A BENEFIT-COST MODEL FOR PAVEMENT RESURFACING AND OTHER COUNTERMEASURES

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A computerized benefit-cost model, developed for the Federal Highway Administration, can be used to evaluate alternative accident reduction countermeasures. The model was designed for use by state highway departments and is capable of evaluating both countermeasures that increase frictional supply and countermeasures that reduce frictional demand. Emphasis was placed on compatibility with typical highway department practices and the capability to provide fair comparisons, in an economic sense, between alternative countermeasures. The model incorporates relationships between skid number and accident rate obtained from an extensive data collection and analysis phase. The effects on accident rate of factors other than skid number are based on the literature. A tested version of the computer program should be available from the Federal Highway Administration in the near future.

This paper describes a computerized cost-benefit model developed for the Federal Highway Administration by Midwest Research Institute (1, 2, 3). The model is intended for use by state highway departments and is compatible with the procedures employed by and the problems facing those organizations. The model was designed to compare alternative accident countermeasures at a given site and to identify the optimal countermeasure on a cost-benefit basis.

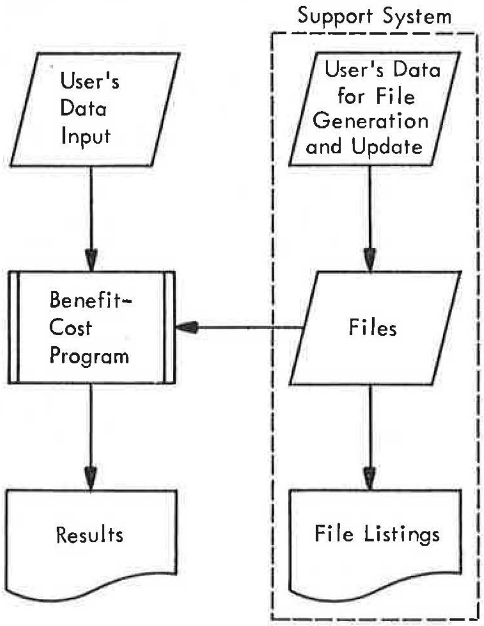
The model is suitable for use in a wet-pavement accident reduction program since it can be used to evaluate and compare countermeasures of two general types: those that increase frictional supply and those that decrease frictional demand. Countermeasures that increase frictional supply include pavement surface modifications such as resurfacing. Countermeasures that decrease frictional demand include geometric and traffic control improvements, such as reconstructing curves and installing warning signs. Although these countermeasures are considered primarily because of their effect on wet-pavement accidents, many of these countermeasures also reduce dry-pavement accidents and such benefits are considered.

Each of the countermeasures to be considered by the model at a given site must be selected by the user. This requires that the user exercise engineering judgment to select appropriate countermeasures. The model assumes that each countermeasure selected for analysis by the user is warranted and physically feasible. Typically, the user will select several alternative countermeasures for comparison at a given site. The model not only selects the most cost-beneficial countermeasure, but also provides detailed information on the costs, benefits and annual net return of each alternative. This information is extremely useful to the highway administrator in programming and budgeting.

System Configuration

The computerized benefit-cost model is part of a system illustrated in Figure 1. Input data for the program is obtained from two sources, as shown in the figure. The first source is the support system files maintained by the user. These files contain long-term values such as countermeasure costs, lives, effectiveness estimates, etc., which must be updated periodically but do not need to be supplied by the user each time the model is used. The second source is the user's input data supplied for each analysis. These data describe the type of analysis to be performed, the site to be analyzed, and the countermeasures to be considered. The user also has the option to override values from the system files in the analysis of specific cases where the typical values contained in the file are inappropriate.

