating a 70 percent reduction in accidents associated with the installation of flashing lights.

Countermeasure Costs

Relying heavily on a report by the California Public Utilities Commission [167], Hopkins and Hazel made the following cost estimates for grade-crossing protection devices [169, p. 33]:

> California now estimates the average new installation of gates plus flashing lights at $17,700, lights alone, $9,200, and upgrading from lights to gates, $19,700. These figures are relatively low compared to many others; another large state estimates $41,000, $29,000, and $19,000, respectively, for the same categories. (These, on the other hand, are somewhat higher than are commonly reported).

Installing Delineators on Horizontal Curves

The AASHTO Blue Book defines a delineator as follows [1970, p. 221]:

> Delineators are ... marking devices utilized to guide traffic, particularly at night. Reflector units sometimes are mounted on suitable supports and installed at certain heights and spacings to delimit the roadway where alignment changes may be confusing or where paths to be followed are otherwise not clearly defined.

It is suggested in NCHRP 130 that "...post delineators should be used at all curves over 5 degrees of curvature having a central angle exceeding 20 degrees" [171, p. 42].

Countermeasure Effectiveness

A 1966 study by Taylor and Foody [172] indicated that delineators on curves are, indeed, effective countermeasures in reducing accidents. This study included 557 curves at which delineators were installed, and 357 curves which served as a control. All curves had degrees of curvature greater than or equal to five degrees. The delineators were installed during calendar years 1961 and 1962. Accident data for two-year periods before and after installation of the delineators were used in the analyses shown below.

	Accident Frequency	
	Before	After
Delineated Curves	1244	1164
Control Curves	624	691

($X^2 = 6.10$; $pr < .05$)

(Adated from Table 1, [172])

On the basis of the accident frequencies, it should be predicted that during the after period the delineated curves should have sustained 1,378 accidents, if the delineators were totally ineffectual. The finding that only 1,164 delineated curves sustained accidents during the after period represents a savings of 15.53 percent.

Effectiveness of the delineators in reducing accidents are shown in the next two tables as functions of degree of curvature and central angle.

Degree of Curvature	Curve	Accidents Before	Accidents After	Accident Reduction (%)
5°	Delineated	183	149	24.09
	Control	124	133	
6° - 7°	Delineated	264	267	14.87
	Control	149	177	
8° - 9°	Delineated	259	231	24.64
	Control	109	129	
10° - 17°	Delineated	353	361	7.76
	Control	184	204	
18° & over	Delineated	185	156	-1.89
	Control	58	48	

(Adapated from Table 2, [172])

	Curve	Accidents Before	Accidents After	Accident Reduction (%)
0° - 20°	Delineated	366	364	8.83
	Control	253	276	
20° - 30°	Delineated	315	257	26.47
	Control	146	162	
30° - 40°	Delineated	139	129	33.71
	Control	45	63	
40° - 60°	Delineated	225	206	3.58
	Control	99	94	
60° - 80°	Delineated	96	107	7.12
	Control	40	48	
80° & over	Delineated	103	101	16.25
	Control	41	48	

(Adapated from Table 3, [172])

A second study by Tamburri, Hammer, Glennon, and Lew [173] tends to corroborate the basic findings of Taylor and Foody. In this study an unspecified number of curves were treated with "...simple white paddles mounted on timber or steel posts..." [173, p. 66]. In the study period before the delineators were installed, the accident rate at the curves was 1.59 accidents per million vehicles miles. After the delineators were installed, the accident rate fell to 1.04 accidents per million vehicle miles, a reduction of 34.6 percent.

A second analysis of 221 curves treated with post delineators showed the effectiveness of the treatment as a function of the sharpness of the curve. As can be seen in Table 26, curves with radii less than or equal to 500 feet sustained 1.89 accidents per million vehicle miles before treatment and 1.33 accidents per million vehicle miles after treatment, a reduction of 29.6 percent. For curves with radii longer than 500 feet the delineation treatment was ineffective.

Countermeasure Costs

The material cost for a single pole-mounted delineator currently is about $6.00 [174]; the cost installed, about $15.00. Spacing of delineators at curves ranges from about 50 feet to 200 feet or more. Typically,

Table 26. Effectiveness of Delineators on Curves

Accident Type	Accidents/MVM Before	After	
Fatal Accident	.11 (5)	.07 (3)	(Accidents on Curves)
Injury Accident	.66 (29)	.36 (16)	
PDO Accident	.82 (36)	.61 (27)	
TOTAL	1.59 (70)	1.04 (46)	
MVM	44.0	44.1	

(Adapted from Table 42, [173]).

Curve Radius (ft)*	Accidents/MVM Before	After	
500	1.89 (64)	1.33 (48)	(221 curves constitute data base)
501 - 1000	0.97 (21)	1.04 (24)	
1001 - 2000	0.28 (4)	0.59 (9)	
2001 - 5000	0.37 (12)	0.57 (20)	
5000	0.29 (5)	0.37 (7)	
TOTAL	0.88 (106)	0.84 (108)	
MVM	119.8	128.2	

(Adapted from Table 44, [173]).

*One foot equals .3 meters.

the cost for an entire installation is about $200.00 to $600.00 [161]. The service life of an individual delineator is fairly low because of vandalism and being struck by vehicles. Typical estimates of service life range from five to ten years. Since the delineator system usually will be in place longer than the individual delineator, one way to treat a delineator system would be to use a fairly long service life, say twenty years, but to assume that the maintenance cost per delineator is fairly high, say $3.00 to $5.00 per delineator per year; this maintenance cost would include the cost of replacing damaged delineators but would not include changing the entire delineator system at a specific location.

Installing Impact Attenuators at Raised Gore Areas

> Crash cushions are protective systems which prevent errant vehicles from impacting hazards by either smoothly decelerating the vehicle to a stop when hit head-on, or by redirecting it away from the hazard for glancing impacts. These barriers are used to shield rigid objects or hazardous conditions that cannot be removed, relocated or made breakaway... The most common application of a crash cushion is in the ramp exit gore wherein practical design for the site calls for a bridge rail end in the gore [138, p. 128].

Countermeasure Effectiveness

In 1973 Viner and Boyer [175] conducted an analysis of field accident data of vehicle impact attenuators reported by the states under the National Experimental and Evaluation Program Project No. NEEP-4, administered by the Office of Highway Operations, Federal Highway Administration. Analyses were made of 393 accidents at 188 installations of the following six types of attenuators:

1. Fibco impact attenuator (sand filled)
2. Hi-Dro Cushion (water filled)
3. Steel Drum attenuator
4. Tor-Shok (U-shaped tubular guardrail)
5. Dragnet (not for gore areas)
6. Vermiculite Concrete Barrier (frangible vermiculite concrete)

The analysis included data received through October 1972 from 33 states, the District of Columbia, the Commonwealth of Puerto Rico, and the Dominion of Canada. A summary of the accidents is shown in Table 27.

The available accident information was examined by Viner and Boyer to determine those events which would have resulted in death or serious injury had the attenuator not been in place. Accidents in which a rigid object would have been struck at speeds greater than 25 mph (40 km/hr) were considered to be such events. The authors noted, however, that it was seldom possible to estimate the speed at which a vehicle would have struck the rigid object within ±10 mph (±16 km/hr), and thus the conclusions drawn from this determination must be tempered by this consideration. Table 28 gives a summary of the accidents judged likely to have resulted in death or serious injury had the attenuator not been present. The table shows that only five fatalities and twelve hospitalizing injuries occurred in these 68 cases. Thus, in 75 percent of these accidents, only minor injuries or property-damage-only accidents resulted. In almost half of these accidents, severity of the incident was reduced to property damage only.

Viner and Boyer also tabulated the number of hit-and-run accidents (Table 29). Fifty-two percent of all accidents were reported as hit-and-run. These data give insight into the attenuation effectiveness by showing the large percentage of impacts that were reduced to only a brief delay with presumably little or no damage or injury. The authors also estimated that nine hit-and-run accidents may have resulted in death or serious injury had the attenuator not been present.

The researchers determined that 4.1 accidents per year of exposure were experienced at gores where the impact attenuators were installed (Table 30). Most of the installations in the study were in existing gores, rather than in new construction, and in many cases, the attenuator had been placed in front of the existing parapet nose. The researchers note that this reduces the amount of weaving room available in the gore and increases the number of accidents.

Viner and Boyer also attempted to tabulate "before" and "after" accident data. Unfortunately, pre-installation accident data were reported for only seven percent of the sites tabulated, and some of the data were

Table 27. Impact Attenuator Accidents

Attenuator Type	No. of States(1)	No. 1 Install(2)	Accidents			Percent Injury Plus Fatal	Injury Plus Fatal Accidents 90% Confidence Limits
			Total	Injury(4)	Fatal		
Fibco	19	91	198	16	2(5)	9	5 - 13%
Hi-Dro Cushion	17	48	106	16	1(5)	16	11 - 24%
Steel Drum(3)	13	30	66	12	1	20	12 - 31%
Tor-Shok	7	16	20	8	1(5)	45	22 - 63%
Vermiculite Concrete	1	2	2	0	0	--	---
Dragnet	1	1	11	0	0	--	---
Total	36	188	393	52	5	15	

(1) Includes District of Columbia, Puerto Rico, and Canada.
(2) Actual installations only, no planned installations included.
(3) High speed designs only, no low speed clusters included.
(4) Includes both hospitalizing and minor injuries.
(5) Includes one fatal accident verbally reported.

SOURCE: Reference [175]

Table 28. Accidents Judged Likely to Have Resulted in Death or Serious Injury had Attenuator Not Been Present

			Category of Reported Accidents		
Attenuator Type	Total	Fatal	Hospitalizing Injury	Minor Injury	Property Damage Only
Fibco	34	2 (2)	3	8	21
Hi-Dro Cushion (1)	13	1 (2)	4	2	6
Steel Drum	13	1	2	7	3
Tor-Shok	7	1 (2)	3	2	1
Vermiculite Concrete	1	0	0	0	1
Total	68	5	12	19	32

(1) High speed design only, no low speed clusters included.
(2) Includes one fatal accident verbally reported.

SOURCE: Reference [175]

Table 29. Number of Hit-and-Run Accidents

Attenuator Type	Total Number of Accidents	Number of Hit-Run Accidents	Percent
Fibco	198	122	62
Hi-Dro Cushion[1]	106	44	42
Steel Drum	66	29	44
Tor-Shok	20	6	35
Vermiculite Concrete	2	2	100
TOTAL	392	203	52

[1]High speed designs only, no low speed clusters included.

SOURCE: Reference [175]

Table 30. Frequency of Occurrence of Accidents with Impact Attenuators in Gores

Site Examined	117
Accidents	402
Total Months of Exposure	1,184
Accidents per Year of Exposure	4.1

qualitative in nature. Also, the time over which the pre-installation data was gathered was not specified, so that a rate of accident occurrence could not be computed. However, barriers were installed at seven sites in Connecticut where before and after data were available. These data are shown in Table 31. In Table 31 the "before" data include only police records of accidents, whereas the "after" data are from maintenance reports. The researchers note that to compare the data, it is necessary to account for the difference in reporting procedures. Based on an unpublished New York study on guardrail accidents, Viner and Boyer estimate that, in addition to the eighteen reported "before" accidents, another twenty unreported accidents would be expected. Thus, the "before" and "after" accidents shown in Table 31 would essentially be the same. Thus, the researchers estimated that about one accident per year occurred at these sites prior to barrier installation, as compared to two accidents per year after reducing the weaving room by installing impact attenuators in front of the existing parapet nose. The researchers note that the accident data prior to installation cover about five years per barrier so that a part of this difference is probably due to increased traffic. They also stated that it appears that this type of installation can indeed result in substantially increasing the number of accidents involving the hazard.

Table 31. Data from Seven Sites in Connecticut Before and After Installing Fibco Impact Attenuators in Front of an Existing Parapet Nose

	Before Installation	After Installation
Accidents	18*	37**
Total Months of Exposure	475	227
Accidents per Site per Year of Exposure	0.46	2.0

*Reported accidents

**Observed barrier damage incidents

SOURCE: Reference [175]

In 1973, Kruger [176] reported on the accident experience with Hi-Dro Cushions in Seattle. In that report he indicated that there are many 1940-vintage viaducts and expressways in Seattle with short ramp deceleration lanes, restricted or nonexistent gore recovery areas, sign distance restrictions, and inadequate horizontal clearance. Following a city-wide study in 1968, primary sites for the installation of vehicle impact attenuators were determined. Six Hi-Dro Cushion units were installed between 1968 and 1971. The Seattle accident experience is shown in Table 32. The author does not specify the time period of the "before" and "after" data.

Table 32. Accident Data at Hi-Dro Cushion Locations

Accident Severity	Number of Accidents	
	Before Installation	After Installation
Property Damage Only	7 (19%)	18 (69%)
Injury (all classes)	29 (78%)	8 (31%)
Fatality	1 (3%)	0 (0%)
Total	37	26

The first crash cushions on Texas freeways were installed in Houston in October, 1968 [77]. Three concrete abutment gore locations were the scene of eight fatal accidents reported between September, 1965 through October, 1968. Modular Crash Cushions were installed at these three locations as well as at two other gore positions in late October, 1968. Records show there were thirteen accidents involving these installations through October, 1969, with no serious injuries or fatalities at any of these sights.

An in-depth study of the steel drum crash cushions installed in Houston continued until March 12, 1971, when the fiftieth accident was recorded. At that time, there had been seven crash cushions installed on the Houston urban freeways. According to White and Hirsch [178], there were no police records on 31 of the 50 accidents. There were six accidents in which injuries were reported; only one fatality occurred.

Hirsch, et al. [179] reported on their continued monitoring of the vehicle impact attenuators in Texas. They report that at the end of 1974 there were 135 installations throughout the State of Texas. There were 117 steel drum crash cushions with the remainder being sand inertia-type barriers.

A summary of the statewide accident data involving vehicle impact attenuators during 1974 is shown in Table 33. During this year, there were 180 impacts with the 135 installations. Ten percent of 18 of those occurred in Fort Worth at IH-35N (NB) and IH-30 (WB). Of the 180, there were 73 known impacts on the noses of the attenuators and two known impacts on the side into the fish scales or redirection panels. Of the two known side impacts, one resulted in the only fatality of a vehicle occupant, and only the second fatality since 1968.

Table 33. Summary of Accident Data with Vehicle Impact Attenuators in Texas* 1974

	Number of Installations	Impacts	Fatalities	Reported Injuries	Reported Property Damages
Texas Crash Cushion Steel Drums	117 (60 in Houston)	160 (81 in Houston)	1**	25 (10 in Houston)	96
Fitch Inertia Barrier	14	13	0	7	4
Sand Tire Inertia Barrier	4	1	0	0	1
Totals	135	180	1	32	103

*Courtesy of the State Department of Highways and Public Transportation, File D-18.

**Fatality resulted from angle impact into side of steel barrier VIA with redirection panels. Vehicle was redirected and struck conrete parapet wall on both sides of the highways, then overturned.

SOURCE: Reference [175]

Marquis [180] has continued to compile accident data with vehicle impact attenuators in Texas. Table 34 is a summary of the accident experience for the years 1974, 1975, and 1976. The data show that of 476 collisions with the 244 attenuators during the three year period, only one fatality occurred -- the one in Fort Worth mentioned earlier. There were 81 reported injuries and 119 reported property-damage-only accidents.

Tye [181] reported on the other 200 site-years of operating experience with crash cushions in California amassed through 1975 from 129 crash cushions in service anywhere from two to 61 months. He highlighted the accident experience with the crash cushions and provided data concerning replacement costs and new installations. No "before" and "after" accident analyses were conducted.

Table 34. Summary of Accident Data with Vehicle Impact Attenuators in Texas for the Years 1974, 1975, and 1976

VIA	No. Installed	Known Impacts	Fatalities	Reported Injury	Property Damage
Texas Crash Cushion Steel Drums	165	430*	1	71	107
Fitch Inertia Barrier	62	32	0	9	10
Sand Tire Inertia Barrier	17	14	0	1	2
Totals	244	476	1	81	119

* Note: Nuisance impacts (generally three or less drums damaged) are not included.

SOURCE: Reference [175]

From the time the first crash cushion went into service in 1970 until the end of 1975, there were 222 reported collisions with the crash cushions:

	Number	Percent
Fatal	2	0.9
Injury	48	21.6
Property Damage	172	77.5
Total	222	100.0

Based on reports, 67 percent of the crash cushion collisions occurred during the hours of darkness, and 33 percent occurred during daylight hours. Tye indicated that the percentage of darkness collisions is grossly disproportionate in view of the fact that 27 percent of urban highway travel occurs during the dark hours. This indicates that there may be visibility problems with crash cushions, their location, and/or the people that run into them.

Countermeasure Costs

Table 8 provided some information on the range of initial costs and repair costs associated with different impact attenuation systems. The balance of this section will present further cost information on impact attenuation systems.

Table 35 provided by Viner and Boyer [175], presents a tabulation of the installation and maintenance (restoration to operational status) costs of the attenuator devices included in their study. The cost tabulated for installation covers labor and materials for site preparation, freight charges for delivering the device, engineering services for installing the device (on occasion, and usually with the installation of the first device), and the purchase price for the device. The study by Kruger [176] gives the installation costs for two types of Hi-Dro Cushions -- the cell cluster design and the cell sandwich design (see Table 36). The 1976 study by Tye [181] provides additional installation cost information on crash attenuation systems (see Tables 37 and 38). Finally, the estimated service lives of four crash attenuation systems are shown in Table 39 [18].

Table 35. Installation and Maintenance Costs of Impact Attentuator Devices

	Installation			Maintenance		
Attenuator	High	Low	Average (1)	High	Low	Average (2)
Fibco	$4,400	$1,320	$2,557(25)	$2,800	$18	$966(62)
Hi-Dro Cushion	7,700	1,100	4,941(23)	600	4	221(42)
Hi-Dro Cluster	4,866	1,538	2,439(32)	661	10	137(8)
Steel Drum	11,485	500	5,323(8)	808	50	295(15)
Tor-Shok	6,506	5,694	6,117(3)	2,500	70	745(10)
Vermiculite Concrete	9,870	6,560	8,215(2)	Barrier replaced with Fibco.		

(1) Number in parentheses refers to the number of installations included in computing the average cost.

(2) Number if parentheses refers to the number of repairs included in computing the average cost.

SOURCE: Reference [175]

Table 36. Typical Installed Costs of Units
(Labor by City Forces)

1. Cell Cluster (conveyor belt design)		
Back-up structure (concrete)	approx.	$1,500 installed
Cells (average 50/cluster) @ $30 each	approx.	1,500
Conveyor belt (plylon 350 or equal) and associated hardware, cable	approx.	500
Unit installation	approx.	200
		$3,700
2. Cell Sandwich (5-bay for 50 mph)		
Back-up (concrete)	approx.	$2,000 installed
Cell sandwich (medium width)	approx.	6,500
Unit installation	approx.	400
		$8,900

Table 37. 1975 Summary of Vehicle Impact Attenuator Repair Costs

Average cost to repair collision damage:

	1973 Hits	1974 Hits	1975 Hits
Sand Barrels	13 - $630.51	7 - $1,456.64	33 - $887.01
Water	15 - $211.78	22 - $ 186.64	60 - $167.29
Hi-Dri	----	1 - $ 365.91	2 - $304.90
Steel Drum	5 - $368.79	6 - $1,186.70	1 - $329.32

Total Experience through 1975:

	Total Hits	Total Repair	Average Repair
Sand Barrels	73	$ 58,098.39	$795.87
Water	120	23,186.00	$193.22
Hi-Dri	3	957.72	$325.24
Steel Drum	26	19,085.23	$763.41
Total	222	$101,345.34	

Crash Cushion Installations:

	Number To 12-31-74	Number To 12-31-75	Exposure To 12-31-75
Sand Barrels	33	64	1,022 Months
Water	46	59	1,342 Months
Hi-Dri	2	2	40 Months
Steel Drum	3	4	150 Months
Total	84	129	2,554 Months (212 Years Approx.)

SOURCE: Reference [181]

Table 38. Bid Prices for New Crash Cushions

Type	Number	Range	Average
Sand			
1973	1		$6,500
1974	25	$2,800 - $4,600	$3,800
1975	13	$3,250 - $3,695	$3,543
1976	39	$2,000 - $5,230	$2,916
Water			
1973	15	$11,500 - $14,667	$13,391
1974	35	$15,333 - $17,670	$16,893
1975	2	$15,000 - $16,660	$15,830
1976	14	$10,778 - $16,000	$12,438
HiDri			
1973	2	One project	$16,775
1976	12	One project	$17,691

Table 39. Estimated Service Life of Four Crash Attenuation Systems

Crash Attenuation System	Service Life in Years*	
Inertia	5 - 7	
	North	South
Steel Drums	2 - 3	4 - 7
Hi-Dro Cushions	10 - 12	
Hi-Dry Cushions	15 - 20	

*Assumes the cushions are not struck during service life.