Figure 1. Benefit-Cost Program Operation



Comparison of Alternatives in the Model

Alternative countermeasures are compared in the model with the appropriate base condition using the benefit/cost ratio, defined as:

$$B/C = \frac{AC_b - AC_c + MO_b - MO_c + UC_b - UC_c}{CC_c - CC_b} \quad (1)$$

where AC = Equivalent uniform annual accident costs,

MO = Equivalent uniform annual maintenance and operating costs,

UC = Equivalent uniform annual user costs,

CC = Equivalent uniform annual capital costs, and

subscript b indicates the base condition, while

subscript c indicates the countermeasure challenging the base condition.

Each of these cost items is discussed in a later section of the paper.

Experts are not in agreement on the location in the fraction of the MO and UC terms. We follow Winfrey (4), placing the terms in the numerator. With this form, the denominator contains capital costs exclusively. However, the reader should be aware that, while the choice to place the MO and UC terms in the numerator or denominator does affect the magnitude of the benefit/cost ratio, it does not affect the final ranking of countermeasures determined by the model.

The alternative countermeasures being evaluated are compared in two stages: economic feasibility and project formulation. In the economic feasibility stage, each countermeasure is compared with the existing or planned base condition. Alternative countermeasures with benefit/cost ratios less than unity are eliminated in this stage. Alternatives with benefit/cost ratios greater than unity in the economic feasibility stage are considered further in the project formulation stage. In the second stage, pairs of alternative countermeasures are compared in order of increasing equivalent uniform annual capital costs. The lowest cost countermeasure is the base condition for the first comparison. The first challenger is compared to this base condition. If a benefit/cost ratio less than unity results, the challenger is rejected. If a benefit/cost ratio greater than unity results, the challenger then becomes the base for subsequent calculations. The countermeasure remaining after all challengers have been compared sequentially is the most cost-beneficial.

Economic Aspects

The model logic is applicable to year-end cash flows, which are typically used for highway analyses. For comparative purposes, all costs and benefits are expressed as equivalent uniform annual cash flows. The interest rate (minimum attractive rate of return) used to convert one-time costs to equivalent uniform annual costs can be selected by the user.

Extensive logic is employed in the model to insure that the comparisons between countermeasures are economically fair. The required logic is complicated by the diversity of countermeasure types and the variety of situations where they may be considered for application. However, detailed logic has been provided to make the model compatible with typical highway department practices as described in the next section.

Compatability With Highway Department Practices

The computerized model is designed to handle many of the considerations that complicate benefit-cost analyses for highway applications and to provide results that are fair in an economic sense. Many economic analyses neglect these considerations or depend on judgment rather than quantitative results. The model is designed to handle such situations appropriately within the model, so that the user is not required to supply complex input or extensive judgment.

One common situation which receives special treatment in the model is a decision to resurface or rebuild the analysis facility that has been made, but not yet carried out. Two types of decisions are handled by the model. The first type is a decision and budgeting commitment that will be implemented prior to or simultaneously with the countermeasure(s) evaluated, referred to as a prior decision. The second type is a decision to resurface or rebuild the facility after the countermeasure(s) are implemented, referred to as a future plan.

A typical prior decision is the decision to resurface a site to improve riding quality and to safeguard the pavement structure. Once this decision has been made, but before it is implemented, it may be appropriate to consider resurfacing the facility with a special material to improve its skid resistance properties. In such a case, the economic analysis should include only the additional cost of the special surface course, since the decision has been made and an amount of funds have been committed to resurface the facility. When a special surface course is considered, the model charges the base condition with the cost of the planned surface course. The cost of the special surface course is then compared fairly with the costs already committed by the prior decision. However, if geometric or traffic control countermeasures are evaluated against the base condition, the funds already committed by the prior decision do not enter the calculation. The influence of the prior decision is carried into project formulation by crediting the economically feasible surface countermeasures with the funds already committed. This aspect of the model provides an accurate account of the incremental costs of surface countermeasures where prior decisions for surfaces have been made. Current practices frequently do not provide a systematic method for analyzing this situation, which may involve multiple budget funding.