Widening Bridges

Of the nation's 564,000 bridges, about 407,000 -- 72 percent -- were built prior to 1935. Particularly noteworthy is the vast number of older bridges on county secondary and rural roads totaling approximately 343,000, or 92 percent, out of a total of 373,000.

Some 105,000 bridges -- about one out of every five bridges in the nation, including 40,000 on roadways which are eligible for federal aid -- have been identified as being "critically deficient."

In compliance with the national bridge inspection standards called for in the Federal-Aid Highway Act of 1968, the states inspect and inventory all bridges on Federal-aid highways. Of the almost 40,000 which have been judged deficient, over 8,900 are structurally unsound, and 30,500 are "functionally obsolete."

Countermeasure Effectiveness

The benefits to be derived from bridge widening are generally conceded to be positive. However, the amount or degree of benefit derived from bridge widening is open to speculation. Two attempts are made in this section to calibrate the benefits attributable to bridge widening. The first estimates are based on data provided in a Colorado study [184], and the second estimates are based on some data provided in the Jorgenson-Westat [118] report.

Colorado Data

Some 219 bridges on rural two-lane primary roads were considered in this study. During a four year period, these bridges sustained 94 primary accidents (a primary accident is one in which structure width is the primary causal factor).

Accident rates (accidents per million vehicles) associated with these bridges were then plotted as a function of bridge width. The method of least squares was used to fit a second order equation to the plotted data. The estimated equation calculated at TTI was:

$$Y = 0.387 - 0.10\,X + 0.009\,X^2$$

where Y = accidents per million vehicles

X = bridge width in feet minus 25

Note that the minimal value of Y occurs at a bridge width of 30.5 feet. On the basis of this finding, it is concluded that the optimum width for bridges on two-lane rural roads is 30.5 feet (9 m).

By applying this equation to a selected range of bridge widths, a series of predicted accident rates can be generated:

Bridge Width (ft)*	Predicted Accident Rate (Accidents per million vehicles)
18	1.53
19	1.31
20	1.11
21	.93
22	.77
23	.62
24	.49
25	.39
26	.30
27	.22
28	.17
29	.13
30	.11
30.5	.11

*One foot equals .3 meters.

From the predicted accident rates shown above, a very gross measure of the degree to which accident rates might be reduced via the simple expedient of widening a bridge can be calculated. For example, from the above data it can be seen that bridges which are 20 feet (6 m) wide sustain 1.11 accidents per million vehicles, on the average. Bridges which are 23 feet (7 m) wide sustain only 0.62 accidents per million vehicles. Thus, by increasing bridge width from 20 to 23 feet (6 to 7 m), the accident rate should be reduced by 44.1 percent. Similarly, other reductions in accident rate associated with bridge widening can be calculated. See Table 40 and Figure 21.

Again, it should be emphasized that the data shown in Table 40 are very coarse and are predicted upon the most generous of assumptions. They are shown here only because so few data which purport to show the effect of "bridge widening" exist in the literature.

Jorgenson-Westat Data

Figure H-15 in the Jorgenson-Westat report [118] depicts bridge accidents (accidents per 100 million vehicles) as a function of "bridge width minus roadwidth (in feet)". The maximal accident rate, 120 accidents per 100 million vehicles, is associated with bridges which are six feet narrower than the approaching roadways, i.e., bridge width (BW) minus road with (RW) equals -6. Those bridges which are twelve feet wider than the approaching roadways are associated with approximately seven accidents per 100 million vehicles. The following table provides a comparison of accident rates and the relative width of bridges, BW-RW:

Relative Bridge Width (BW-RW)	Accidents per 100 Million Vehicles
-6	120
-4	103
-2	87
0	72
2	58
4	44
6	31
8	20
10	12
12	7

Table 40. Reductions (%) in Accident Rates Associated With Increases in Bridge Width

Bridge Width After Widening*	Original Bridge Width*												
	18	19	20	21	22	23	24	25	26	27	28	29	30
19	14.4												
20	27.5	15.3											
21	39.2	29.0	16.2										
22	49.7	41.2	30.6	17.2									
23	59.5	52.7	44.1	33.3	19.5								
24	68.0	62.6	55.9	47.3	36.4	21.0							
25	74.5	70.2	64.9	58.1	49.4	37.1	20.4						
26	80.4	77.1	73.0	67.7	61.0	51.6	38.8	23.1					
27	85.6	83.2	80.2	76.3	71.4	64.5	55.1	43.6	26.7				
28	88.9	87.0	84.7	81.7	77.9	72.6	65.3	56.4	43.3	22.7			
29	91.5	90.1	88.3	86.0	83.1	79.0	73.5	66.7	56.7	40.9	23.5		
30	92.8	91.6	90.1	88.2	85.7	82.3	77.6	71.8	63.3	50.0	35.3	18.2	
30.5	92.8	91.6	90.1	88.2	85.7	82.3	77.6	71.8	63.3	50.0	35.3	18.2	00.0

*One foot equals .3 meters.

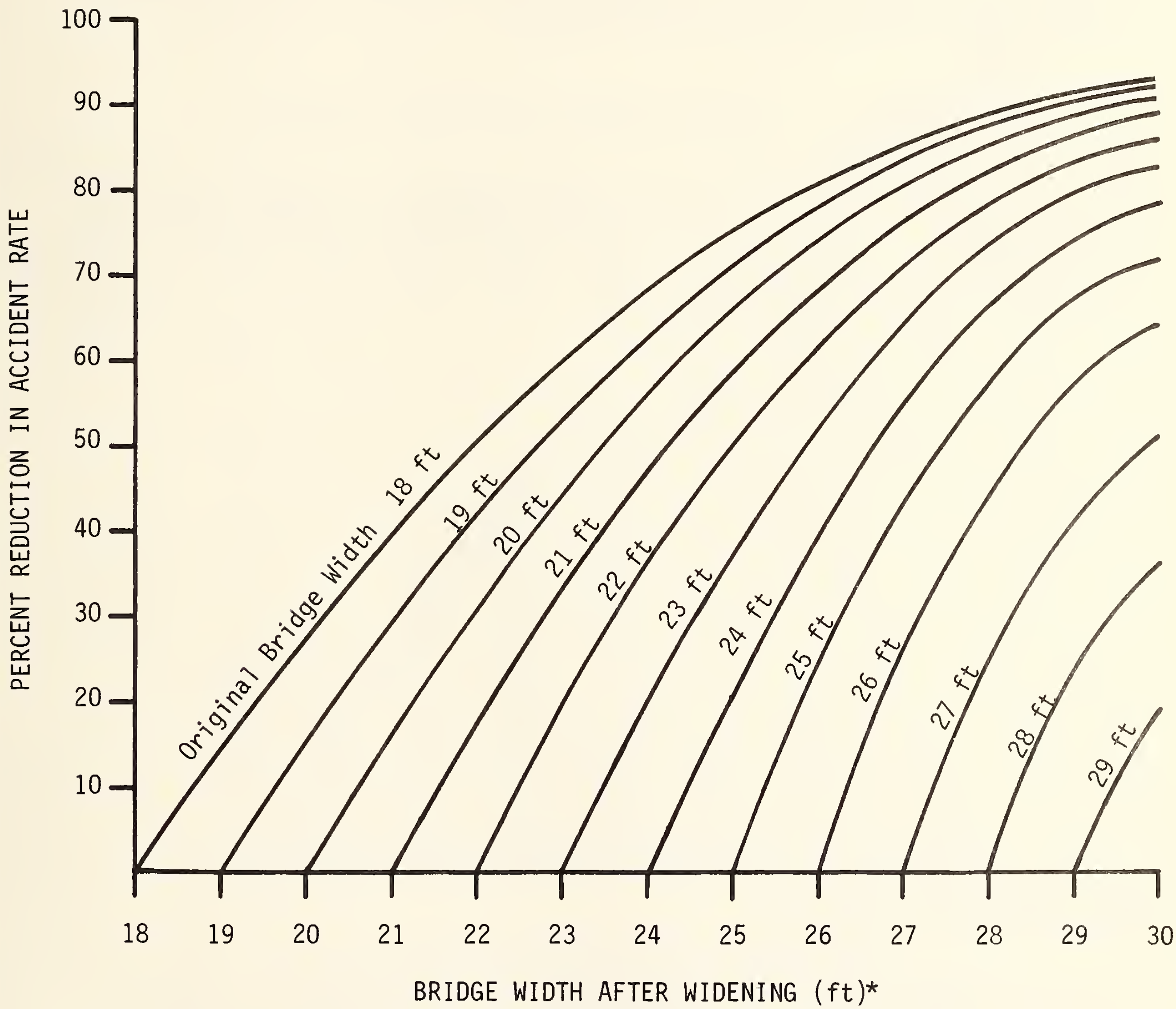

Figure 21. Percent Reduction in Accident Rate Associated With Increases in Bridge Width

*One foot equals .3 meters.

It should be noted that the values shown previously relating accidents to relative bridge width were determined through visual inspection of Figure H-15 in the Jorgenson-Westat report. On the basis of those figures, the effectiveness which might be expected to be produced via bridge widening can be calculated (see Table 41 and Figure 22). The means of calculating effectiveness is identical to the procedure used to calculate effectiveness with the Colorado data [184].

Table 41. Percent Reduction in Accident Rates

Bridge Dimensions After Treatment (BW-RW)	Original Bridge Dimensions: Bridge Width (BW) Minus Roadway Width (RW) in feet*								
	-6	-4	-2	0	2	4	6	8	10
-4	14.2								
-2	27.5	15.5							
0	40.0	30.1	17.2						
2	51.7	43.7	33.3	19.4					
4	63.3	57.3	49.4	38.9	24.1				
6	74.2	69.9	64.4	56.9	46.6	29.5			
8	83.3	80.6	77.0	72.2	65.5	54.5	35.5		
10	90.0	88.3	86.2	83.3	79.3	72.7	61.3	40.0	
12	94.2	93.2	92.0	90.3	87.9	84.1	77.4	65.5	71.7

*One foot equals .3 meters.

The same weaknesses which were obtained when the Colorado data were used to calculate accident reduction effectiveness due to bridge widening apply here. Again, the reader is cautioned that measures of effectiveness derived from simple regression equations are subject to much error.

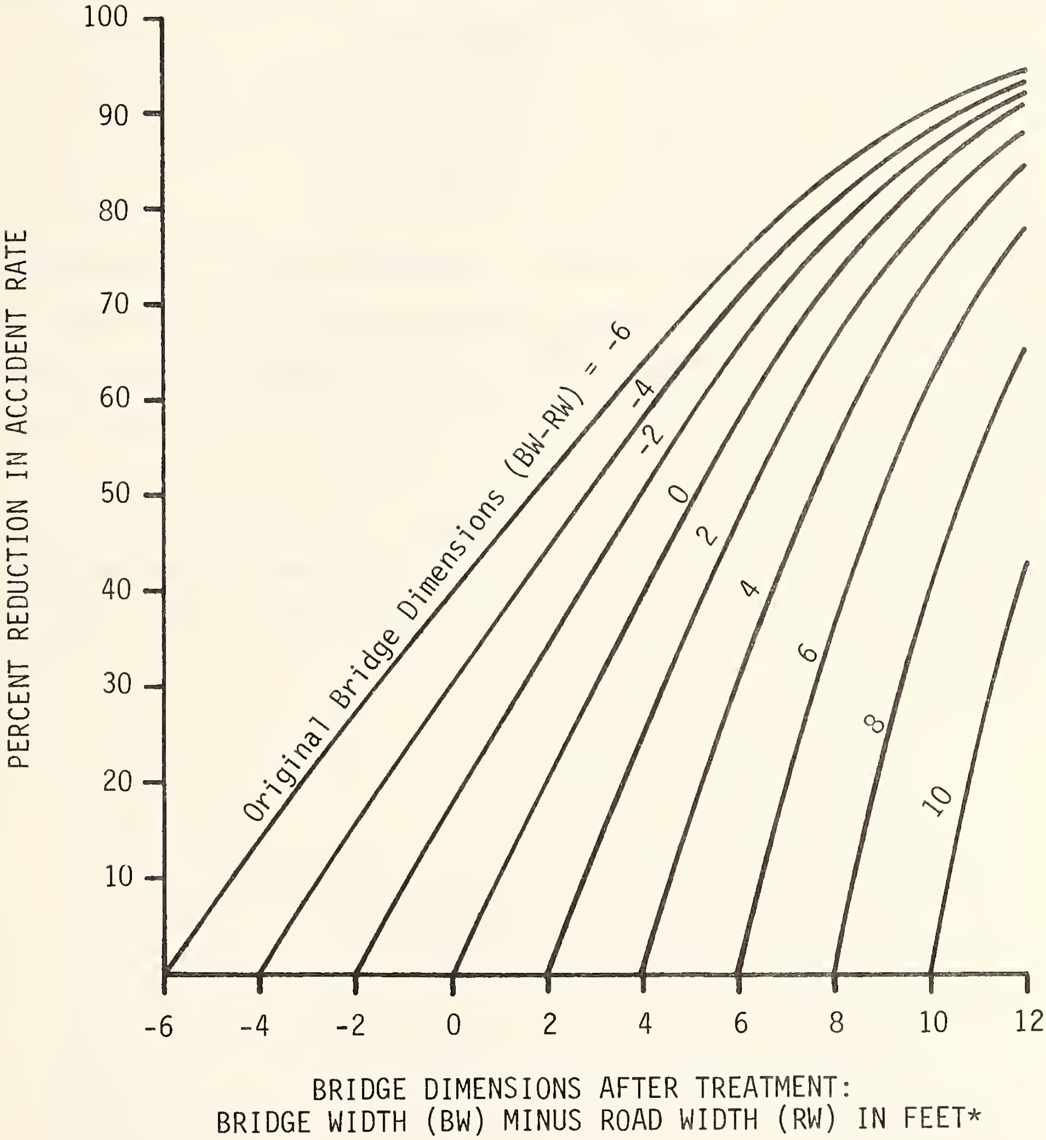

Figure 22. Percent Reduction in Accident Rate Associated With Increases in Relative Bridge Width

*One foot equals .3 meters.

Countermeasure Costs

The cost of widening an existing bridge varies widely, depending upon the type and design of the bridge, the location of the bridge, and the amount of traffic on the bridge. A survey [185] made in 1969 indicated the following costs per square foot for widening concrete bridge decks:

Colorado	$16/sq. ft
Illinois	$50/sq. ft.
New York	$25/sq. ft.
Virginia	$30/sq. ft.

Considering the inflation that has occurred since these estimates were made, these costs probably have increased by 50 to 100 percent, which would indicate that $50 per square foot would be a good ballpark figure for widening bridges. Individual states should make their own estimates for this countermeasure since costs vary so widely.

Widening bridges usually may be expected to increase the functional life of bridges that are structurally sound. The service life of such structures usually could be expected to be fairly long -- say, from twenty to fifty years.

PART FIVE: RECOMMENDED COST-EFFECTIVENESS TECHNIQUES

XI. GENERAL RECOMMENDATIONS

In discussing the problem of allocating safety funds among competing safety projects with state highway personnel in several states, it became clear that most states which we visited are desirous of better allocating systems for the disbursement of their funds. All of the states which we visited are making sincere efforts to deploy their safety funds in an optimal manner. Each state is attempting to reduce the greatest number of deaths, injuries, and accidents while meeting budgetary and category constraints imposed by state and federal legislatures.

It was concluded, however, that the states need a better overall framework for evaluating accident countermeasures. Especially needed are: (1) better ways of calculating accident costs and performing statistical tests for determining the significance of numbers of accidents of different types, (2) better measures of countermeasure effectiveness, and (3) improved techniques for considering large numbers of projects in the optimization phase. These problems are addressed in Chapters XII, XIII, and XIV. The purpose of the present chapter is to address data needs and other general findings of this report regarding the quality and availability of input data for cost-effectiveness analysis which are as follows:

1. <u>Accident data</u> -- Since the late 1960's and early 1970's, the states have made great strides in upgrading the quality of their traffic records systems. While much remains to be done by way of improving both the accuracy of accident data and the amount of environmental information contained in those accident data, it was concluded that accident data bases held by the states do not constitute an impediment to the use of cost-effectiveness models by the states.
2. <u>Highway/traffic/environmental data</u> -- The quality of the highway, traffic, and environmental data held by the states is quite good. More efforts are needed to automate some of the data bases and to insure compatibility across data bases, but these problems are minor. The quality and availability of highway, traffic, and environmental data bases do not constitute an impediment to the use of cost-effectiveness models by the states.
3. <u>Cost data</u> -- In order to rationally allocate safety funds among competing safety projects, it is necessary to know the

costs of constructing, maintaining, and repairing the countermeasures, as well as the service life. The states visited indicated that they have cost estimates for many different types of safety projects, but often these estimates are unreliable. One state indicated that estimates of project construction costs typically run forty percent behind actual construction costs. More efforts are needed to upgrade the reliability and validity of all costs associated with safety projects.

4. Countermeasure effectiveness -- As Chapter X in this report points out, the effectiveness of many different countermeasures is only poorly known. Some countermeasures have not been evaluated at all, while others have been poorly evaluated. Many evaluations are based on fallacious use of the before-after design (see criticisms by Michaels [186] and Griffin, et al. [187]) which results in spuriously high levels of effectiveness. Much more work is needed in this area. The absence of evaluations of many countermeasures constitute major impediments to the use of cost-effectiveness models by the states.

In addition to the specific findings concerning the quality and availability of input data for the cost-effectiveness model, other general impediments to the use of cost-effectiveness models by the states emerged during the course of the project. These impediments are discussed in the remainder of this chapter.

Categorical Funding

Federal highway safety funds are not allocated to state highway departments in one lump sum, but in categories. Thus, a state is not provided with a generic safety budget, but with a given budget to improve railroad-highway grade crossings, another budget for edgeline marking, another budget for improving bridges, etc. Such a budgetary system is antithetical to the deployment of an idealized cost-effectiveness model. Such a budgetary system puts artificial constraints on the selection of competing highway safety projects and assures that some low yield projects in one budgetary category with funds available will be chosen at the expense of higher yield projects in other categories which are out of funds. (Figures 23 and 24 depict the use of cost-effectiveness models with lump sum budgeting and categorical budgeting. From a theoretical point of view, the first is much to be preferred).