The other type of decision that receives special consideration in the model is a future plan to resurface, rebuild or abandon a facility. Such decisions may limit the service life normally expected from the countermeasures being analyzed. The term <u>applied life</u> is used to describe the period of time for which the countermeasure capital items will actually be employed for their intended purpose. All countermeasures are not equally vulnerable to future actions. For this reason, the model contains codes for the vulnerability of countermeasure items to future actions and provisions for salvage value or remaining value after removal. There is flexibility to account for situations such as turn-lane countermeasures that can remain as part of the rebuilt facility.

Some countermeasures considered by the model may require acquisition of additional right-of-way. The model logic recognizes that right-of-way costs, lives (ammortization periods), and future worths should often be specified independently from the associated values for the other capital items in the countermeasure. Therefore, the model accepts and processes right-of-way quantities separately from other capital costs, but combines appropriate equivalent uniform annual capital costs in the final analysis. Flexibility is provided for special situations like right-of-way that is required in the future, but must be acquired ahead of schedule for implementation of a countermeasure.

<u>Model Treatment of Major Factors</u>

Traffic Volume

The model user must supply the Average Daily Traffic (ADT) for the analysis site in the year when the countermeasures will be installed. In addition, the user must specify the pattern of ADT change throughout the analysis period by one of four methods: (1) constant ADT (no growth); (2) linear ADT growth; (3) compound ADT growth; or (4) year-by-year values for future ADT. The final option is useful when ADT growth is not expected to follow a simple pattern as, for example, when the opening of a parallel facility is expected to cause a sharp decrease in ADT for a future year. The model requires the ADT for only one facility for analysis of a highway section or a non-intersection location, but ADT for both a major and a secondary facility is required for analysis of an intersection site.

Skid Number

The skid number at 64 km/hr (40 mph), S , is represented in the model as a function of cumulative traffic passages:

$$S = S_o + C_s \ln(T) \qquad (2)$$

subject to the constraints

$$T \geq 1.$$

$$S \leq S_f \text{ when } C_s > 0., \text{ and}$$

$$S \geq S_f \text{ when } C_s < 0.$$

where S_o = Initial skid number

S_f = Final or limiting value of skid number

C_s = Coefficient representing rate of change of skid number

T = Cumulative traffic passages/10^5

The values of S_o , S_f and C_s are characteristic of each type of surface course considered as a countermeasure and are obtained from the support system files. The model can be adapted to any type of surface course aggregate and any rate of traffic wear by selection of appropriate values for S_o , S_f and C_s. Specific values for S_o , S_f and C_s have been identified from several sources in the literature (<u>5</u>, <u>6</u>, <u>7</u>). The model uses the above relationship to update the skid number during each year of the analysis period to account for the effect of traffic passages. If the facility is resurfaced during the analysis period, the cumulative traffic passages are set equal to zero in that year.

Accident Rate

The user must supply the expected number of annual accidents for the analysis site in the period before countermeasure implementation. This value is used within the model to calculate the overall accident rate defined for highway sections as:

$$r = \frac{(N)(10^6)}{(L)(ADT)(365)} \qquad (3)$$

where r = Overall accident rate (accidents/MVM)

N = Annual number of accidents

L = Section length (miles)

ADT = Average daily traffic (vehicles)

The model accounts for three factors that influence the accident rate at the analysis site during the analysis period: (1) changes in skid number, (2) changes in traffic volume, and (3) installation of geometric and traffic control countermeasures. The benefit/cost model incorporates specific accident rate-skid number relationships developed during the project. These relationships, presented in detail in the following section, are used to determine the effect on accident rate of both abrupt changes in skid number due to resurfacing and gradual changes in skid number due to traffic passages.

The accident rate at the analysis site is also influenced by changes in traffic volume. The accident rate-traffic volume relationships used in the model are based on regression results reported by Fee (8).