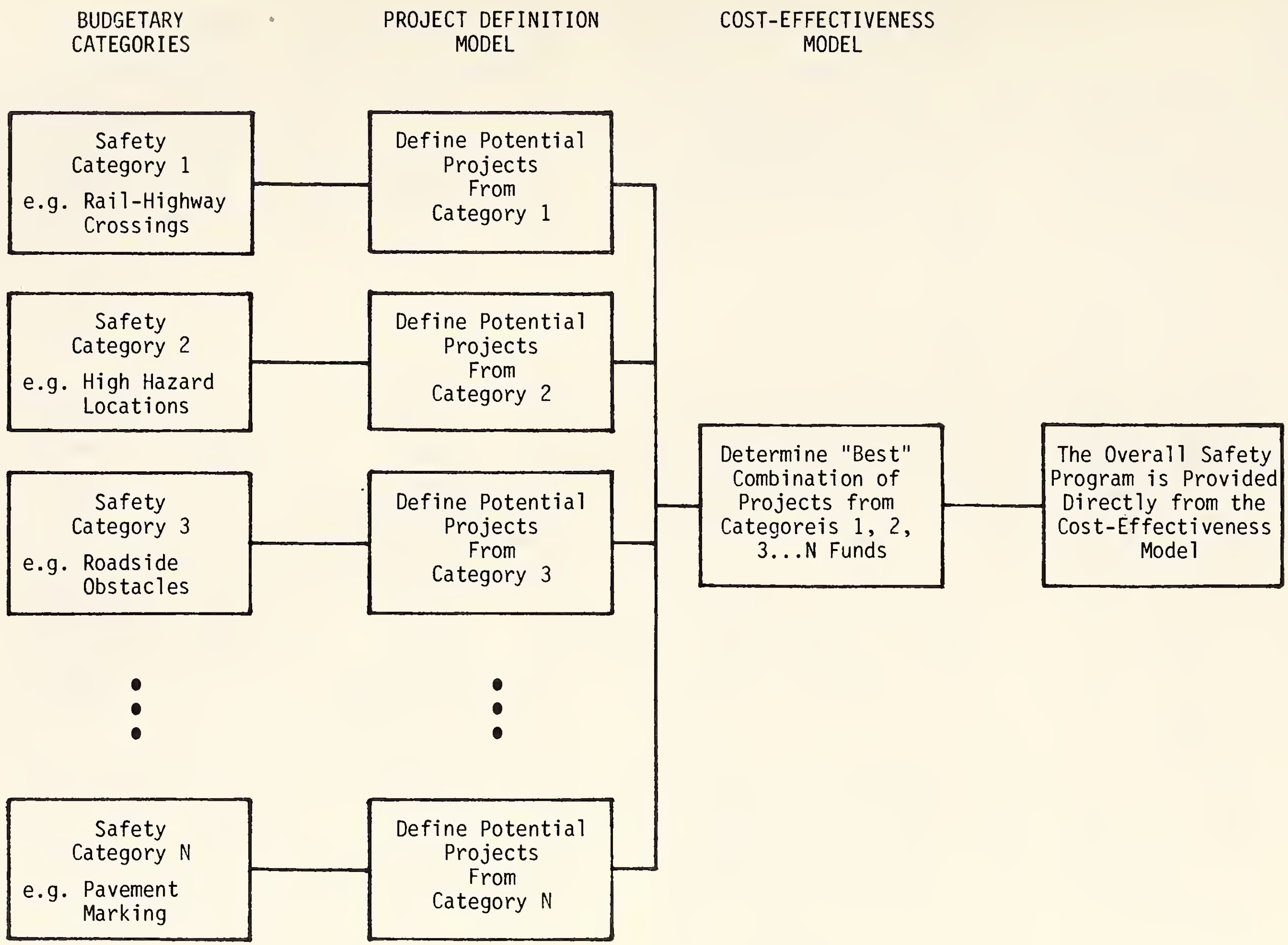

Figure 23. Cost-effectiveness Model with Lump Sum Budgeting

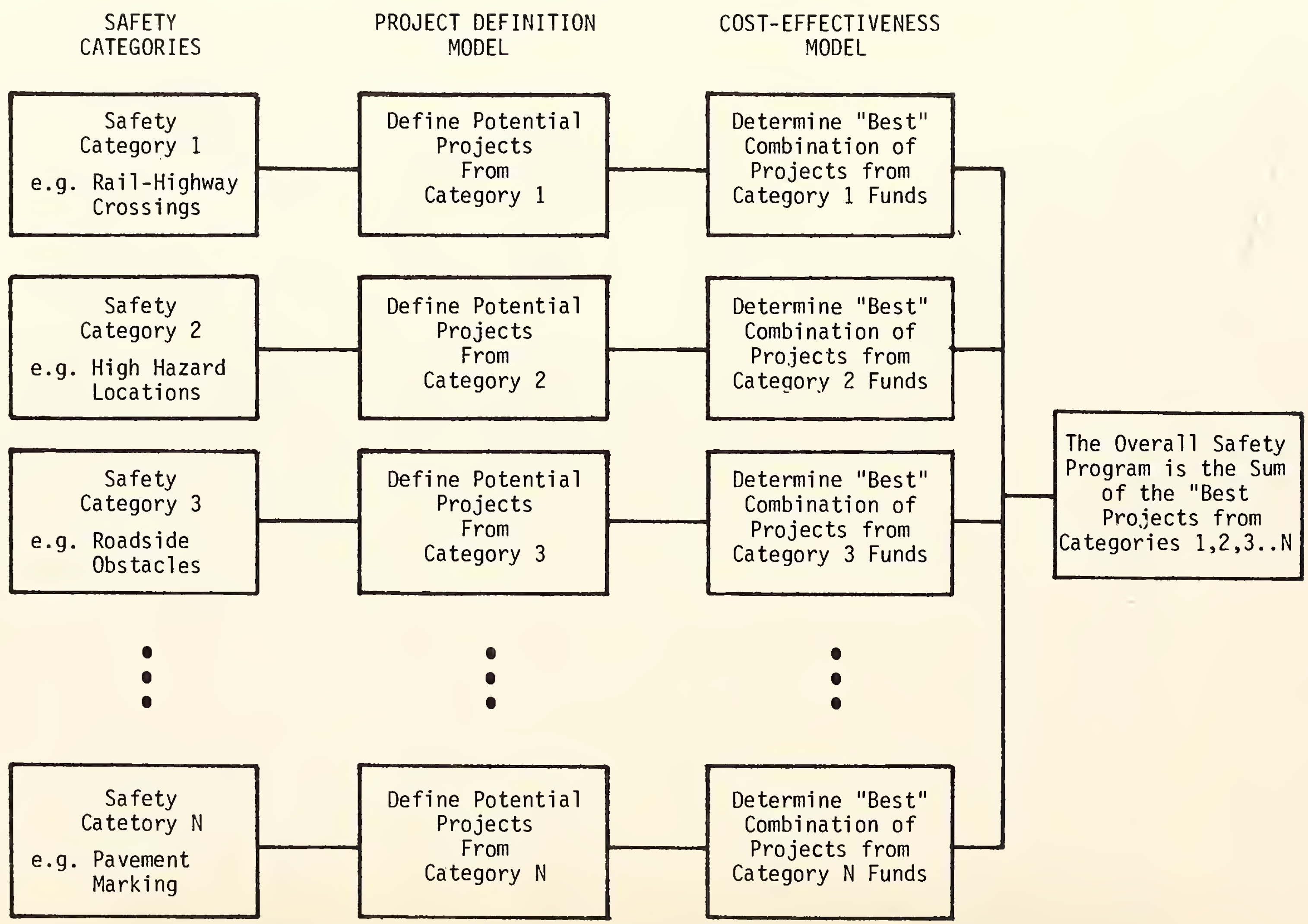

Figure 24. Cost-effectiveness Model with Categorical Budgeting

In fact, the categorical budgets granted to the states by the United States Congress are not as inflexible as Figure 24 suggests. The Highway Safety Act of 1976 states in Section 206 paragraph (b) [188]:

> The Secretary may approve the transfer of 100 percentum of the apportionment under one section to the apportionment under any other such sections if such transfer is requested by the State highway department, and is approved by the Secretary as being in the public interest, if he has received satisfactory assurances from such State highway department that the purposes of the program from which funds are to be transferred have been met.

However, the transferability of funds among safety categories may be more difficult than the previous citation suggests. One state which we visited reported that they had tried to shift funds from one category to another in order to fund projects which they thought had a higher priority. The request was refused at the divisional or regional level of FHWA not on the grounds that the funds could not be spent better in other categories, but because projects still existed to be funded in the first category. The Secretary can agree to such transfers only "...if he has received satisfactory assurances from such State that the purposes of the program from which funds are to be transferred have been met" [188].

Perhaps the state in question was not communicating adequately with FHWA. Perhaps the divisional and regional offices of FHWA were interpreting the "will of Congress" too strictly. It is not our function to resolve this situation. However, the fact remains that the state in question has decided not to make any more requests to FHWA to move funds out of what they believe to be a low priority category and into a higher priority category.

If situations such as this are allowed to continue, the "transferability clauses" which the United States Congress has written into recent highway safety acts may become inoperative through disuse. If that occurs, the categorical budgetary system shown in Figure 24 will become the standard operating procedure for the states and hopes of optimally allocating safety funds within the states will be reduced.

Divided Administration of State Highway Safety Programs

In several of the states which we visited, it became apparent that the state's overall highway safety program is not administered or coordinated through one division or office. Instead, the maintenance division might be responsible for roadway resurfacing projects, another division might authorize bridge improvements, while a third division might assume responsibility for railroad-highway grade crossing safety. The Governor's Highway Safety Representative, a man not located within the state highway department, might oversee the three plus FHWA standards in the 402 program.

By dividing highway safety responsibilities among several independent or quasi-independent offices and divisions -- within the highway department, and perhaps outside the department -- it becomes very difficult to coordinate a state's overall highway safety program. Under such circumstances, it is even more difficult to define the division, the office, and the individual within a state highway department who should oversee and assume responsibility for allocating the state's safety funds in a cost-effective manner.

Use of Accident Data

It was suggested above that the states possess adequate traffic accident data bases to identify high accident locations and to determine the precipitating factors at those locations. Unfortunately, the available accident data is not always used to the extent possible. One state which we visited indicated that accident printouts (by highway section and milepoint) are sent to the districts at periodic intervals for purposes of identifying accident locations in need of treatment. Of the several districts within the state, our source indicated that only one district uses the accident information in any systematic way for purposes of identifying highway segments and locations which might be in need of treatment or repair. As Council and Hunter said [89, p. 183]:

> This need for improved traffic records systems is accompanied by an additional need -- that of convincing potential users that the system is reliable and usable. That is, a well designed system incorporating carefully collected data will be of no use in the roadway safety area if the researchers and administrators refuse to use it. This problem was pointed out in Texas, a

state with one of the best roadway research programs in the nation. The authors did not study the Texas record system and no judgement is made concerning its reliability or utility. However, regardless of the true merits of the system, comments from researchers, FHWA personnel, and highway program administrators indicated that they had little faith in the system.

Definition of More Safety Projects

In defining safety projects, there is a tendency among the states to recommend treatments and countermeasures only for those locations which are sustaining the largest number of accidents, or the largest number of fatal accidents. Generally, this procedure is appropriate, but in many cases the state would be better advised to treat locations with lower total accident rates and lower fatal accident rates. According to the Comptroller General [71, p. 10]:

> Developing a list of the most hazardous locations does not assure that the maximum safety benefits are being received for each dollar spent. When selecting hazardous locations for study, there is no assurance that the most hazardous location identified through accident analysis will be the most cost-effective project to perform. Instead, the combined safety benefits of several less hazardous locations may be greater and cost less than correcting the most hazardous location. However, until a large number of locations are studied, this will not be apparent.

It is suggested here that more potential safety projects should be put forward for cost-effectiveness analysis. If a state finds itself in the position of funding 90 percent of the safety projects which are proposed, then little discrimination among the programs vying for funding is taking place, i.e., nearly all projects (90%) are being funded. A cost-effectiveness model is, after all, little more than a means of discriminating among potential projects and identifying that array of projects which will maximize predefined criteria while meeting specified constraints. If a cost-effectiveness model does not receive a sufficiently large pool of candidate safety projects on which to make its discriminations, then the value of the model if reduced. Taking the extreme case, if available funds are sufficient to cover the sum of the costs of all input projects, then the model is absolutely useless -- all projects will be funded. By the same reasoning, if a high percentage of candidate safety projects submitted to cost-effectiveness analysis can be funded, the value of the analysis process is diminished.

Proposing Multiple Treatments for the Same Location

Once a high accident location has been identified, and the decision has been made that remediation is necessary, plans are drawn up for the imposition of one or more countermeasures. Typically, the remedial treatment proposed to correct the situation represents the "best treatment" available from an engineering point of view, or a standard remedial treatment commonly employed to correct deficiencies of the type in need of repair. Rarely are two or more different treatments proposed for the same location. Instead, the district engineer or safety engineer proposes one specific safety project to correct a hazardous condition at a given location. When the proposed project is submitted to the highway department, the project is either approved or disapproved in an all-or-none fashion.

It is suggested that when and if cost-effectiveness models are used to aid in the allocation of state safety funds, multiple treatments should be proposed to correct the same situation. The most advantageous economic treatment for a high accident location is not necessarily the most advantageous treatment from an engineering perspective. If, for example, a given railroad-highway grade crossing is sustaining an unacceptable number of accidents, a variety of treatments could be proposed to correct the situation, such as grade separation, automatic gates, automatic lights, or general illumination of the area. The "best" treatment for this particular grade crossing must not be considered in an absolute sense but rather in relation to other safety projects which the state could fund at other grade crossings and at other locations in need of treatment. If only one treatment were proposed for this location (say, installation of automatic gates), the treatment might not be deemed appropriate for funding, i.e., other projects' input to the model might have produced a higher level of return on investment. Another proposed treatment to this grade crossing (e.g., general illumination of the crossing) might very well have been selected by the model as appropriate for funding. By submitting a wide variety of safety projects to cost-effectiveness analysis, and by submitting multiple projects for redress of accidents which occur at specific locations to such analysis, the power or efficiency of a cost-effectiveness model will be enhanced.

Continual Definition of Safety Projects

Most of the discussion in this report has assumed that on a given day a pool of potential safety projects is available to a state highway department for submission to a cost-effectiveness model. By plugging the input data into the model on the first day of the fiscal year, a list of projects for the coming year can be obtained.

At the present time, potential safety projects are not collected and saved for purposes of analysis on a given day. Instead, district engineers forward potential safety projects to their state capital for approval on a continuing basis. Typically, the proposed project is accompanied by an estimated benefit-cost ratio. An administrator in the state capital reviews the proposed projects as they come in. If, early in the year, the funds in a given budgetary category are plentiful, nearly any project with a benefit-cost ratio greater than 1.0 will be approved. Later in the year, as funds become more scarce in given budgetary categories, only those proposed projects with higher benefit-cost ratios (e.g., 1.8 or 2.0) will be approved. No attempt is made to compare all potential safety projects on the same day. Project approval, then, is an on-going process.

If cost-effectiveness models are ever to be applied by the states in a useful manner, some modifications of this process must take place. If such modifications cannot be introduced, any attempt at cost-effectively allocating safety funds will fail.

Conclusions

These six administrative/political impediments to the use of cost-effectiveness models by a state should be considered as the state attempts to develop improved techniques for the allocation of highway safety funds. Before any cost-effectiveness model is seriously applied by a state, these impediments must be addressed.

Of the four sets of input data for cost-effectiveness models which we reviewed (accident, highway/traffic/environmental, cost and effectiveness data), it was found that the effectiveness data constitute the most serious impediment to the deployment of cost-effectiveness models by the states. Any effort to design cost-effectiveness models for use by the states should be paralleled by vigorous efforts to upgrade the quantity and quality of effectiveness evaluations of highway safety projects and countermeasures. If adequate input data to a cost-effectiveness model are not available, the ability of the model to optimally allocate highway safety funds is significantly reduced.

XII. RECOMMENDED ACCIDENT COST AND EFFECTIVENESS SUBMODELS

Several considerations are critical to any analysis of highway accident countermeasures. These considerations are:

1. Accident cost values used, and types of cross-classification,
2. Method of calculating accident cost, including tests of significance,
3. Method of estimating countermeasure effectiveness, and
4. Method of considering countermeasure interaction.

The methods, or submodels, recommended by this study for considering the first three items listed above are interrelated. That is, different cross-classifications are proposed for calculating accident costs, and these same cross-classifications play an integral part in determining which accident costs are used in different situations, as determined by statistical tests. Moreover, it is proposed that estimates of countermeasure effectiveness be developed for accidents of different severity, and the same cross-classifications can be used with these estimates. Use of these subcategories in estimating reductions in accident costs also is a first step toward developing improved estimates of countermeasure interaction.

Development of Accident Costs

In Chapter VII, it was recommended that three components be used for evaluating the value of reduced risk of fatalities. These components are: (1) value of lost resources, such as medical expenses and property damage, (2) value of the person's net output used to support others, and (3) value of a person's life to himself as indicated by market experiments. The third component, the value of a person's life to himself, is omitted from most calculations of the cost of fatalities. The only exceptions are NHTSA values, which underestimate this cost. Recent studies indicate that an appropriate value to place on this third component is about $257,000 in 1975 dollars (or about $300,700 after updating to 1978 dollars).

It is recommended that improved accident cost values be developed using costs of fatalities derived using values such as those given above. Further, it is recommended that these values be developed for different categories of accidents, by type of area, type of roadway, type of design feature, and location of accident. Accident costs are needed for these categories to correct for weaknesses in the methods currently used for calculating accident costs, which is discussed more fully in the next section.

To develop accident cost values for the different categories of accidents outlined above, it is not possible to use NHTSA or NSC values since these are not available for these categories, even though it may be possible to use NHTSA values to estimate injury costs.

It is recommended that the following steps be followed in developing improved accident estimates:

1. Develop estimates of the average number of fatalities per fatal accident, injuries (by severity) per fatal accident, and injuries (by severity) per injury accident for cross-classifications by type of area, type of road, type of design feature, and location of accident.
2. Develop estimates of the cost of fatalities and injuries per fatal accident for each cross-classification by multiplying average number of fatalities per fatal accident by the cost per fatality derived using a market-oriented approach and by multiplying average number of injuries per fatal accident by NHTSA values for injury cost.
3. Develop estimates of the cost of injuries per injury accident for each cross-classification by multiplying average number of injuries per injury accident by average cost per injury.
4. Develop estimates of the cost of property damage for fatal, injury, and PDO accidents for each cross-classification (this probably can be accomplished by using values from state accident cost studies).
5. Add together the appropriate costs from steps 2, 3, and 4 to derive costs of fatal accidents, injury accidents, and PDO accidents for each cross-classification. Also, using estimates of the proportion of fatal to injury accidents for each cross-classification, derive average fatal plus injury accident cost for each cross-classification.

It should be noted that California uses accident cost values somewhat similar to those outlined above, with three exceptions: (1) values developed using the above procedures would use higher accident costs for fatalities, being based on a market-oriented approach, whereas California's method is similar to that of NSC and thus includes *no* value for a person's life to himself; (2) it is recommended that NHTSA values, which are higher than California's values, be used for injury costs; and (3) California uses values that are different only by type of area (urban, suburban, rural), whereas the method recommended in this report would use the additional cross-classifications of type of road, type of design feature, and location of accidents (it might be worthwhile to develop further cross-classifications).

Method of Calculating Accident Costs

After accident costs have been estimated for the different categories outlined in the previous section, it then is possible to use improved procedures for estimating accident costs. The following discussion first examines weaknesses of current procedures and then outlines improved procedures.

Weaknesses of Currently Used Methods

Most states use accident cost values developed by the National Highway Traffic Safety Administration or the National Safety Council. These sources report costs by accident severity but do not further differentiate how accident costs vary by type of area, type of roadway, type of accident, etc. Most states that use NHTSA or NSC accident cost values calculate accident costs by one of two methods, each of which can lead to errors in estimating accident costs.

The first of these two methods entails using the NHTSA or NSC costs for fatal accidents, injury accidents, and property-damage-only accidents. Average accident costs by severity type are multiplied by the *actual* numbers of accidents per year in each severity category to derive annual accident costs. Standard percentage reduction factors are applied to these annual costs to obtain estimates of the expected annual reduction in accident costs. This method has two weaknesses: (1) the same average accident costs are used for all types of area (urban and rural), types of roadway, etc., even though accident costs differ significantly by these categories, and (2) small numbers of fatal accidents, which may or may not be statistically significant, unduly influence choices of improvement projects.

This latter weakness, and the lack of a way to adjust for it, may be the primary reason some states are reluctant to use high values for fatal accident costs and also the reason other states are reluctant to estimate costs by severity category.

The second commonly-used method for estimating accident costs is simply to multiply total annual accidents by the cost of the average accident, averaged over all severities, to derive annual accident costs. Standard percentage reduction factors are applied to these annual accident costs to derive expected reduction in annual accident costs. This method also has two weaknesses, the first of which is that statewide average accident costs do not differentiate costs according to type of area, type of roadway, etc. The second weakness is that no allowance is made for locations with greater than average numbers of fatalities or injuries, even if these numbers are significantly greater than average.

Recommended Statistical Significance Approach

The method recommended in this study for calculating accident costs is a logical extension of the approach currently used in California, which was discussed in detail in Chapter V. California's method is the best method identified in this study, and the extensions to the method recommended in this study will further improve the method. The primary change recommended in California's method of calculating accident costs is to use more subcategories of accident costs, since there is a statistically significant difference among these subcategories.

Basically, California's procedure consists of successively comparing *actual* numbers of accidents, by severity category for an accident location, to the *expected* numbers of accidents calculated using proportions of accidents by severity category for that type of area (urban, suburban, or rural) and type of roadway (2-lane, 4-lane, undivided, etc.). The successive steps that are followed are:

1. First calculate the expected number of fatal accidents for a location by multiplying the total number of accidents observed at that location by the proportion of fatal to total accidents for that type of roadway and area. Using a statistical chart (e.g., see page 13), determine whether the

number of observed fatal accidents is greater than the expected number by a statistically significant amount. If it is, calculate accident costs as follows:

Total Annual Accident Cost =

(Average Annual Number of Observed Fatal Accidents)
x (Average Cost of Fatal Accidents for that Type of Roadway and Area)

\+ (Average Annual Number of Observed Injury Accidents)
x (Average Cost of Injury Accidents for that Type of Roadway and Area)

\+ (Average Annual Number of Observed PDO Accidents)
x (Average Cost of PDO Accidents for that Type of Roadway and Area).

2. If the observed number of fatal accidents is not significantly greater than the expected number of fatal accidents for that type of roadway and area, the next step is to compare the observed number of fatal accidents *plus* injury accidents with the expected number of fatal accidents *plus* injury accidents. The expected number of fatal accidents plus injury accidents is calculated by multiplying the proportion of fatal accidents plus injury accidents for that type of roadway times the observed number of accidents at the location under consideration. If the observed number of fatal plus injury accidents is significantly greater than the expected number of fatal plus injury accidents, annual accident costs are calculated as follows:

   Total Annual Accident Cost =

   (Average Annual Number of Observed Fatal Accidents Plus Injury Accidents)

   x (Average Cost of Fatal Accidents Plus Injury Accidents for that Type of Roadway and Area)

   \+ (Average Annual Number of Observed PDO Accidents)
   x (Average Cost of PDO Accidents for that Type of Roadway and Area).

3. If observed fatal plus injury accidents are not significantly greater than expected, the next step is to check the injury accidents. If observed injury accidents are significantly greater than expected, but fatal plus injury are not (which would be a rare case), then accident costs are calculated as in the preceding formula except that "average cost of injury accidents" is substituted for "average cost of fatal plus injury accidents."