The effects of 87 individual geometric and traffic control countermeasures incorporated in the model are based on percentage accident reduction estimates reported in NCHRP Report 162 (9), as modified by a correction factor discussed in the following section. The effectiveness estimates obtained from the literature are the most reliable presently available. However, recognizing that individual states may have available more reliable estimates for their particular traffic and climatic conditions, the user can update the support system file, and replace the estimates supplied with the model.

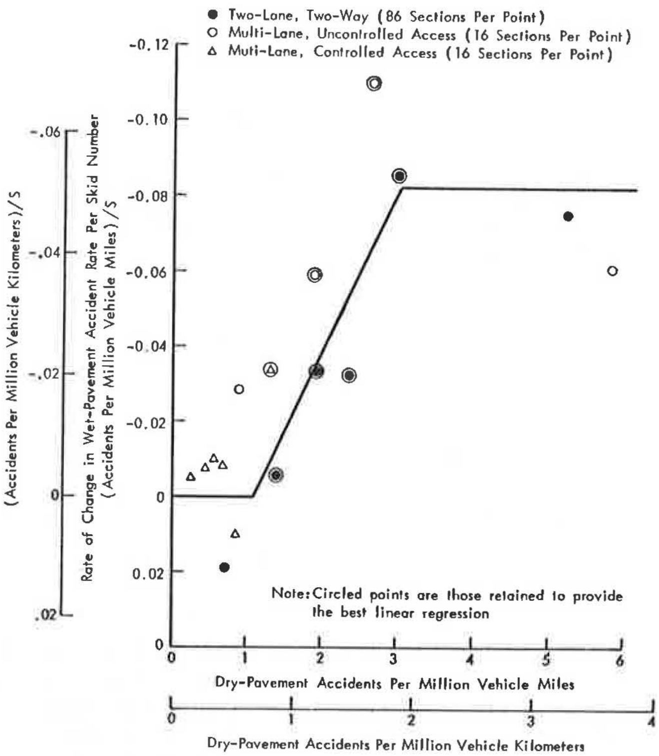
Accident Rate-Skid Number Relationships

The model development included an extensive investigation of the relationship between wet-pavement accident rate and skid number (1). Accident rate, skid number, traffic and weather data were assembled for each of 2 years on 428 highway sections in 15 states. The data were analyzed with a number of statistical techniques. Analysis of covariance proved to be the most useful with factors area type (urban/rural), highway type and ADT. The independent variable was skid number at 64 km/hr (40 mph), S , and the dependent variable was wet-pavement accident rate, r_w , expressed as wet-pavement accidents per million vehicle-miles of travel under wet-pavement conditions.

The analysis of covariance identified a family of linear relationships between r_w and S with a common slope of -0.0286 accidents per million vehicle-kilometers per skid number (-0.046 accidents per million vehicle-miles per skid number). The correlation coefficients ranged from 0.28 to 0.43. The magnitude of the slope indicated that skid number does have a substantial effect on wet-pavement accident rate. For example, an increase of 10 in skid number at 64 km/hr (40 mph) would, on the average, reduce wet-pavement accident rate by 0.286 accidents/MVKm (0.46 accidents/MVM) which is about 15% of the mean wet-pavement accident rate.

Additional analyses showed that the relationship between wet-pavement accident rate and skid number is strongly dependent on the dry-pavement accident rate, r_d . This finding is illustrated in Figure 2 where $(\partial r_w/\partial S)$ is plotted against r_d for all rural highway types. The magnitude of $(\partial r_w/\partial S)$, the sensitivity of wet-pavement accident rate to skid number, was for the most part in accord with expectations.

Figure 2. Rate of Change of Wet-Pavement Accident Rate with Skid Number as a Function of Dry-Pavement Accident Rate for Rural Highways.