4. If none of the above categories is found to be significantly greater than expected, accident costs are calculated as follows:

Total Annual Accident Cost =

(Average Annual Number of Accidents of All Types)
x (Average Cost of Accidents of All Severities for that Type of Roadway and Area).

In the preceding formulas, "Average Annual Number of Accidents" typically refers to an average over the last three years at a high accident location.

In California's method, the expected reduction in annual accident costs is calculated by multiplying the Total Annual Accident Cost, as calculated by one of the preceding formulas, by standard percentage reduction factors, derived from California before-after studies, with prescribed limits based on statewide averages (see Chapter V for further discussion of California's method).

California's method utilizes average accident costs for accidents of different severities, i.e., fatal, injury, PDO, that differ according to type of area (rural, suburban, urban), but that are the same for different types of roadway within each area type.

It is recommended that an approach similar to that used in California be implemented. It further is recommended that an improved version of this approach be developed which would utilize California's method of determining the significance of accident severity classes. However, the average cost of accidents of different severities would be calculated not only for different types of area, as in California, but also for different types of roadway, design features, and accident locations.

Additional subclassifications within each of these categories may be desirable, especially according to *location of accident* (run-off-road, on roadway). Other subclassifications that could be studied are type of weather, type of pavement surface, other pavement characteristics, and amount of natural light (night, day). *In determining the type of subclassifications to use, the prime consideration would be whether or not there is a statistically significant difference among accident costs in different classes of a subcategory.*

In addition to the above subcategories, it may be desirable to construct accident cost estimates for specific types of run-off-road accidents that can be used with countermeasures directed toward a specific type. For example, it would be desirable to have accident cost values for specific categories of fixed object collisions within the subcategories of curves and tangents.

To develop accident costs by severity type within each category or subcategory, three critical data are needed: (1) the average numbers of fatalities and injuries per fatal accident, (2) the average number of injuries per injury accident, and (3) the average property damage cost per accident for each severity type. Although further research may be needed to develop better estimates of the types of injuries occurring in accidents in different situations, a significant improvement over current practice can be made by using per-fatality costs and per-injury costs together with numbers of fatalities and injuries per accident in different situations to develop average costs for those situations. For example, assume a state decided to follow the above recommendations and used the previously listed categories for *type of area* (either urban and rural or urban, suburban, and rural), *type of roadway* (2-lane, 4-lane undivided, 4-lane divided, etc.), *type of design feature* (tangent, curve, traffic intersection, railroad grade crossing, and possibly bridge), and *location of accident* (run-off-road, on roadway). The proportion of accidents of each severity would be calculated for each cross-classification within these categories. Also, the average numbers of fatalities per fatal accident and injuries per injury accident, and average cost of property damage for fatal, injury, and property-damage-only accidents would be calculated. These data, together with average costs per fatality and per injury, would be used to develop tables of average accident costs, by accident severity, for each cross-classification within the above categories.

To use those accident cost tables to evaluate, for example, a countermeasure that would be used to reduce accidents at a curve on a two-lane rural road, the safety analyst would first check to see if actual accidents on the curve in question are more severe than expected (using the statistical tests previously outlined). If observed accidents are more severe than expected, costs would be calculated as the number of observed accidents by severity multiplied by the appropriate accident costs by severity type for rural, 2-lane curves. If observed accidents are not more severe than expected, then average per-accident costs (averaged over all severities) for rural, 2-lane curves would be used. It would be necessary to develop procedures for specifying which subcategory of accident percentages and costs to use for a specific countermeasure.

The subcategory of rural, 2-lane curves probably should include both run-off-road and non-run-off-road if the countermeasure is, for example, improved delineation and pavement marking on the curve or improved alignment of the curve. However, if further research indicated that improved delineation and pavement marking at curves on 2-lane, rural roads affected only run-off-road accidents, then further subcategorization would be used. The extent to which further subcategories should be developed depends upon whether there is a statistically significant difference among accident severities within classes of the subcategory. Also, judgment must be used to determine whether these subcategories can be matched with countermeasure effectiveness data.

Two further points should be made. California's use of a system similar to that outlined above indicates that classifications by type of area and type of roadway can be used to improve accident cost estimates. A review of severities by other subclassifications indicates that the California approach can be modified and improved by using these further subclassifications. To the extent that there is a statistically significant difference among the classes derived by further subclassification, there is an error in not using these further subclassifications. This error is greatest where no subclassification is used, that is, where average costs by severity type are used for all countermeasures in all situations. This is the case for all states currently using NSC or NHTSA values, since neither of these sources specifies accident costs for the categories outlined above. Use of such "statewide values," without statistical tests, can lead to relatively large errors in estimating accident costs, as compared to the more accurate California procedure and the modified approach outlined above.

In addition to modifying the California method by using further subcategories and calculating accident costs, by severity, for each of these subcategories, it is recommended that an attempt be made to develop estimates of countermeasure effectiveness that correspond to and can be used with these subcategories; this is discussed more fully in the next section.

Method of Estimating Countermeasure Effectiveness

Since most existing accident countermeasure effectiveness data are in terms of percentage reduction factors, and since most states are familiar with using this type of effectiveness measure, these percentage reduction factors are recommended as the best method to use at this time, even though improvements should be made in these measures. In general, an attempt should be made to determine if percentage reduction factors differ with different types of cross-classifications discussed previously, or at a minimum, the classes designated as type of area and type of roadway. Further, an attempt should be made to develop percentage reduction factors by severity of accident, showing how much accident countermeasures are expected to reduce fatal accidents, injury accidents, injury plus fatal accidents, PDO accidents, and all accidents.

For those situations where reduction factors are available by accident severity, it is recommended that such factors be used with the appropriate, corresponding category of accident costs by severity type, if that category is statistically significant as determined by tests described previously. These reduction factors would be used as follows:

1. If countermeasure effectiveness (percentage reduction in accidents) is available by severity and if the observed severities at a candidate location are greater than expected, then the reduction in accident costs should be calculated using percentage reductions and accident costs for each severity category. For example, if observed fatal accidents are greater than expected at a candidate location, accident costs for each severity type (fatal accident, injury accident, PDO accident) are calculated by multiplying the average accident costs for each severity type by the number of observed accidents of that type. Then, percentage reduction factors for each severity type would be multiplied by the calculated accident cost for that severity type to obtain estimated reduction in accident costs for each severity type.

If the number of observed fatal accidents is not significantly greater than expected, but the number of observed fatal accidents plus injury accidents is significantly greater than expected, then fatal-plus-injury cost (for the relevant type of area, roadway, etc.) is multiplied by the observed number of fatal accidents plus injury accidents. The cost of property-damage-only accidents is then estimated by multiplying the actual number of PDO accidents by the appropriate average cost of PDO accidents.

2. If countermeasure effectiveness is not known by severity, but there is a significant difference in observed and expected accidents by severity, then accident costs should be calculated by severity type. Then the overall percentage reduction factor for all accident types should be applied to the total cost of accidents (sum of costs by severity type).

3. If countermeasure effectiveness is known by severity type, but there is not a significant difference in observed and expected accidents by severity, then accident costs by severity type should be calculated as follows: First, calculate average numbers of accidents per year in each severity type by multiplying the *expected* proportion of accidents by severity type for this type of average area, roadway, etc. by the total average annual accidents that the countermeasure is expected to affect at the candidate location. Then the estimated number of accidents of each severity type is multiplied by the appropriate accident cost for that severity type to estimate average annual accident costs by severity type. Then reductions in accident costs are calculated by multiplying the reduction factors for fatal, injury, and PDO accidents by the corresponding average annual costs for fatal, injury, and PDO accidents.

4. If observed accidents for the more severe types are not above the expected number, and if reduction factors are not known by severity type, then the average accident costs for accidents of all severities in that category should be used. Reduction in accident costs is estimated by multiplying the overall accident reduction factor for that type of countermeasure by the total accident cost calculated using average accident costs for all severities.

Although some attempts have been made to summarize existing literature and data on countermeasure effectiveness, there remains a need for a comprehensive survey of effectiveness measures. Such a survey should attempt to develop estimates of countermeasure effectiveness by severity type, including fatal accidents plus injury accidents as a separate category, and also by type of area, type of roadway, and other classifications such as those outlined previously. In addition, other variables need to be considered in some cases, depending upon the nature of the countermeasure; examples include bridge width relative to roadway width for bridge-related countermeasures and, for fixed objects, distance from roadway and size of hazard. In any case, it should be clear that the measure of effectiveness for a specific location does not have to be the average for locations of that general type, but rather can be based on characteristics of the specific location if reduction factors that are related to such characteristics are available.

Methods of Considering Countermeasure Interaction

Interaction among highway accident countermeasures is not fully considered in existing cost-effectiveness techniques. Two difficulties must be overcome before interaction can be more fully considered. First, the structure of the effectiveness subsystem must be changed to allow for explicit consideration of countermeasure interaction. Second, additional study of different combinations of countermeasures is needed before better measures of interaction can be developed.

The procedures outlined previously for calculating accident costs by type of area, type of roadway, type of design feature, and location of accident promotes the use of a structure that should facilitate consideration of countermeasure interaction. In addition, following the recommendation of considering several countermeasures at high accident locations should lead to a better understanding of what types of countermeasures can be combined at different location types.

A further step can be taken toward developing better measures of countermeasure interaction by explicitly recognizing different types, or levels, of interaction. Four types of countermeasure interaction have been identified that ideally should be considered in cost-effectiveness analysis: (1) localized interaction, which is confined to a specific location, (2) roadway interaction, which is relevant to a section of roadway, typically several miles in length, (3) highway design standardization, which may affect accident rates throughout the highway system, and (4) general interaction, which is used to signify the effect of non-highway programs that have an effect on regional, statewide, or national accident rates or severities.

Localized Interaction

Localized countermeasure interaction occurs at specific accident locations, especially where several countermeasures are considered, both independently and in different combinations. If several countermeasures are considered at each accident location, as recommended, this type of interaction usually occurs. Typically, this type of interaction would occur when different countermeasures are considered at specific locations such as intersections, curves, bridges, and groups of roadside hazards in close proximity. Examples of this type of interaction are:

1. At intersections, there often is the possibility of using different types of traffic signals, turn lanes, and pavement markings. Although estimates of accident reductions from use of some combinations of these countermeasures are available, there remains a need to better determine how these countermeasures interact.

2. At curves and at bridges there often are the alternatives of using pavement markings, delineators, and signs. In addition, there usually is the possibility of improving horizontal and vertical alinement. Most of these alternatives affect the probability that a vehicle will run off the road or involuntarily cross the center stripe. Other alternatives affect the probability that a vehicle will have an accident and determine the type of accident, once the vehicle has involuntarily left its traffic lane. These alternatives include removing roadside obstacles and providing improved cross-sections, such that vehicles that run off the road are not as likely to overturn. Often, the effectiveness of any combination of these alternatives is less than the sum of the effectiveness of the same alternatives taken independently. However, combinations may interact in such a way that the effectiveness of the combination is greater than the sum of the parts. Interaction among many localized alternatives can be considered in much the same way as roadway interaction, the principal difference being that interaction among countermeasures at curves and bridges is more localized and, in a sense, is a subcase of roadway interaction.

3. Groups of roadside hazards that are in close proximity must be considered in combination for estimates of effectiveness to be accurate. The roadside hazard program developed in Texas is perhaps the best example of a system that attempts to accurately estimate the effectiveness of removing

different combinations of roadside hazards that appear in close proximity. This program can consider, for example, the effects of removing guardrails and several fixed objects that may be behind the guardrail, in addition to estimating the hazard of the sideslope behind the guardrail. It is common for some locations to have numerous objects for which localized interaction must be considered.

Roadway Interaction

Roadway interaction is defined as interaction among countermeasures that affect the probability that a vehicle will involuntarily leave its traveled lane and other countermeasures that affect the likelihood of a vehicle being in an accident given that it has left its own lane, i.e., encroached.

Among the highway-related features that probably affect the probability that a vehicle will involuntarily leave its traveled lane are: (1) pavement characteristics, such as roughness, skid resistance, and luminosity, (2) roadside signing and delineators, especially those that warn of changes in alinement, and (3) roadway geometry, including horizontal and vertical alinement, number of lanes, type of shoulders, and medial and marginal access control. Of course, these highway-related features interact with other driver, traffic, and environmental variables.

Other highway-related features that affect the likelihood of an accident, given that a vehicle has left its travel lane, are: (1) the roadway cross-section, especially sideslopes that may cause vehicles to overturn or run into an embankment, (2) median width and barriers, and (3) the number, location, and type of roadside obstacles.

As noted previously, consideration of interaction among countermeasures at curves can be considered as localized interaction, if, for example, specific countermeasures are considered that affect encroachment rates and other countermeasures affect the probability that an encroaching vehicle will have an accident. Such localized consideration of interaction effects usually will not be sufficient for countermeasures that affect an entire section of roadway, several miles in length.

To consider roadway interaction, countermeasures that affect roadway encroachment rates on an entire section of roadway would be considered simultaneously with countermeasures affecting accident rates of encroaching vehicles. To fully apply this recommendation, states, for example, should divide their entire highway systems into different categories, not only into categories according to type of area and type of roadway, but also according to type of design feature. Types of design feature would include the major categories of intersections (and interchanges), railroad grade crossings, and roadway sections excluding intersections and railroad crossings. Roadway sections should further be divided between tangent sections and curved sections (and perhaps other sections with vertical alinement that restricts sight distance). A first step toward using such divisions would be taken should states follow the procedures recommended herein for considering accident costs and severity proportions using these subclassifications. A second step would be attained when states attempted to obtain accident reduction factors for these same subclassifications and also the subclass of run-off-road. A third step would be provided when consideration of interaction effects on a section of roadway is considered.

Interaction among countermeasures on a section of roadway should be considered when both countermeasures that affect encroachment rates and countermeasures that affect accident probabilities of encroaching vehicles are considered for a section of roadway. For example, a countermeasure that affects encroachment rates might be expected to reduce the number of vehicles that run off the road on tangent sections by five percent and on curves by ten percent. Consideration of the effectiveness of roadside obstacle removal on this same roadway section should include this interaction effect. Similarly, the benefit from reducing encroachment rates would be reduced if a roadside clearance program reduces the likelihood of an encroaching vehicle being in an accident. Usually the effect of interaction in reducing standard percentage reduction factors would be fairly small. For example, if one countermeasure reduced encroachment rates at a curve by ten percent, the effectiveness of roadside obstacle removal at that curve would be reduced by about ten percent, a relatively small interaction effect. Therefore, until other improvements are made in other parts of the cost-effectiveness system, it probably would be premature to devote major efforts to roadway interaction at this time.

Nevertheless, a better understanding of roadway interaction should be developed with the goal of considering such interaction more fully in the near future. Such consideration might yield interesting results, such as better determining the relative benefits of increased division of traffic lanes, improved sideslopes, and increased roadside clearance as opposed to emphasis, for example, on skid resistance.

Highway Design Standardization

A particularly difficult type of interaction to quantify and consider in safety programs is the effect on accident rates of highway design standardization. There is little doubt that changes in design can present difficulties to motorists. For example, incomplete sections of Interstate highways, where motorists travel on an Interstate for a long distance and then must switch to a lower design standard over a short section of roadway, have been noted to have high accident rates. Although this effect has been noted for incomplete sections of Interstate, the magnitude of the effect in other situations has not been well quantified. On a long trip, a motorist might travel, for example, on roadways with several different designs. Other motorists traveling on some of the same roadways would have traveled on other types of roadways. Unknown is the effect on accident rates of the motorist's traveling on different roadway types and also of his interacting with other motorists who have traveled on other roadway types. A better understanding of these types of interaction probably would lead to a better understanding of accident rates and countermeasure effectiveness in different situations. Perhaps the best that can be done at this time, however, is to promote standardization along trip routes traveled by motorists and treat high accident locations, whereever they occur. More research is needed in this area.

General Interaction

General interaction is the term used herein to signify the effect on non-highway safety programs that have an effect on regional, statewide, or national accident rates or severities. General interaction includes changes in motorist behavior or characteristics and changes in vehicles.

Changes in motorists' behavior include changes in their use of safety devices, their use of alcohol and drugs, their speeds of travel, etc. Changes in vehicles include changes in vehicle size and performance, vehicle crashworthiness, availability of different types of restraint systems, etc.

The effects of fuel shortages and increased small car usage on traffic deaths and injuries recently was studied by Joksch [189] using a relationship between risk of fatal or serious injury and vehicle weights developed by Mela [190]. Joksch projected risk ratios for four future scenarios of vehicle sizes. These four scenarios are shown in Table 42. Scenarios A, B, and C are somewhat similar, but scenario D envisions a much higher proportion of smaller cars in future years. The effects of vehicle size on relative risk is shown in Figure 25 for single car crashes, car-car crashes, car-truck crashes, and all crashes combined. Joksch also projected the effects of seat belt and air bag usage on scenarios C and D, shown in Figure 26. He concluded that air bags would more than offset the effects of increased numbers of small vehicles. It is clear from Joksch's estimates that changes in vehicle size and safety devices can have a significant effect on accident severities. Moreover, these effects differ by type of accident, with large numbers of small cars increasing the severity of multiple vehicle accidents relative to single vehicle accidents. These effects have two quite important implications for allocating funds in safety programs. First, the possible effects are of sufficient magnitude that they should be explicitly considered in cost-effectiveness analysis. For example, Joksch's values indicate that countermeasures that tend to affect multiple vehicle crashes should be emphasized more relative to single vehicle crashes than would be the case if the proportion of small cars did not increase. Also, if air bags are expected to become prevalent and seat belt usage is expected to increase, short-term countermeasures would become more attractive than before. Explicit procedures need to be developed for changing Joksch's relationships so that effects on numbers of fatalities and injuries and on accident costs can be predicted in future years. The second implication of Joksch's research is that future study of countermeasure

Table 42. BC Projections of Automobile-Market Classes for Various Scenarios (percent)

Year	Subcompact	Compact	Intermediate	Standard	Lux
1972 A, B, C, D	19	13	21	35	12
1974 A, B, C, D	22	17	24	29	8
1975 A, B	21	16	22	31	[illegible]
C	20	15	22	32	[illegible]
D	25	20	24	24	[illegible]
1980 A, B	20	12	20	33	[illegible]
C	19	10	19	35	[illegible]
D	40	25	25	6	[illegible]
1985 A	20	10	20	33	[illegible]
B, C	19	9	18	35	[illegible]
D	40	25	25	6	[illegible]

*The luxury car class includes a sizable number of larger and more expens "standard" vehicles, e.g., some Mercurys, Dodges, Buicks, Oldsmobiles a Pontiacs.

Source: Joksch, [189, Executive Summary, p. 12]

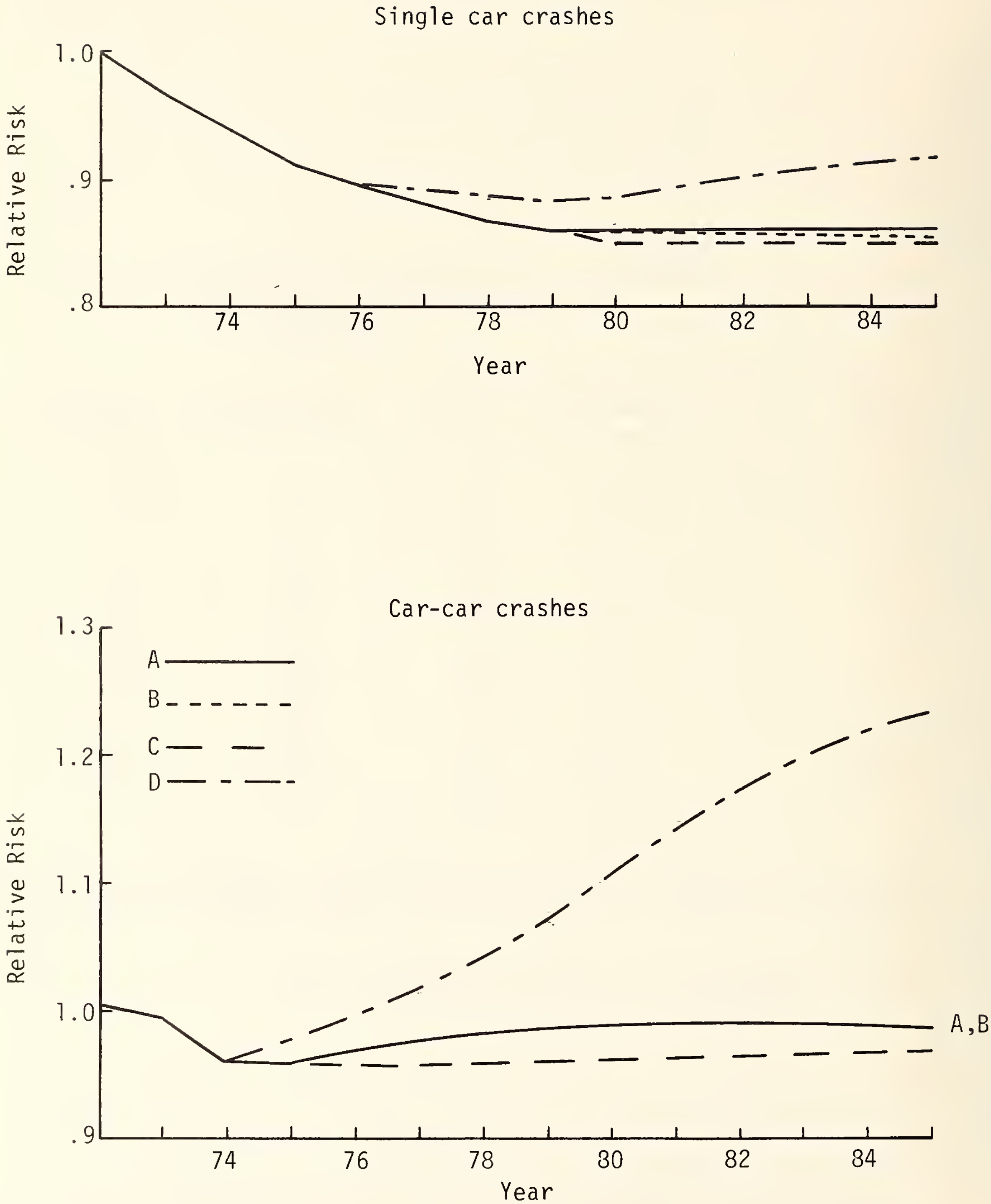

Figure 25. Projections of the average (over all cars) risk of fatal or serious injury to a driver of a car in a crash, under the scenarious A, B, C and D.

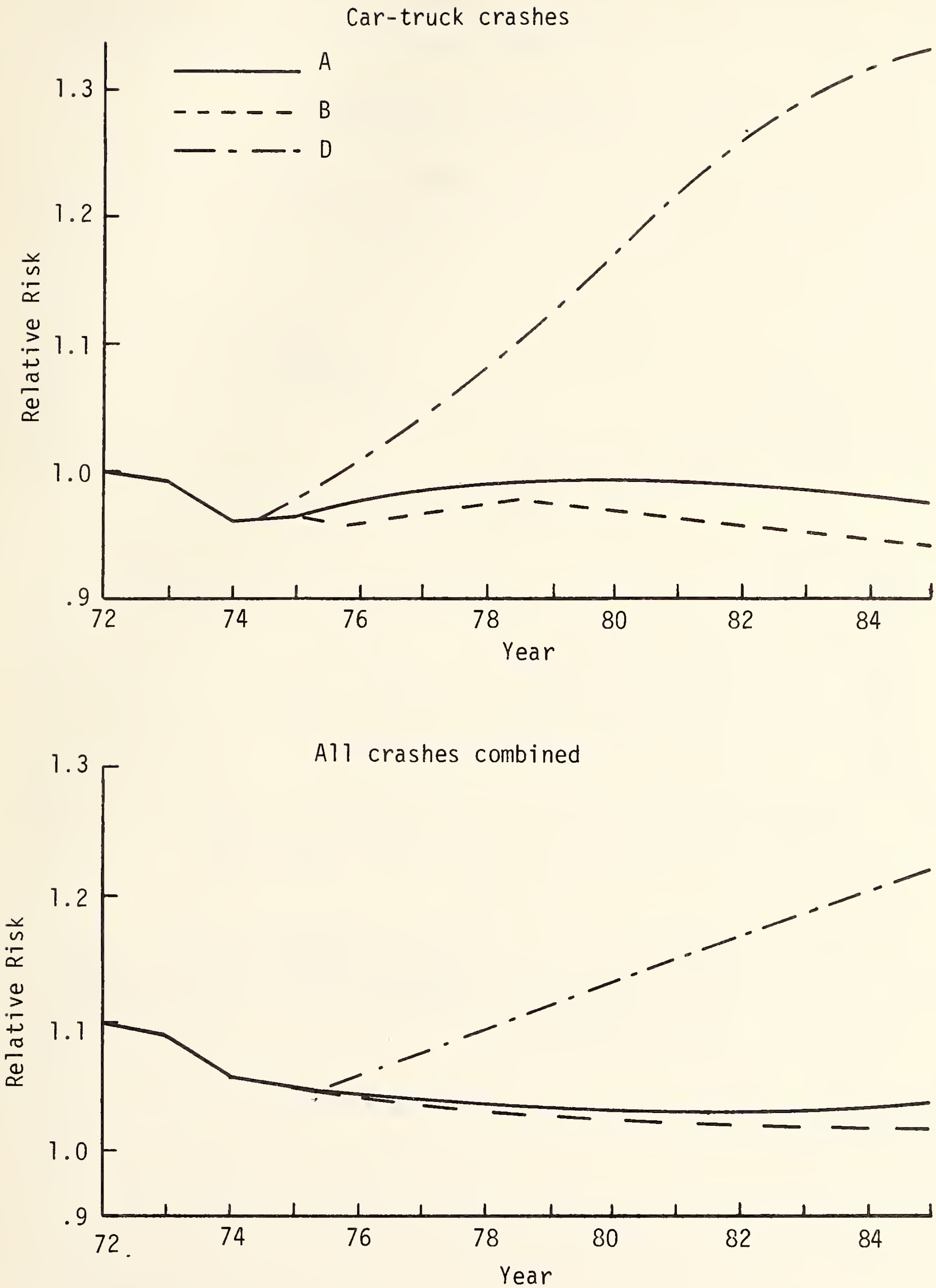

Figure 25. Projections of the average (over all cars) risk of fatal or serious injury to a driver of a car in a crash, under the scenarious A, B, C, and D. (continued)

SOURCE: Joksch, [189, Executive Summary, p. 14]

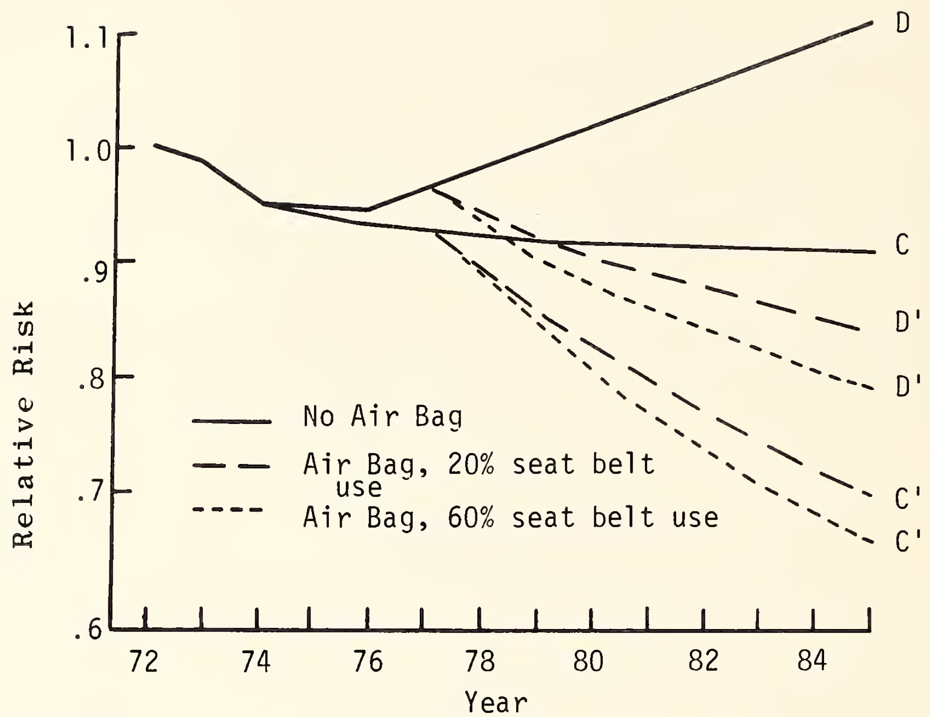

Figure 26. Projections of automobile occupant fatality risk, relative to 1972, under assumptions of no air bags, and installation of air bags in all cars from the 1978 model year on.

SOURCE: Joksch, [189, Executive Summary, p. 15]

effectiveness, especially before-after studies, should attempt to control effects of vehicle size and use of safety devices.

Theories for Predicting Accidents

Research should be directed toward developing testable hypotheses, or theories, for predicting number of accidents of different types in different situations. These theories then need to be tested and validated before being used to predict the effectiveness of accident countermeasures. One theory of accidents that shows considerable promise is the Encroachment-Probability model which uses predictions of the probability that vehicles will run off the road, together with predictions that vehicles will have an accident (usually overturning or hitting a fixed object), given that they have run off the road.

Programs to reduce accidents from roadside hazards first were based on studies which showed the proportion of roadside accidents occurring within given distances of the roadway. From this type of data, it was shown that certain percentages of all roadside accidents occurred within given distances of the edge of the pavement, and programs were developed to clear hazards within certain distances of the roadway. In terms of model development, the next important study on roadside accidents was the development by Hutchison and Kennedy [191] of information on the rate of roadside encroachments and statistical distributions of the angle at which vehicles leave the roadway and the distance that they travel from the roadway. This information was used by McFarland and Ross [192] to develop the first cost-effectiveness model that used as a submodel the Encroachment-Probability scheme for predicting the probability that vehicles will hit fixed objects placed different distances from the roadway. McFarland and Ross used their cost-effectiveness model to evaluate different roadway lighting configurations considering (1) different placement of lighting units in the median, staggered on two sides of roadway, one side of roadway, (2) different spacings of poles, (3) poles placed different distances from the roadway, and (4) poles with different types of breakaway bases. Glennon extended the McFarland-Ross model to consider other types of roadside hazards [193]. In his study, Glennon made two changes in the original model: (1) the model was changed to consider obstacles of different sizes, and (2) the model was changed to consider obstacles with different severity indices (whereas the McFarland-Ross model used different accident costs for different types of hazards, i.e., different types of lighting installations). Two major improvements recently have been made in this type of model. First, Weaver and Woods [194] further developed and field tested this type of model in Texas and developed detailed procedures and a computer program for using the method. Texas is using this program developed by Weaver and Woods to survey and evaluate the state highway system, and other states are studying use of the approach.

Glennon and Wilton [195] extended the Encroachment-Probability model by developing additional data for different types of highways. This data covered encroachment probability, angles of encroachment, lateral displacements, and severity indices for different obstacles. In addition, in Volume II of their study, the TTI computer program was modified to make use of this new data. The major limitations of these Encroachment-Probability models are:

1. As currently structured, these models only consider roadside safety programs.
2. The latest models consider the effect of traffic volume and general type of highway (i.e., urban arterials, rural nonfreeway, freeway) on model inputs but do not consider other important influences, such as roadway curvature, roadway delineations, and roadway slipperiness.
3. The severity index is stated in terms of the proportion of injury and fatal accidents to total accidents. This index is weighted and adjusted to account for the increased probability of death or severe injury for higher values of the index. However, there is no direct prediction of the precise number of accidents of different types. This creates problems in interpreting precisely the results of the model and in checking the model's validity. Also, it is not possible to compare the results of a safety program based on this model with results of safety programs based on other indices. Such inter-program comparisons are not possible even if only accident costs are considered and certainly not if other types of benefits and accident-related costs are considered.

The Encroachment-Probability model can be improved by directly addressing the above model limitations. For example, the model with its same Encroachment-Probability structure can be revised to consider the head-on and sideswipe accidents in addition to roadside accidents. In the case of head-on and sideswipe accidents, vehicles encroach across a center stripe or median rather than off the side of the road. Probability models for predicting the number of encroaching vehicles that will sideswipe or hit head-on other vehicles need to be developed. This probability could be stated as a function of median width (if any), traffic volumes, and vehicle paths.

Furthermore, by defining the influence of such variables as roadway curvature, roadway delineation, and roadway slipperiness on encroachments, this same model structure can be used to evaluate the influence of changes in these variables on head-on, sideswipe, and run-off-road accidents. This model would have the advantage that it could be used directly to consider interactions between countermeasures. For example, countermeasures that reduce the number and/or severity of roadside obstacles and other countermeasures that reduce the number of encroachments (across the center stripe and off either side of the road) could be considered separately and in different combinations.

The Encroachment-Probability model as described above would not consider angle, turning, and rear-end accidents, most of which would occur at intersections and roadway access points; nor would it consider passing accidents or other accidents such as motor vehicles hitting pedestrians and animals, overturning in the roadway, hitting objects in the roadway, or falling from a moving vehicle.

In order to develop a cost-effectiveness technique that uses the improved Encroachment-Probability model described above and also is capable of considering other types of accidents, two changes would have to be made in the model:

1. The overall model structure would have to be more general, so that the Encroachment-Probability model would be a submodel of the general model, and
2. The effectiveness measures would have to be put in more explicit terms, either using full societal costs or costs plus other effectiveness measures, expressed in such a way that multiple-criteria decision-making rules can be used.

By putting effectiveness measures in more explicit terms, it would be possible to compare different types of countermeasures.

Enough study of Encroachment-Probability models was made in this project to conclude that further development of this approach is warranted. Unfortunately, time limitations precluded detailed development of this approach.

XIII. CONSIDERATION OF OTHER MOTORIST COSTS

For many accident countermeasures, the only benefit that should be considered is reduction in accident costs. Even though many countermeasures have effects on motorist comfort and feelings of safety, it is beyond the state of the art to consider these effects at this time. However, vehicle operating costs and travel time costs should be considered in evaluating new highway construction and major highway reconstruction affecting such factors as vertical and horizontal alinement, number of lanes, and access control. Essentially, the procedures given in the revised Red Book [13], or methods such as those discussed in Chapter V for California and Texas, should be followed. However, two improvements should be made in the way these methods consider accident costs for major construction. First, it is recommended that improved accident cost estimates be developed for different situations using market-oriented values for fatalities and better estimates of numbers of fatalities and injuries per accident. Second, better methods need to be developed for predicting accident rates for different alternatives.

Since highway-railroad grade crossings and traffic intersections were two of the types of alternatives reviewed in this study, special attention was devoted to these. Additional road user costs of grade crossings were considered for comparison to safety benefits derived from the installation of flashing light signals at crossings as an accident countermeasure. However, it appears that no additional costs are incurred by road users due to the signals alone. It is hypothesized that the ordinary prudent driver would stop at the crossing at about the same time as the signals begin flashing if he knew there was a train approaching. Therefore, he incurs no additional delay. Further, it may well be that such signals may actually reduce road user cost by eliminating many speed reductions to look for trains in the absence of signalization.

The remainder of this chapter discusses a method for considering motorist costs, including vehicle operating costs and time costs, at intersections. An alternative to the procedure outlined here is given in the revised Red Book [13] and should be studied by the safety analyst.

To accurately assess the total economic impact of signalization on an intersection, it is important to estimate not only the safety benefits to be derived, but also the operational costs to be incurred. Aside from intangible factors such as driver frustration, the tangible factor most appropriate to the development of operating cost is delay. Fleischer [20] subdivides delay costs into vehicle operating costs and road user time costs. The following paragraphs describe a technique for estimating the total operating costs attributable to signalization.

If the presignalization control method in effect is two-way stop control, then there is obviously some delay incurred at the intersection. The effect of this delay must be subtracted from the effect of delay due to signalization to obtain a reasonable estimate of the difference in operating costs.

Delay Due to Two-Way Stop-Control

The average delay per vehicle on the controlled approaches (assumed to be the minor, or lower ADT approaches) of a two-way stop-controlled intersection is defined as:

$$E(v) = \frac{1}{Q - q_c} \qquad (1)$$

where: $E(v)$ = average delay per vehicle (sec)

Q = saturation flow rate (vps)

q_c = minor street flow rate per approach (vps)

Saturation flow rate, Q, is defined as:

$$Q = \frac{q_m e^{-q_m T}}{1 - e^{-q_m T}} \qquad (2)$$

where: q_m = major street flow rate (vps)

e = Naperian base

T = critical gap = 6 seconds

Q may also be determined graphically using Figure 27. Once Q is known, it is possible to compute the average delay per vehicle, E(v). Although q_m is the total major street flow rate for both directions, q_c must be the minor street flow rate per approach. For the purposes of this analysis, the directional flow on the minor approaches was assumed to be equal. It was also assumed that all minor street vehicles stayed on the minor streets, i.e., no turns onto the major street.

To compute q_m and q_c, it was necessary to estimate what percentages of the total intersecting ADTs were peak hour traffic and off-peak traffic. It was assumed that there were four hours of peak traffic, each composed of eight percent of the ADT, and 20 hours of off-peak traffic, each composed of 3.4 percent of the ADT. Thus, total daily traffic was considered in the analysis (4 x .08 + 20 x .034 = 1.00). Analyses were conducted for distributions of intersecting volumes of 67 percent major street/33 percent minor street, and 75 percent major street/25 percent minor street. The results were compared to field data reported by Vodraska, et al. [191]. It was found that the 75/25 distribution most accurately fit the field data, and thus was used for the balance of this analysis.

Computations of average daily delay due to two-way STOP control were made for both peak and off-peak traffic. These computations took the following form:

Total Peak Hour Delay per Day =

$$E(v) \times q_c \times 3600 \times 2 \times 4 \qquad (3)$$

where: E(v) = average delay per vehicle (sec) from Equation 1

$q_{(c)}$ = minor street flow rate per approach (vps)

3600 - to convert q_c to vehicles per hour

2 - to account for both approach legs

4 - to account for four peak hours per day

Total Off-Peak Delay per Day =

$$E(v) \times q_c \times 3600 \times 2 \times 20$$

A summary of these computations is shown in Table 43.

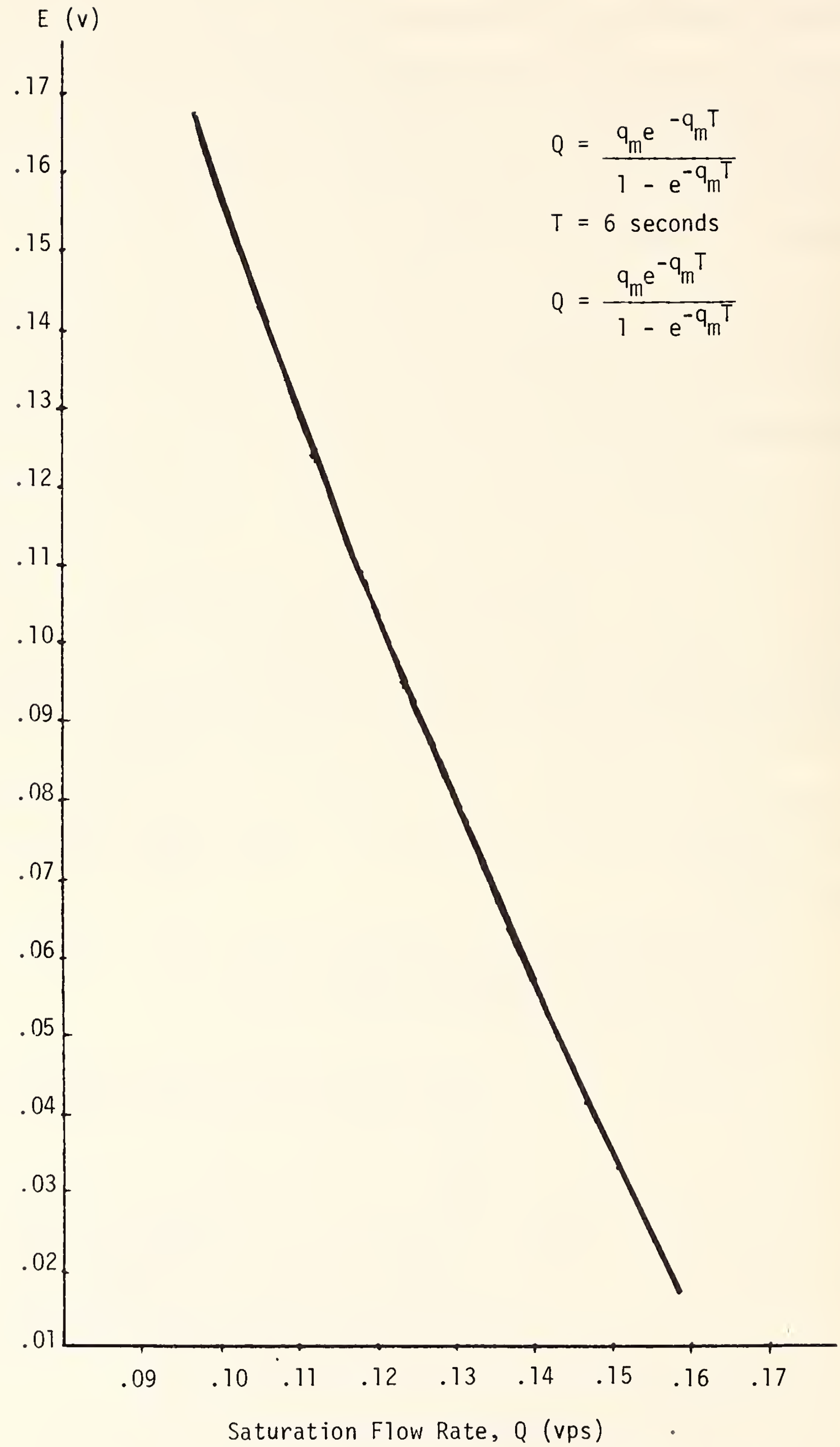

Figure 27. Saturation Flow Rate and Expected Vehicle Delay

Table 43. Estimated Total Daily Delays for Two-Way Stop Control

ADT	Peak E(v)	Peak q_c	Peak Delay	Off-Peak E(v)	Off-Peak q_c	Off-Peak Delay	Total Daily Delay
1,000	6.42	.0027	499	6.18	.0012	1,068	1,567
1,500	6.66	.0042	806	6.29	.0018	1,630	2,436
2,000	6.89	.0056	1,111	6.38	.0024	2,205	3,316
2,500	7.15	.0069	1,421	6.46	.0030	2,791	4,212
3,000	7.44	.0083	1,778	6.56	.0035	3,306	5,084
3,500	7.72	.0097	2,157	6.64	.0041	3,920	6,077
4,000	8.04	.0111	2,570	6.74	.0047	4,562	7,132
4,500	8.38	.0125	3,017	6.86	.0053	5,236	8,253
5,000	8.73	.0139	3,495	6.97	.0059	5,922	9,417
5,500	9.12	.0153	4,019	7.06	.0065	6,608	10,627
6,000	9.53	.0167	4,584	7.19	.0071	7,351	11,935
7,000	10.46	.0194	5,844	7.43	.0083	8,880	14,724
8,000	11.55	.0222	7,385	7.67	.0094	10,382	17,767
9,000	12.85	.0250	9,252	7.93	.0106	12,104	21,356
10,000	14.46	.0278	11,577	8.20	.0118	13,933	25,510

Note: These values are valid only for 75/25 volume distributions.

A description of the procedures followed in estimating daily delay for two-way stop control is best illustrated using an example of 5000 ADT:

Daily Major Street Volume = .75 x 5000 = 3750 vpd

Daily Minor Street Volume = .25 x 5000 = 1250 vpd

Total Peak Hour Delay

$$\text{Peak Hour } q_m = \frac{3750 \times .08}{3600} = .0833 \text{ vps}$$

$$\text{Peak Hour } q_c = \frac{1250 \times .08}{3600 \times 2} = .0139 \text{ vps per approach}$$

From Figure 27, Q = .1284

$$\text{Then } E(v) = \frac{1}{Q-q_c} = \frac{1}{.1284-.0139} = 8.73 \text{ sec}$$

Total Daily Peak Hour Delay =

$$E(v) \times q_c \times 3600 \times 2 \times 4 =$$

$$8.73 \text{ sec} \times .0139 \frac{\text{vps}}{\text{approach}} \times 3600 \frac{\text{seconds}}{\text{hours}} \times 2 \text{ approaches} \times$$

$$4 \frac{\text{hours}}{\text{day}} = 3495 \text{ seconds of delay per day}$$

Total Off-Peak Delay

$$\text{Off-Peak } q_m = \frac{3750 \times .034}{3600} = .0354 \text{ vps}$$

$$\text{Off-Peak } q_c = \frac{1250 \times .034}{3600 \times 2} = .0059 \text{ vps per approach}$$

From Figure 1, Q = .1494

$$\text{Then } E(v) = \frac{1}{Q-q_c} = \frac{1}{.1494-.0059} = 6.97 \text{ sec}$$

Total Daily Off-Peak Delay =

$$E(v) \times q_c \times 3600 \times 2 \times 20 = 6.97 \times .0059 \times 3600 \times 2 \times 20 =$$

5922 seconds of delay per day

Total Daily Delay

Total Daily Delay = Total Daily Peak Hour Delay + Total Daily Off-Peak Delay

= 3495 + 5922

= 9417 seconds

The results of similar computations for combined intersecting ADTs of 1000 to 10,000 vpd are summarized in Table 43. It should be noted that these values were computed for example purposes and apply only to intersecting volumes distributed 75 percent on the major street and 25 percent on the minor street. Similar values for different distributions could be computed using the foregoing procedures.

Delay Due to Signalization

There are numerous techniques available for estimating delay at signalized intersections. One of the most widely accepted techniques is the British method [192]. Using this method, the average delay per vehicle on approaches to a fixed time signal may be computed from the following:

$$d = (Cf_1 + \frac{f_2}{q}) \frac{100-f_3}{100}$$

where: d = average delay per vehicle on approach (sec)

C = cycle length (sec)

$$f_1 = \frac{(1-\frac{G}{C})^2}{2(1-\frac{q}{s})}$$

G = effective green time (sec)

q = approach flow (veh/sec)

s = saturation flow (veh/sec)

$$f_2 = \frac{x^2}{2(1-x)}$$

$$x = \frac{CQ}{Gs}$$

$$f_3 = \frac{0.65 \left(\frac{C}{q_2}\right)^{1/3} x^{2+5(G/C)}}{Cf_1 + \frac{f_2}{q}}$$

To use this formula, demand flow rates for each approach, saturation flow rate, and effective green time must either be obtained from field measures or be estimated.

For this analysis, approach flow rates were estimated as described in the section of delay due to stop control. That is, peak hour and off-peak flow rates for each approach were estimated as follows for main street (q_m) and cross street (q_c):

Peak Hour

$$q_m = \frac{0.08 \times ADT \times 0.75}{3600 \times 2} = \text{vehicles/sec per approach}$$

$$q_c = \frac{0.08 \times ADT \times 0.25}{3600 \times 2} = \text{vehicles/sec per approach}$$

Off-Peak

$$q_m = \frac{0.034 \times ADT \times 0.75}{3600 \times 2} = \text{vehicles/sec per approach}$$

$$q_c = \frac{0.034 \times ADT \times 0.25}{3600 \times 2} = \text{vehicles/sec per approach}$$

Saturation flow rate, s, is the maximum rate at which vehicles enter the intersection in a single lane after the queue start-up delay has been eliminated and while a continuous demand exists. Studies have indicated that a value of s = 0.50 is suitable for estimation purposes.

Effective green time, G, is estimated for this analysis as green time plus amber time. Other factors exist that could influence this value.

The expected average delay per vehicle, d, was computed for each approach. A volume distribution of 75 percent main street and 25 percent cross street was assumed. The G/C ratio was assumed to exactly match the volume distribution. That is, 75 percent of the total cycle time (C) was devoted to effective green time (G) on the main street, and 25 percent to the cross street. Calculations were performed for two different cycle lengths, 60 seconds and 40 seconds. Although a 60-second cycle is probably more common, it was felt that a 40-second cycle would be more representative at the low approach volumes (up to 10,000 ADT) since delay (d) is highly sensitive to cycle length at the volumes under consideration.

Finally, the term $\frac{"100-f_3"}{100}$ was omitted from the equation since it becomes negligible at low volumes (e.g., $f_3 = 3.0 \times 10^{-5}$).

Expected delays per vehicle for each approach (main street, cross street) were computed for peak and off-peak conditions. The results of these computations are shown in Tables 44, 45, 46, 47.

Total expected delay during the peak hours was computed by summing daily peak hour delays on the main street approaches and on the cross street approaches:

$$\text{Daily peak hour delay} = d_1 \times q_{m_1} \times 2 \times 3600 \times 4 + d_2 \times q_{c_2} \times 2 \times 3600 \times 4$$

where: d_1 = main street delay per vehicle (Table 44)

d_{m_1} = main street approach flow rate (Table 44)

2 - accounts for two approach legs

3600 - converts q to hourly flow

4 - accounts for four peak hours per day

d_2 = cross street delay per vehicle (Table 45)

q_{c_1} = cross street approach flow rate (Table 45)

Similarly, total off-peak delay per day was computed as:

$$\text{Daily off-peak delay} = d_3 \times q_{m_2} \times 2 \times 3600 \times 20 + d_4 \times q_{c_2} \times 2 \times 3600 \times 20$$

where: d_3 = main street delay per vehicle (Table 46)

q_{m_2} = main street approach flow rate (Table 46)

2 - accounts for two approach legs

3600 - converts q to hourly flow

20 - accounts for 20 off-peak hours per day

d_4 = cross street delay per vehicle (Table 47)

q_{c_2} = cross street approach flow rate (Table 47).

Table 44. Average Peak Hour Delay per Vehicle, Main Street

ADT	Approach Flow Rate q_{m_1} $(\frac{veh}{sec})$	Average Daily per Vehicle d_1 (sec) C = 60 G = 45 S = 0.5	C = 40 G = 30 S = 0.5
1,000	.00835	1.94	1.30
1,500	.0125	1.97	1.33
2,000	.01667	2.00	1.36
2,500	.02085	2.04	1.38
3,000	.025	2.07	1.41
3,500	.02915	2.10	1.44
4,000	.0333	2.14	1.47
4,500	.0375	2.18	1.50
5,000	.04165	2.21	1.53
5,500	.04585	2.25	1.56
6,000	.05	2.29	1.59
7,000	.05835	2.37	1.66
8,000	.0667	2.45	1.73
9,000	.075	2.54	1.80
10,000	.0833	2.63	1.88

Table 45. Average Peak Hour Delay per Vehicle, Cross Street

ADT	Approach Flow Rate q_{c_1} $(\frac{veh}{sec})$	Average Daily per Vehicle d_2 (sec) C = 60, G = 15, S = 0.5	Average Daily per Vehicle d_2 (sec) C = 40, G = 10, S = 0.5
1,000	.0027	17.05	11.39
1,500	.0042	17.16	11.48
2,000	.0056	17.25	11.57
2,500	.0069	17.34	11.64
3,000	.0083	17.44	11.72
3,500	.0097	17.55	11.81
4,000	.0111	17.67	11.90
4,500	.0125	17.75	11.98
5,000	.0139	17.86	12.07
5,500	.0153	17.97	12.16
6,000	.0167	18.07	12.26
7,000	.0194	18.29	12.44
8,000	.0222	18.52	12.64
9,000	.0250	18.76	12.84
10,000	.0278	19.01	13.06

Table 46. Average Off-Peak Delay per Vehicle, Main Street

ADT	Approach Flow Rate q_{m_2} $(\frac{veh}{sec})$	Average Daily per Vehicle d_3 (sec) C = 60 G = 45 S = 0.5	C = 40 G = 30 S = 0.5
1,000	.00355	1.90	1.27
1,500	.0053	1.91	1.28
2,000	.0071	1.93	1.29
2,500	.00885	1.94	1.30
3,000	.01065	1.95	1.32
3,500	.0124	1.97	1.33
4,000	.01415	1.98	1.34
4,500	.01595	2.00	1.35
5,000	.0177	2.01	1.36
5,500	.0195	2.02	1.37
6,000	.02125	2.04	1.39
7,000	.0248	2.07	1.41
8,000	.02835	2.10	1.43
9,000	.0319	2.13	1.46
10,000	.0354	2.16	1.48

Table 47. Average Off-Peak Delay per Vehicle, Cross Street

ADT	Approach Flow Rate $q_{c_2}\,(\frac{veh}{sec})$	Average Daily per Vehicle d_4 (sec) C = 60, G = 15, S = 0.5	C = 40, G = 10, S = 0.5
1,000	.0012	16.95	11.32
1,500	.0018	16.99	11.35
2,000	.0024	17.03	11.38
2,500	.0030	17.08	11.42
3,000	.0035	17.11	11.44
3,500	.0041	17.15	11.48
4,000	.0047	17.19	11.51
4,500	.0053	17.23	11.55
5,000	.0059	17.27	11.58
5,500	.0065	17.32	11.62
6,000	.0071	17.36	11.65
7,000	.0083	17.44	11.72
8,000	.0094	17.52	11.79
9,000	.0106	17.61	11.86
10,000	.0118	17.70	11.94

Total daily delay due to signalization was obtained by summing peak hour delays and off-peak delays. These values are shown in Table 48 for 60-second cycle lengths and in Table 49 for 40-second cycle lengths.

Additional Delay Costs Due to Signalization

As mentioned previously, Fleischer [20] separated the cost of delay into added vehicle operating costs and added road user time costs. Added vehicle operating costs were computed as follows:

$$C_1 = 0.4 + 0.07\ d,$$

where: C_1 = cost per vehicle in cents

d = expected delay per vehicle in seconds

These vehicle costs are shown in dollars per year for stop control and signal control in Table 50, columns A and D.

Added road user time costs are given by:

$$C_2 = .000783\ d,$$

where: C_2 = cost per vehicle in dollars

d = expected delay per vehicle in seconds

These user costs are summarized in dollars per year in Table 50, Columns B and E.

Total annual cost of delay for stop control and signal control are shown in columns C and F. The added delay cost due to signalization of a medium volume intersection are obtained by subtracting total delay costs due to stop control (column C) from total delay costs due to signalization (column F). These annual additional delay costs are shown in column J. These added annual costs must be compared to the expected safety benefits to be derived from signalization as an accident countermeasure to assess the true benefits of the countermeasure.

It should be noted that Fleischer's work was reported in 1969. Increases in fuel cost and road user time cost since that time will probably increase the total added cost of signalization.

Table 48. Expected Daily Delay in Seconds for Cycle Length = 60 Seconds

ADT	Peak				Off-Peak				Total Daily Delay (sec)
	Main St.		Cross St.		Main St.		Cross St.		
	d_1	Delay (sec)	d_2	Delay (sec)	d_3	Delay (sec)	d_4	Delay (sec)	
1,000	1.94	466	17.05	1,326	1.90	971	16.95	2,929	5,692
1,500	1.97	709	17.16	2,076	1.91	1,458	16.99	4,404	8,647
2,000	2.00	960	17.25	2,782	1.93	1,973	17.03	5,886	11,601
2,500	2.04	1,225	17.34	3,446	1.94	2,472	17.08	7,379	14,522
3,000	2.07	1,490	17.44	4,169	1.95	2,990	17.11	8,623	17,272
3,500	2.10	1,763	17.55	4,903	1.97	3,518	17.15	10,125	20,309
4,000	2.14	2,052	17.65	5,642	1.98	4,034	17.19	11,634	23,362
4,500	2.18	2,354	17.75	6,390	2.00	4,594	17.23	13,150	26,488
5,000	2.21	2,651	17.86	7,150	2.01	5,123	17.27	14,673	29,597
5,500	2.25	2,971	17.97	7,918	2.02	5,672	17.32	16,212	32,773
6,000	2.29	3,298	18.07	8,691	2.04	6,242	17.36	17,749	35,980
7,000	2.37	3,983	18.29	10,219	2.07	7,392	17.44	20,844	42,438
8,000	2.45	4,706	18.52	11,841	2.10	8,573	17.52	23,715	48,835
9,000	2.54	5,486	18.76	13,507	2.13	9,784	17.61	26,880	55,657
10,000	2.63	6,309	19.01	15,220	2.16	11,010	17.70	30,076	62,615

Table 49. Expected Daily Delay in Seconds for Cycle Length = 40 Seconds

ADT	Peak				Off-Peak				Total Daily Delay (sec)
	Main St.		Cross St.		Main St.		Cross St.		
	d_1	Delay (sec)	d_2	Delay (sec)	d_3	Delay (sec)	d_4	Delay (sec)	
1,000	1.30	313	11.39	886	1.27	649	11.32	1,956	3,804
1,500	1.33	479	11.48	1,389	1.28	977	11.35	2,942	5,787
2,000	1.36	623	11.57	1,866	1.29	1,319	11.38	3,933	7,741
2,500	1.38	829	11.64	2,313	1.30	1,657	11.42	4,933	9,732
3,000	1.41	1,015	11.72	2,802	1.32	2,024	11.44	5,766	11,607
3,500	1.44	1,209	11.81	3,299	1.33	2,375	11.48	6,778	13,661
4,000	1.47	1,410	11.90	3,804	1.34	2,730	11.51	7,790	15,734
4,500	1.50	1,620	11.98	4,313	1.35	3,101	11.55	8,815	17,849
5,000	1.53	1,835	12.07	4,832	1.36	3,466	11.58	9,838	19,971
5,500	1.56	2,060	12.16	5,358	1.37	3,847	11.62	10,876	22,141
6,000	1.59	2,290	12.26	5,897	1.39	4,253	11.65	11,911	24,351
7,000	1.66	2,790	12.44	6,950	1.41	5,035	11.72	14,008	28,783
8,000	1.73	3,323	12.64	8,082	1.43	5,838	11.79	15,959	33,202
9,000	1.80	3,888	12.84	9,245	1.46	6,707	11.86	18,103	37,943
10,000	1.88	4,510	13.06	10,456	1.48	7,544	11.94	20,288	42,798

Table 50. Difference in Annual Costs Due to Delay at Stop-Controlled and Signal-Controlled Intersections.

ADT	Stop Control Costs			Pre Timed Signal Costs*			Difference in Costs		
	Vehicle (c_1) Col. A	User Col. B	Total Col. C	Vehicle Col. D	User Col. E	Total Col. F	Vehicle Col. G	User Col. H	Total Col. J
1,000	1,860	448	2,308	2,432	1,087	3,519	572	639	1,211
1,500	2,812	696	3,508	3,669	1,654	5,323	857	958	1,815
2,000	3,767	948	4,715	4,898	2,212	7,110	1,131	1,264	2,395
2,500	4,726	1,204	5,930	6,136	2,781	8,917	1,410	1,577	2,987
3,000	5,679	1,453	7,132	7,346	3,317	10,663	1,667	1,864	3,531
3,500	6,663	1,737	8,400	8,600	3,904	12,504	1,937	2,167	4,104
4,000	7,662	2,038	9,700	9,860	4,497	14,357	2,198	2,459	4,657
4,500	8,679	2,359	11,038	11,130	5,101	16,231	2,451	2,742	5,193
5,000	9,706	2,691	12,397	12,403	5,708	18,111	2,697	3,017	5,714
5,500	10,745	3,037	13,782	13,687	6,328	20,015	2,942	3,291	6,233
6,000	11,809	3,410	15,219	14,982	6,959	21,941	3,173	3,549	6,722
7,000	13,982	4,208	18,190	17,574	8,226	25,800	3,592	4,018	7,610
8,000	16,219	5,078	21,297	20,163	9,489	29,652	3,944	4,411	8,355
9,000	18,596	6,103	24,699	22,834	10,844	33,678	4,238	4,741	8,974
10,000	21,118	7,291	28,409	25,535	12,231	37,766	4,417	4,940	9,357

*Based on 40-second cycle length.

The actual benefits to be derived from the employment of signalization must consider not only the safety benefits, but also the added delay cost to the road user. Table 51 presents the computation of actual benefits over the service life for hypothetical projects 16-22. Total delay cost over the service life (column F) is the product of service life (10 years) and average annual delay cost (column E). Expected accident reduction benefits over the service life (column G) was computed from accident reduction benefits estimated in each project and from DOT accident costs (see page 63 of Task A Technical Report [1]). Column H shows the difference between column G and column F.

Table 51. Reduction in Countermeasure Benefits Due to Additional Delay Cost of Signalization

Project	Present ADT	Present Annual Delay Cost[1]	Terminal Year ADT	Terminal Year Annual Delay Cost[1]	Average Annual Delay Cost	Total Delay Cost over Service Life	Expected Accident Reduction Benefit[2]	Total Actual Benefit
	Column A	Column B	Column C	Column D	Column E	Column F	Column G	Column H
16	$8,000	$8,355	$10,000	$9,357	$8,856	$88,560	$289,106	$200,546
17	4,000	4,657	5,000	5,714	5,186	51,860	704,033	652,173
18	5,000	5,714	5,500	6,233	5,974	59,740	1,058,066	998,326
19	3,000	3,531	3,500	4,104	3,818	38,180	285,861	247,681
20	2,000	2,395	5,000	5,714	4,055	40,550	293,876	253,326
21	1,500	1,815	4,500	5,193	3,504	35,040	203,607	168,567
22	1,000	1,211	3,500	4,104	2,658	26,580	418,164	391,584

Notes:

[1] From Table 50.

[2] From Project data and DOT Accident Costs.

XIV. RECOMMENDED COST-EFFECTIVENESS TECHNIQUES

Review of theoretical models for cost-effectiveness and of procedures currently being used by different levels of government to evaluate safety alternatives was the basis for concluding that a technique using benefits and costs would be the best, most implementable cost-effectiveness technique to develop in this study. The principal benefit of safety projects, as might be expected, is reduction in accidents. Therefore, the principal needs are (1) to develop improved procedures for estimating the accident reduction potential of projects, (2) to put weights on different types of accidents, and (3) to have a cost-effectiveness technique for selecting the alternatives that reduce weighted accidents by the largest amount for a given expenditure of safety funds. This chapter discusses the best methods for meeting the third of these needs.

Recommended Techniques

If only one alternative is considered at each accident location, then simple benefit-cost ratios can be used to rank alternative safety projects. It is the recommendation in this study, however, as discussed in Chapter XI, that several alternatives be considered at most accident locations. If this recommendation is followed, simple benefit-cost ratios cannot be used to select the optimal set of projects and locations. There are three other techniques, however, that can be used to select the "optimal" set of projects. Each of these techniques is superior to simple benefit-cost ratios.

Typically, a state would identify a large number of potential locations, say 100 to 1000 locations per time period, e.g., annually or quarterly. Several alternative countermeasures would be identified for each location and the expected benefits and costs would be calculated for each of these alternatives. Benefits normally would be calculated for the first year and the terminal year for each alternative. If benefits (accident cost reduction) are assumed to vary directly with traffic volume, then terminal year benefits would equal first-year benefits multiplied by the ratio of forecasted terminal year traffic to first-year traffic. Using either a nomograph or formula (see p. 13), the present worth of benefits expected during the service life of the project can easily be calculated. Similarly, the present worth of future maintenance and operating costs can easily be calculated by multiplying a uniform series present worth factor (for the given service life and discount rate) by the annual maintenance and operating cost. By adding this present value of future costs to the initial cost of the alternative, the present worth of all project costs is obtained.

Given the present worth of future benefits, the present worth of future maintenance and operating costs, and the initial project cost, any one of three methods can be used to determine which locations should be improved and the alternative that should be used at that location. These methods are: (1) dynamic programming algorithm, (2) integer programming algorithm, and (3) incremental benefit-cost analysis, with improved algorithm.

Dynamic Programming

Only one technique was identified in this study as being currently used to evaluate large numbers of locations having mutually exclusive (nonindependent) safety projects. This technique was dynamic programming as used in Alabama and Kentucky, which was discussed in Chapter V. Their use of this technique, together with specifying several alternative countermeasures at each high-accident location, has been shown to result in the unambiguous choice of projects which gives more expected benefits for a given safety budget than would the use of simple benefit-cost ratios. (It should be recognized, however, that their comparisons are between dynamic programming and use of *simple* benefit-cost ratios, not *incremental* benefit-cost ratios, as discussed more fully in a later section). The only constraints that may keep a dynamic programming solution from being the best possible solution for a fixed budget are: (1) the budget must be divided into discrete increments to be considered in the dynamic programming algorithm, and (2) project costs must be rounded to this same increment or some multiple of this increment. Even though this increment can be made quite small, calculation time increases substantially as the increment is made smaller, if there are many alternatives. Even though this usually can be considered to be an inconsequential problem, it is worth noting.

Although it is recommended that slight changes be made in the formulation of the objective functions used by Alabama and Kentucky, the basic procedure used in each state is superior to other procedures currently being used. Alabama's objective function is to maximize the present worth of future benefits subject to a constraint on initial cost. Kentucky's formulation is to maximize the present worth of future benefits subject to present worth of all costs.

There are two alternative formulations that are superior to those of Alabama and Kentucky. First, if the objective is to allocate a fixed initial cost budget, it is recommended that the objective function be to maximize the present worth of future benefits less present worth of future costs subject to a constraint on initial cost. Another formulation, which is consistent with all costs being the relevant constraint but recognizes that a fixed initial cost budget is being allocated, is to maximize the present worth of future benefits less initial cost and present worth of future costs, subject to a constraint on initial cost.

Integer Programming

A method that represents an alternative to dynamic programming is integer programming. Integer programming gives answers similar to dynamic programming but has two relative advantages. First, since integer programming does not entail considering the fixed budget in discrete increments and does not require rounding of (constrained) project costs, the solution sometimes will be superior to that given by dynamic programming, and hence, gives the best possible solution for a fixed budget. The second advantage is that integer programming usually requires less computer time.

Although integer programming has not been used to evaluate safety projects, enough evaluation was made in this study to determine that implementation of this method would be relatively easy and straightforward.

Incremental Benefit-Cost Algorithm

Incremental benefit-cost analysis, with use of an improved solution algorithm which was developed on this project, offers a viable alternative to either of the above methods. This method can be used to array projects in an order such that no preferable ordering of projects can be obtained for the same cumulative cost. This method gives approximately the same choice of projects as does either dynamic or integer programming in many cases. Usually, the only difference would be the difference in the choice of the marginal projects within a budget. Since, in practice, a safety budget usually is not absolutely fixed for any given time period, it is believed that the difference in choice of projects given by this method and the other two methods is more a theoretical curiosum than a practical problem. The incremental benefit-cost method has the advantage of ranking, from best to worst, all increments of expenditures, instead of specifying the best group of projects for a given budget. It is believed that the improved algorithm for incremental benefit-cost analysis which was developed in this project is superior to previous formulations of benefit-cost analysis in two respects. First, it outlines an efficient way of ranking increments of expenditure for mutually exclusive (nonindependent) alternatives for a large number of projects. Second, and perhaps the more unique aspect of the algorithm, a clear method is given for averaging successive increments of expenditure, at a specific location, whenever any increment of expenditure at a location gives a higher increment benefit-cost ratio than the next least costly increment (or, in some cases, combinations of increments). This algorithm is outlined below.

Let: A_{ij} = alternative project j at location i,

C_{ij} = present value of current and future costs of A_{ij},

$MC_{ij} = C_{ij} - C_{i,j-1}$, the marginal or incremental cost of A_{ij},

B_{ij} = present value of current and future benefits of A_{ij},

$MB_{ij} = B_{ij} - B_{i,j-1}$, the marginal or incremental benefit of A_{ij},

$R_{ij} = MB_{ij}/MC_{ij}$, the marginal benefit-cost ratio of A_{ij}, and

$i = 1, 2, \ldots m$; $j = 1, 2, \ldots n$.

The steps in the algorithm are as follows:

1. For each location i, array the A_{ij} in increasing order of C_{ij}.
2. Calculate R_{ij} for each A_{ij}.
3. For each location i, delete from the array any A_{ij} for which $R_{ij} \leq 1$. If A_{ij} is deleted, then recompute $R_{i,j+1}$ using $B_{i,j-1}$, $C_{i,j-1}$, $B_{i,j+1}$, and $C_{i,j+1}$. Renumber all A_{ij} in location i, so that there are no "missing" j values.
4. For each location i, compare R_{i1} to R_{i2}. If R_{i2} is greater than R_{i1}, then combine these two increments to form the marginal benefit-cost ratio $R^*_{i2} = (MB_{i1} + MB_{i2})/(MC_{i1} + MC_{i2}) = MB^*_{i2}/MC^*_{i2}$. Leave A_{i1} in the array, in case budget limitations exclude A_{i2} from selection but allow A_{i1}. Then compare R^*_{i2} to R_{i3}; if R_{i3} is greater than R^*_{i2}, then combine increments to form $R^*_{i3} = (MB_{i1} + MB_{i2} + MB_{i3})/(MC_{i1} + MC_{i2} + MC_{i3}) = MB^*_{i3}/MC^*_{i3}$. Leave A_{i2} in the array as before. If any R_{il} is less than $R_{i,l-1}$ (or $R^*_{i,l-1}$) but R_{il} must be combined with $R_{i,l+1}$ to form $R^*_{i,l+1} = (MB_{il} + MB_{i,i+1})/MC_{il} + MC_{i,i+1}) = MB^*_{i,l+1}/MC^*_{i,l+1}$, then compare $R^*_{i,l+1}$ to $R_{i,l-1}$ (or $R^*_{i,l-1}$). If $R^*_{i,l+1}$ is greater than $R_{i,l-1}$ (or $R^*_{i,l-1}$), then combine increments to form $R^{**}_{i,l+1} = (MB^*_{i,l-1} + MB^*_{i,l+1})/(MC^*_{i,l-1} + MC^*_{i,l+1}) = MB^{**}_{i,l+1}/MC^{**}_{i,l+1}$.

   Continue this combination procedure as long as an R_{il} (or R^*_{il}, etc.) is greater than the immediately preceding incremental ratio ($R_{i,l-1}$, $R^*_{i,l-1}$, etc.). This procedure yields an "average" benefit-cost ratio and is requisite in the case of increasing R_{ij} values, since benefits from a given increment of expenditure cannot be realized unless previous increments are spent.

   If any R_{il} (or R^*_{il}, etc.) is less than the relevant preceding increment, then no combination is necessary.
5. Arrange all alternatives, along with their relevant corresponding marginal costs (MC_{ij}, MC^*_{ij}, etc.), in decreasing order of their relevant (R_{ij}, R^*_{ij}, etc.) incremental benefit-cost ratios.
6. Choose alternatives in order from highest to lowest incremental benefit-cost ratios, accumulating corresponding marginal costs, to determine which alternatives to include in the budget. If

some A_{ij} cannot be accepted without exceeding the budget limit, then exclude that A_{ij} from consideration and proceed until another alternative or alternatives can be accepted. Selection ends when no more alternatives can be added without exceeding the budget limit.

This algorithm ensures that the optimal set of projects will be chosen for any cumulative cost calculated in Step 6. It is superior to any algorithm based simply on simple (nonincremental) benefit-cost ratios because it allows for inclusion of those increments of expenditure that are above the ratio-maximizing level at specific locations but that give incremental benefit-cost ratios larger than the maximum ratio at other locations. This is precisely the same reason that dynamic programming and integer programming techniques give greater benefits than the simple benefit-cost ratio method. It also allows for simultaneous determination of preferred locations and preferred expenditures at those chosen locations.

It should be noted, however, that, if a fixed budget is allocated such that any funds not spent on one or more alternatives cannot be reallocated to a different use, then this algorithm may not select that set of projects yielding maximum benefits for the allocated budget. This is because having left-over funds that cannot be used elsewhere is equivalent to selecting a project A_{ij} with MC_{ij} equal to the amount of the left-over funds and MB_{ij} equal to zero, so that R_{ij} is equal to zero. In such a situation, total benefits could possibly be increased by dropping a selected alternative or alternatives and including a previously unselected alternative or group of alternatives that would result in fewer surplus funds. In any real-world situation, this problem would probably not arise or at least not be serious, so that the total benefits obtained by using this incremental benefit-cost algorithm would be approximately equal to the total benefits obtained from the set of projects selected, given a budget level, by a dynamic programming procedure.

It should be emphasized that the principal reason this algorithm will not necessarily give the best possible solution *for a fixed budget* is related to the last part of Step 6 above, which states that if some alternative A_{ij} (which would be, in a sense, the first submarginal alternative) cannot be accepted without exceeding the budget limit, then exclude that A_{ij} from consideration and proceed until another alternative or alternatives (further down the array) can be accepted. The reason dynamic or integer programming may give a better solution for a fixed budget is that these methods always consider the possibility of including the above submarginal alternative A_{ij}, *even if it necessitates dropping from the budget alternatives that are higher in the array.*

Types of situations in which the above consideration becomes especially important are those where alternatives (especially the alternatives that are near the budget cutoff level) vary considerably in cost, are quite large relative to the size of the budget, and have widely varying incremental benefit-cost ratios. (In the extreme case where all expenditure increments are exactly the same size, this incremental benefit-cost algorithm always will provide the best possible solution. At the other extreme, it is possible to work out examples where the best possible solution is to include the above "submarginal A_{ij}" and drop all other alternatives from the solution).

Since most safety budgets are usually large relative to the cost of any one alternative, and since states should consider a large number of alternatives, it is the conclusion of this study that the problem of selecting the proper marginal projects within a fixed budget is not an important problem. At a minimum, the magnitude of this problem is offset by the advantage of having a ranking of increments of expenditure from best to worst with one pass through the algorithm.

Two other points are worth mentioning. First, even if the "submarginal alternative" is not included in the fixed budget for a particular time period, there is always the possibility, as pointed out in the revised Red Book [13], of including the alternative in the budget for the next time period or of partially funding the alternative during the first time period and completing the alternative within the next time period's budget. At most, the loss would be the difference in benefits *for one time period.*

The second point to be made is that examination by a trained analyst of the marginal projects within a budget often will immediately show whether benefits can be increased by adding the "submarginal A_{ij}" and dropping other alternatives from the solution. In cases where this "submarginal A_{ij}" is large relative to other projects with higher incremental benefit-cost ratios, such simple solution is not possible. It should be emphasized, however, that rules such as those provided by dynamic programming or integer programming are necessary to ensure finding the best solution for all types of possibilities *with fixed budgets*.

Although this incremental benefit-cost algorithm is relatively straightforward, there are numerous arithmetic calculations and checks that should be made in large problems. Also, for a large number of alternatives, arraying alternatives for different budget levels is a tedious process. For these reasons, the algorithm should be computerized. Special attention should be given to providing output in an easy to understand format. It also would be desirable to input information such that an estimate of number of lives saved and injuries avoided could be output along with dollar benefits. It also might be desirable to output future costs by year.

Benefit-Cost Analysis vs. Dynamic Programming

Kentucky and Alabama use estimates of benefits and costs together with dynamic programming to allocate highway safety funds. In reports [51, 52] describing each of these systems, it is maintained that dynamic programming gives a solution with greater net benefits than the benefit-cost method and that an optimal allocation of funds will always be obtained if the individual project costs are multiples of the increment used in dynamic programming.

These comparisons can be somewhat misleading to anyone not familiar with both techniques. While the comparisons are correct as far as they go, it should be recognized that they are comparing dynamic programming with the simple benefit-cost ratio method, not with the *incremental* benefit-cost ratio method. When properly used, the incremental benefit-cost ratio method: (1) is generally capable of reaching solutions that are comparable to those given by the dynamic programming method, (2) gives the optimal allocation of funds for cumulative project costs *without* the constraining condition that individual project costs be multiples of the increment used in dynamic programming, and (3) can be used to solve for the optimal solution for cumulative budget cost with only one pass through the solution algorithm. As emphasized previously, however, dynamic and integer programming are better methods for solving precisely the fixed budget problem; the question raised above was whether this was the problem that must be solved in determining the best mix of safety projects during any time period. This conclusion regarding benefit-cost analysis disagrees with several previous assessments, those of Brown [51, 198], Pigman [52], and Fleischer [22, 23], apparently because they did not have an algorithm similar to that proposed in this study.

Even though the preceding discussion has noted the differences among dynamic programming, integer programming, and incremental benefit-cost, it should be emphasized that *all three techniques give similar answers, and all three techniques are superior to use of simple benefit-cost ratios.* Moreover, any of these methods can be used to maximize any uni-dimensional number for a safety program. Even though it is recommended, and has been assumed, that net benefits in dollar terms are being maximized, it would have been possible to use reductions in deaths, fatal accidents, fatal plus injury accidents, all accidents, weighted accidents, etc., as the number being maximized.

Comparison of Methods

An example problem is presented below for purposes of comparing four methods of solving the problem of allocating a fixed budget. These four methods are: (1) simple benefit-cost ratios, (2) incremental benefit-cost ratios, (3) dynamic programming, and (4) integer programming.

Simple Benefit-Cost Ratios

The most commonly used procedure for comparing safety alternatives is the use of simple benefit-cost ratios. The following steps are used in this procedure:

1. Calculate the ratio of benefits to costs for each alternative at each location.

2. Select the alternative with the highest benefit-cost ratio at each location and array these alternatives in order of decreasing benefit-cost ratios.
3. Beginning with the highest B/C ratio, select alternatives until the available budget is exhausted.

For example, consider the following set of projects recommended for consideration at four different locations assuming that the budget is $9,000.

Location	Alternative	Benefit	Cost	B/C Ratio
I	I-A	40,000	11,000	3.64
	I-B	32,000	9,000	3.56
	I-C	10,000	2,500	4.00
II	II-A	35,000	5,200	6.73
	II-B	20,000	3,010	6.64
III	III-A	10,000	1,000	10.00
	III-B	30,000	4,600	6.52
IV	IV-A	5,000	490	10.20
	IV-B	12,000	1,200	10.00

Following step two results in the following list of chosen alternatives:

Location	Alternative	B/C Ratio	Cost	Cumulative Cost
IV	A	10.20	490	490
III	A	10.00	1,000	1,490
II	A	6.73	5,200	6,690
I	C	4.00	2,500	9,190

With the budget of $9,000, the locations and alternatives chosen would be IV A, III A, and II A with associated benefit of $50,000 and unexpended funds of $2,310.

Incremental Benefit-Cost

Using the same example as before and following the first five steps of the improved incremental benefit-cost algorithm outlined previously gives the following listing:

Loc./Alt.	Cost	Benefit	Incremental Cost (ΔC)	Incremental Benefit (ΔB)	$^{\Delta B}/_{\Delta C}$
I-B	2,500	10,000	2,500	10,000	4.00
I-C	9,000	32,000	6,500	22,000	3.38
I-A	11,000	40,000	2,000	8,000	4.00 (3.53)
II-B	3,010	20,000	3,010	20,000	6.64
II-A	5,200	35,000	2,190	15,000	6.85 (6.73)
III-A	1,000	10,00	1,000	10,000	10.00
III-B	4,600	30,000	3,600	20,000	5.56
IV-A	490	5,000	490	5,000	10.20
IV-B	1,200	12,000	710	7,000	9.86

The last column gives incremental benefit-cost ratios. In two cases, the incremental benefit-cost ratio of a more costly alternative was higher than the next lower alternative. The first case is I-A with an incremental B/C ratio of 4.0 which is higher than the 3.38 of I-C; therefore, these increments are combined for an average incremental benefit-cost ratio of 3.53, which is shown in parentheses and is the ratio used for ranking this combined increment. Similarly, II-A and II-B are combined to give a ratio of 6.73.

Following Step 5 of the algorithm produces the following ranking:

Loc./Alt.	Incremental Cost	$^{\Delta B}/_{\Delta C}$	Cumulative Cost
IV-A	490	10.20	490
III-A	1,000	10.00	1,490
IV-B	710	9.86	2,200
II-A	5,200	6.73	7,400
II-B*	3,010*	6.64*	*
III-B	3,600	5.56	11,000
I-B	2,500	4.00	13,500
I-A	8,500	3.53	22,000
I-C*	6,500*	3.38*	*

Note that the table contains the two averaged entries II-A (which is a combination of the II-B and II-A increments) and I-A (combination of I-C and I-A). The lower cost parts of these averaged increments have been included in the array with stars, II-B* and I-C*. These increments actually are already included in the array since they are averaged in with II-A and I-A. They are included with stars to signify that they are not added separately in cumulative cost and will only be included in the budget if the budget is insufficient to include the more costly, averaged increments that include them. For example, II-B would be included only if there were not enough funds for II-A but were enough for II-B*, i.e., a budget equal to or greater than $5,210 but less than $7,400.

For the budget of $9,000, the optimum incremental benefit-cost solution is derived by first noting that expenditure increments IV-A, III-A, IV-B, and II-A have a cumulative cost of $7,400, but with the next increment, III-B, the budget is exceeded by $2,000. Since there are no increments further down the list that cost $1,600 or less, the solution as outlined in the algorithm is complete. The alternatives included in the solution are III-A, IV-B, and II-A with a total cost of $7,400, total benefits of $57,000, and unexpended funds of $1,600.

The experienced analyst sometimes can make small changes at the margin and improve the solution given by the algorithm as outlined. For example, it is fairly easy to note that II-A can be omitted from the solution which allows II-B* and III-B to enter the solution. This gives the solution of IV-B, II-B*, and III-B with total cost of $8,810, total benefit of $62,000 and unexpended budget of only $190. This solution is in fact the very best solution, as is noted later in the discussion of integer programming. Even though this substitution may seem somewhat "tricky," the same type of simple substitution often will work even for problems with very large numbers of projects. However, progression to the optimum fixed-budget solution is not always this easy, and even then the analyst is not certain that the optimum fixed budget solution has been reached.

The point that was emphasized several times previously with respect to the incremental benefit-cost algorithm giving the best solution for a given cumulative cost can be illustrated with reference to the last column, "cumulative cost." It is not possible to get a better solution for $490 than IV-A; for $1,490 than IV-A and III-A; for $2,200 than III-A and IV-B; for $7,400 than III-A, IV-B, and II-A; for $11,000 than IV-B, II-A, and III-B; and so forth. Thus, even though the incremental benefit-cost algorithm does not assure selection of the best projects for a fixed budget, it does assure the best ranking and the best solution for the cumulative cost of increments of expenditure.

Dynamic Programming

Dynamic programming is a recursive optimization procedure popularized by Richard Bellman [77] which breaks down an optimization problem in N decision variables into a series of N independent single variable optimizations. It is based upon what is known as the Principle of Optimality.

The optimal set of decisions in a sequential decision process has the property that whatever the initial budget level, decision point, and decisions are up to that point, the remaining decisions constitute an optimal sequence of decisions for the remaining problem. The Principle of Optimality is best explained through use of the example used previously.

Consider what would happen if decisions had already been made at locations IV, III, and II, and decisions at location I were to be examined. Further, assume that no information was available concerning those previous decisions. Using the Principle of Optimality, one would consider the set of feasible decisions given a dollar budget available at that time. Since all money could have been, or none might have been spent, decisions must be determined over this range. Further, an increment of $1,000 will be chosen for this process. Define the following notation consistent with conventional dynamic programming terminology:

Let: Stage 1 = Location I

S_1 = Available Budget

d_1 = Set of Alternatives

$r_1(S_1,d_1)$ = The Benefit (return) associated with decision d_1 at budget level S_1

$d_1{*}$ = The Optimal Decision (that which yields the maximum return)

$f_1{*}(S_1)$ = The Maximum Return for a given budget level S_1

Hence; $f_1{*}(S_1) = \max\limits_{d_1} \{r_1(S_1,d_1)\}$

This is best determined in a tabular fashion. Each entry in the table is the return associated with each S_1/d_1 combination. Note that decision 1.4 has been added and represents "do nothing."

	$S_1 \backslash d_1$	1.1	1.2	1.3	1.4	$d_1{*}$	$f_1{*}(S_1)$
	0	—	—	—	0	1.4	0
STAGE I	1,000	—	—	—	0	1.4	0
	2,000	—	—	—	0	1.4	0
	3,000	—	—	10,000	0	1.3	10,000
	4,000	—	—	10,000	0	1.3	10,000
	5,000	—	—	10,000	0	1.3	10,000
	6,000	—	—	10,000	0	1.3	10,000
	7,000	—	—	10,000	0	1.3	10,000
	8,000	—	—	10,000	0	1.3	10,000
	9,000	—	32,000	10,000	0	1.2	32,000

Note that:

1. The maximum budget is $9,000
2. Some decisions are not possible because they cost more than available budget
3. There are ten possible budget levels using a $1,000 increment
4. "Do nothing" carries a return of "zero" dollars

For example, if all $9,000 is still available at this point, then decisions 1.2, 1.3, and 1.4 are feasible with returns of $32,000, $10,000, and $0 respectively. Decision 1.1 is not feasible (it costs $11,000). If $9,000 is available, then decision 1.2 is optimal with a return (benefit) of $32,000. Similar logic leads to $d_1{*}$ and $f_1{*}(S_1)$ for each possible (available) budget.

Now, suppose we extend this logic and assume that location II is being considered. Again, the amount of money spent at locations III and IV is unknown, so an optimal decision must be determined for each increment of budget from $0 to $9,000.

Define: Stage 2 = Location II

S_2 = Available Budget

d_2 = Set of Alternatives

$r_2(S_2,d_2)$ = The Benefit (return) associated with decision d_2 at budget level S_2

d_2^* = The Optimal Decision

$f_2^*(S_2)$ = The Optimal Return

Note that at this stage:

$$f_2^*(S_2) = \max_{d_2} \{r_2(S_2,d_2)\} + f_1^*(S_1)$$

But S_1 is the amount of money left for Stage 1 (Location I) *after* money at Stage 2 (Location II) has been spent. This amount is determined by:

$$C(S_2,d_2) = S_2 - \{\text{Cost of Decision } d_2\}$$

Hence,

$$f_2^*(S_2) = \max_{d_2} \{r(S_2,d_2) + f_1^*(C_2(S_2,d_2))\}$$

Note that once a decision d_2 has been considered at budget level S_2, $f_1^*(S_1) = f_1^*(C_2(S_2,d_2))$ is already known from the Stage 1 analysis for $1,000 budget increments. The calculations are again summarized in tabular form.

S_2 \ d_2	2.1	2.2	2.3	d_2^*	$f_2^*(S_2)$
0	—	—	0	2.3	0
1,000	—	—	0	2.3	0
2,000	—	—	0	2.3	0
3,000	—	—	10,000	2.3	10,000
4,000	—	20,000	10,000	2.2	20,000
5,000	—	20,000	10,000	2.2	20,000
6,000	35,000	20,000	10,000	2.1	35,000
7,000	35,000	30,000	10,000	2.1	35,000
8,000	35,000	30,000	10,000	2.1	35,000
9,000	45,000	30,000	32,000	2.1	45,000

For example, consider an available budget of \$9,000. If one chooses alternative 2.1, then this costs \$5,200 and leaves \$3,800 for Stage 1. However, with \$1,000 increments one must use the lower increment figure of \$3,000. From the Stage 1 analysis at S_1 = \$3,000, one can obtain $f_1^*(S_1) = f_1^*(3000)$ = \$10,000. This yields a total benefit of \$35,000 (2.1) plus \$10,000 (1.3) = \$45,000. The other alternatives are calculated in the same manner. This calculation illustrates the role of the state variable increments on dynamic programming calculations. This role will be reviewed later in greater detail. For now, observe the following general formulation for the optimal return at Stage n.

$$f_n^*(S_n) = \max_{d_n} \{r_n(S_n,d_n) + f_{n-1}^*(S_{n-1})\}$$

$$S_{n-1} = S_n - \text{Cost of } d_n$$

Using this notation we proceed with Stage 3 (Location III):

S_3 \ d_3	3.1	3.2	3.3	d_3*	$f_3^*(S_3)$
0	—	—	0	3.3	0
1,000	10,000	—	0	3.1	10,000
2,000	10,000	—	0	3.1	10,000
3,000	10,000	—	10,000	3.1,3.3	10,000
4,000	20,000	—	20,000	3.1,3.3	20,000
5,000	30,000	30,000	20,000	3.1,3.2	30,000
6,000	30,000	30,000	35,000	3.3	35,000
7,000	45,000	30,000	35,000	3.1	45,000
8,000	45,000	40,000	35,000	3.1	45,000
9,000	45,000	50,000	45,000	3.2	50,000

At Stage 4 (Location IV) the budget level is known to be \$9,000. This simplifies the calculations to a single line.

S_4 \ d_4	4.1	4.2	4.3	d_4*	f_4*(S_4)
9,000	50,000	57,000	50,000	4.2	57,000

The optimal dynamic programming return is now known to be \$57,000. The sequence of decisions is recovered by working backwards through each stage. At Stage 4; the optimal decision is 4.2; this costs \$1,200 and leaves \$7,800. Hence, Stage 3 is entered at a level of \$7,000 due to the \$1,000 increments. This yields an optimal decision of 3.1; this costs \$1,000 and leaves \$6,000. At Stage 2 with S_2 = \$6,000, the optimal decision is 2.1 and costs \$5,200. This leaves \$800 and sets S_1 = 0. The only feasible decision is d_1* = 0 ("do nothing"). The results are as follows:

Optimal Decision	Benefit	Cost
1.4	0	0
2.1	35,000	5,200
3.1	10,000	1,000
4.2	12,000	1,200
	\$57,000	\$7,400

Excess budget: \$9,000 - \$7,400 =\$1,600

The dynamic programming procedure used by Alabama and Kentucky follows this same procedure, with different schemes for computing the benefit of each alternative. The procedure is computerized, and the budget at stage (n-1) is determined from the decision and budget at stage n by the following:

IST = Budget level at stage n-1

$$XIN = \text{Budget level at stage n}$$
$$CDEC = \text{Cost of decision dn at stage n}$$
$$XINC = \text{Budget increment}$$

The computerized procedure defines IST as follows:

$$IST = \text{The integer root of} \left[\frac{XIN - CDEC}{XINC} + 1.5 \right]$$

For example, suppose we are considering a budget level of $9,000. The first increment will be zero, the second $1000, and the tenth $9,000 (XINC = 1000). Suppose that an alternative costs $2000 at stage n. Hence, the available budget at stage n-1 will be:

$$IST = \text{the integer root of} \left[\frac{9000 - 2000}{1000} + 1.5 \right]$$

or

$$IST = [7.0 + 1.5] = [8.5]$$

Hence, IST = 8.0 (the integer root of 8.5)

This implies a budget of $7,000 which is correct. However, suppose that the alternative cost is only $1,800 in this case; IST = [8.7] = 8.0. Indeed, the correct value is IST = 8.0 for any expenditure greater than or equal to $1,500. However, consider $1,400. In this case:

$$IST = \left[\frac{9000 - 1400}{1000} + 1.5 \right] = [9.1]$$

Hence, IST = 9.0

This implies that for an expenditure of $1,400 from $9,000 there is still $8,000 left. This is obviously not true. In fact, for any expenditure between $1,000 and $1,500, the same result will (erroneously) occur. However, this is what is currently being used in both algorithms. Several comments are in order:

1. If the expenditures and budget increments are in the same units, the procedure is always correct (there is no rounding error).

2. If the factional cost of all alternatives are over 50% of the budget increment, the procedure will always be conservative (underspend the budget).
3. If the factional cost of all alternatives are under 50% of the budget increment, the procedure will always overspend the budget.
4. If there is a mixture of the above cases, the effects may balance each other out, but optimality might still not be achieved.

One can verify that the example which was previously solved used the following formula:

$$IST = \left\lfloor \frac{XIN - CDEC}{XINC} + 1.0 \right\rfloor$$

This is a conservative approach - correct from stage to stage - but it might considerably underutilize the budget. Consider the same example using the Alabama/Kentucky dynamic programming code:

$$IST = \left\lfloor \frac{XIN - CDEC}{XINC} + 1.5 \right\rfloor$$

The following tables and results would be generated:

Stage 1
(Location IV)

S_1 \ d_1	1.1	1.2	1.3	1.4	d_1*	$f_1*(S_1)$
0	—	—	—	0	1.4	0
1,000	—	—	—	0	1.4	0
2,000	—	—	—	0	1.4	0
3,000	—	—	10,000	0	1.3	10,000
4,000	—	—	10,000	0	1.3	10,000
5,000	—	—	10,000	0	1.3	10,000
6,000	—	—	10,000	0	1.3	10,000
7,000	—	—	10,000	0	1.3	10,000
8,000	—	—	10,000	0	1.3	10,000
9,000	—	32,000	10,000	0	1.2	32,000

Stage 2
(Location III)

S_2 \ d_2	2.1	2.2	2.3	d_2*	$f_2*(S_2)$
0	—	—	0	2.3	0
1,000	—	—	0	2.3	0
2,000	—	—	0	2.3	0
3,000	—	—	10,000	2.3	10,000
4,000	—	20,000	10,000	2.2	20,000
5,000	—	20,000	10,000	2.2	20,000
6,000	35,000	30,000	10,000	2.1	35,000
7,000	35,000	30,000	10,000	2.1	35,000
8,000	34,000	30,000	10,000	2.1	45,000
9,000	45,000	30,000	30,000	2.1	45,000

Stage 3
(Location II)

S_3 \ d_3	3.1	3.2	3.3	d_3^*	$f_3^*(S_3)$
0	—	—	0	3.3	0
1,000	10,000	—	0	3.1	10,000
2,000	10,000	—	0	3.1	10,000
3,000	10,000	—	10,000	3.1,3.3	10,000
4,000	20,000	—	20,000	3.1,3.3	20,000
5,000	30,000	30,000	20,000	3.1,3.2	30,000
6,000	30,000	30,000	35,000	3.3	35,000
7,000	45,000	30,000	35,000	3.1	45,000
8,000	45,000	40,000	45,000	3.1,3.3	45,000
9,000	55,000	50,000	45,000	3.1	55,000

Stage 4
(Location I)

S_4 \ d_4	4.1	4.2	4.3	d_4^*	$f_4^*(S_4)$
9,000	60,000	57,000	55,000	4.1	60,000

The optimal solution produced by dynamic programming using the Alabama/Kentucky factor of 1.5 is:

Alternative	Cost	Benefit
4.1	490	5,000
3.1	1,000	10,000
2.1	5,200	35,000
1.3	2,500	10,000
	$9,690	$60,000

Note that, using this dynamic programming approach, the budget of \$9,000 will be *exceeded* by \$690. This is obviously an *infeasible* solution. The result of infeasibility is due to the fact that budget increments did not coincide with increments of expenditures. However, depending upon the frequency and amounts of non-incremental costs, the budget may not be exceeded.

The problem is obviously one of scale, but it is a critical one. For example, if project costs are in hundreds of dollars, and the maximum budget is \$50,000, one would have to use 500 state variable increments at each stage to guarantee optimality. If costs were in dollars and cents, then 5,000,000 increments would be needed at each stage. The problem can, of course, be overcome by appropriate rounding of costs consistent with allowable budget increments. The next section will discuss a technique which avoids all these problems.

Integer Programming Algorithm

Another method for solving the capital budgeting problem is the use of a modified 0-1 knapsack algorithm developed by Robert M. Nauss [199]. In general, this problem concerns choosing the best combination of variables from the total solution set to maximize the total benefit associated with the variables, while acting under a resource constraint. The problem is stated as follows:

$$\max \sum_{j=1}^{J} b_i X_{ij}$$

$$\text{s.t.} \sum_{i=i}^{n} C_i X_i \leq B$$

$$\sum_{k=1}^{k} X_{ik} = 1 \qquad k \varepsilon G_i$$

$$X_i = 0,1$$

where b_i is the benefit coefficient for X_i, C_i is the cost coefficient for X_i and B is the total amount of the resource available. G_i is the generalized upper bound (G.U.B.) constraint for variable X_i. If X_i=1, X_i has been chosen for inclusion in the solution at a profit or benefit of b_i and a use of C_i of the constrained resource. If X_i=0, then the variable X_i has not been chosen for inclusion in the solution. There is a G.U.B. constraint for each location considered; therefore, the number of variables associated with that constraint correspond to location alternatives. Note that one alternative is "do nothing."

Within a G.U.B. constraint, there exists a possibility of eliminating one or more alternatives. If an alternative has a lower benefit coefficient but a higher cost coefficient than another alternative within the same G.U.B. constraint, then that alternative may be eliminated from the problem without affecting the optimal solution.

The mechanics of the integer programming algorithm are complex, and hard solutions to problems of even moderate size are intractable. However, a Fortran IV program of less than 400 cards has been coded to execute the steps of the algorithm. This algorithm has solved problems with 2,000-4,000 variables in under ten seconds. By comparison, the dynamic programming algorithm executes a 270 variable problem in an average of sixteen seconds on an AHMDHAL V/70 computer system. Several points should be mentioned:

1. The algorithm will accept any form of cost or benefit coefficients, including costs and/or benefits expressed in dollars and cents.
2. The algorithm uses a hybrid branch and bound technique and *guarantees* an optimal solution.
3. G.U.B. constraints are handled implicitly in the algorithmic process, and the number of G.U.B. constraints does not significantly affect solution times.

Returning to the previous example, the integer programming algorithm generated the following solution in less than 1/10 of a second.

ALTERNATIVE	COST	BENEFIT
I-4	0	0
II-1	3,010	20,000
III-2	4,600	30,000
IV-2	1,200	12,000
	$8,810	$62,000

Budget Excess: $190

Clearly, this solution is superior to the one using dynamic programming. Again, the same solution can be generated using DP with appropriate selection of a state variable increment. However, to guarantee optimality for an *arbitrary* sequence of location (state) analysis, 900 state variable components ($10.00 increments) would be required at each stage. (If location IV is considered last, an improvement could be made).

Summary and Conclusions

This section has illustrated the use of Benefit-Cost ratio analysis (B/C), Incremental Benefit-Cost ratio analysis (IB/C), Dynamic Programming (DP), and Integer Programming (IP) in solving a selected highway safety accident prevention countermeasure problem. The conclusions are as follows:

1. Integer programming will always yield the optimal solution and is insensitive to the form of cost/benefit coefficients. Further, IP appears to be ten to twenty times faster than DP, based on our computational results.
2. Dynamic programming will not yield feasible results in its present form (Alabama/Kentucky) unless budget coefficients (alternative costs) are in units of the budget increments. Further, the current procedure will only yield *optimal* solutions if the individual budget expenditures and the budget increments are both in the same basic units. However, in that case the DP results will coincide with the IP results.
3. Benefit-cost ratio analysis should never be used when incremental benefit-cost ratio analysis can be applied. A procedure is given in this report.

Finally, with regard to a choice of projects which maximizes total returns for a fixed budget, the following inequality will usually hold:

$$\text{B/C Ratio} \leq \text{IB/C Ratio} \leq \text{Dynamic Programming} \leq \text{Integer Programming}$$

XV. USE OF TECHNIQUES BY DIFFERENT LEVELS OF GOVERNMENT

Recommendations for use of the techniques outlined in this study differ for different levels of government. In this chapter, the ways in which these procedures can be used are discussed.

State and Local Governments

The submodels and cost-effectiveness techniques outlined in Chapters XII, XIII, and XIV are primarily directed toward safety programs of state and local governments, especially those jurisdictions that have sufficient resources to consider a large number of safety alternatives in any given year. The steps that a state or local government could take to implement the recommendations in this study are:

1. Develop improved estimates of accident costs, based on the recommendations in Chapters VII and XII. These costs should use costs for fatalities that include the value of a person's life to himself. Our recommendation is that market-oriented approaches be used to determine this value. The second best approach is that used by NHTSA. Also, different categories of accidents should be used to reflect the different numbers of fatalities and injuries in these categories.
2. For the same cross-classifications used for accident costs (area, roadway, design feature, accident location), develop tables showing the proportion of accidents by severity type (fatal accidents, injury accidents, fatal accidents plus injury accidents, and property-damage-only accidents). Use these proportions to develop estimates of *expected* number of accidents by severity at each candidate location. Using comparisons of observed number of accidents with expected number of accidents, use statistical tests to determine the best method of predicting future accident costs.
3. Specify several alternatives for each hazardous location and estimate initial and future costs for each alternative.
4. Using appropriate accident cost estimates and accident reduction factors by severity type, use procedures outlined in Chapter XII for estimating annual reduction in accident costs for each alternative. Estimate other benefits or disbenefits of alternatives.
5. Calculate the present worth of future benefits and the present worth of initial costs using an appropriate percent discount rate and an appropriate formula or nomograph (e.g., see page 13).

6. Use one of the three methods discussed in Chapter XIV to rank alternatives or select the best alternatives for a given budget.

Federal Highway Administration

There are several activities for which it might be appropriate for the Federal Highway Administration to implement the recommendations in this report. First, additional effort could be made to further develop and help implement, in state and local governments, the cost-effectiveness techniques outlined in this report. More complete analysis of projects by state and local governments, using the procedures outlined in this report, should result in an improved data base that could be used to develop estimates of the effectiveness of national safety programs. It is the conclusion of this research that better estimates of countermeasure effectiveness can be developed at the national level only after better techniques are available for evaluating specific countermeasures at specific locations. Thus, states' annual reports on the effectiveness of safety programs would provide one of the best sources of the cost-effectiveness of accident countermeasures, if proper procedures were used and reported correctly.

There is, however, a more direct way in which the techniques outlined in this study can be used to perform a national highway safety needs study. The following procedures should be used:

1. Define categories of accidents by type of area, roadway type, etc., as outlined in Chapter XIII. Develop estimates of accident costs and proportions of accidents by severity for these categories.
2. Define different types of accident countermeasures that can be applied in these categories.
3. Develop a better summary of the effectiveness of different countermeasures in different situations. The review of selected countermeasures in this report could serve as a starting point for this effort.
4. Develop a sample of projects within these categories either by random sampling or by getting states to give examples of the types of projects that they would like to approve in these categories.
5. Have states fill out standard project sheets for each location and countermeasure type. The data for these locations

would include annual accidents by severity, traffic volumes, physical characteristics of the site, and recommended alternatives and their cost.

6. Using the states' data from accident locations, estimate benefits and costs for all alternatives in the sample.

7. Using one of the procedures outlined in Chapter XIV, either rank these alternatives from best to worst and analyze the results or develop the best sets of projects for different budget levels. If the goal is to determine the benefits for different levels of federal safety expenditure, it will be necessary to estimate the number of projects by countermeasure and category type prior to this step.

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FEDERALLY COORDINATED PROGRAM OF HIGHWAY RESEARCH AND DEVELOPMENT (FCP)

The Offices of Research and Development of the Federal Highway Administration are responsible for a broad program of research with resources including its own staff, contract programs, and a Federal-Aid program which is conducted by or through the State highway departments and which also finances the National Cooperative Highway Research Program managed by the Transportation Research Board. The Federally Coordinated Program of Highway Research and Development (FCP) is a carefully selected group of projects aimed at urgent, national problems, which concentrates these resources on these problems to obtain timely solutions. Virtually all of the available funds and staff resources are a part of the FCP, together with as much of the Federal-aid research funds of the States and the NCHRP resources as the States agree to devote to these projects.*

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems connected with the responsibilities of the Federal Highway Administration under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by keeping the demand-capacity relationship in better balance through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements which affect the quality of the human environment. The ultimate goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge of materials properties and technology to fully utilize available naturally occurring materials, to develop extender or substitute materials for materials in short supply, and to devise procedures for converting industrial and other wastes into useful highway products. These activities are all directed toward the common goals of lowering the cost of highway construction and extending the period of maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural designs, fabrication processes, and construction techniques, to provide safe, efficient highways at reasonable cost.

6. Prototype Development and Implementation of Research

This category is concerned with developing and transferring research and technology into practice, or, as it has been commonly identified, "technology transfer."

7. Improved Technology for Highway Maintenance

Maintenance R&D objectives include the development and application of new technology to improve management, to augment the utilization of resources, and to increase operational efficiency and safety in the maintenance of highway facilities.

* The complete 7-volume official statement of the FCP is available from the National Technical Information Service (NTIS), Springfield, Virginia 22161 (Order No. PB 242057, price $45 postpaid). Single copies of the introductory volume are obtainable without charge from Program Analysis (HRD-2), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.