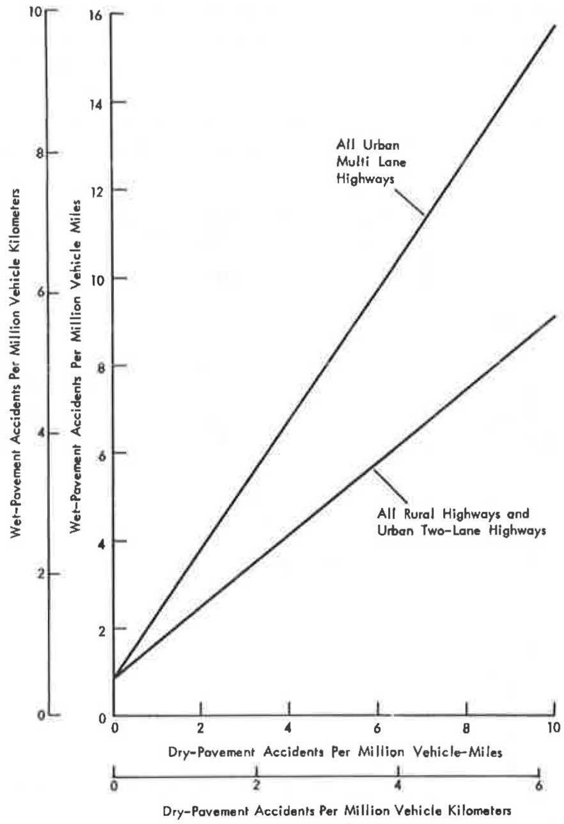
Dry-pavement accident rate was used here as a proxy variable. It was postulated that where dry-pavement accident rate was high there would be more-than-average demand for skid resistance to avoid accidents, and vice versa. The data indicated that this postulate was generally true for rural highway sections. In fact, with dry-pavement accident rate as a factor and skid number as the independent variable, the variance of wet-pavement accident rate is explained as well as it is with more complex multiple factor frameworks.

The sensitivity to skid number $(\partial r_w/\partial S)$, reached a maximum and became constant at large r_d . The data for rural highway sections indicated this unanticipated finding at a high confidence level. In urban areas, the more limited amount of data did not provide an equally well defined relationship between wet-pavement accident rate and skid number. Statistical tests did indicate that the quantitative aspects of the urban relationship were probably different from the rural case, but the general character was probably similar.

The data analyses also found very strong correlations between wet-pavement and dry-pavement accident rates. The regression results are shown in Figure 3.

The intercepts were statistically indistinguishable for all area type-highway type combinations. The slopes were distinguishable for the combinations shown.

Figure 3. Relation Between Dry-Pavement and Wet-Pavement Accident Rates.



The benefit-cost model incorporates the accident rate-skid number relationships shown in Figure 2 and the regression results shown in Figure 3 by employing several simple concepts. First, the overall accident rate on a facility is approximated as a linear combination of the rates under wet- and dry-pavement conditions:

$$r = f_w r_w + f_d r_d \,, \tag{4}$$

where r = overall accidents per MVM,
f_w = Fraction of time pavement is wet,
r_w = Wet-pavement accidents per MVM under wet-pavement conditions,
f_d = Fraction of time pavement is dry, and
r_d = Dry-pavement accidents per MVM under dry-pavement conditions.

Second, the wet-pavement accident rate is expanded as the sum of a part correlated with the dry-pavement accident rate and a part containing the skid number sensitivity:

$$r_w = b_o + b_1 r_d + \frac{\partial r_w}{\partial S}(S - \bar{S}) \,, \tag{5}$$

where b_o and b_1 are coefficients from the wet-dry accident rate regressions. S is the skid number measured at 64 km/hr (40 mph); and $\bar{S}$ is the average skid number for which $r_w = b_o + b_1 r_d$.

In agreement with Figure 2, a three segment representation for $\frac{\partial r_w}{\partial S}$ is employed where each segment has the linear form

$$\frac{\partial r_w}{\partial S} = a_o + a_1 r_d \tag{6}$$

The coefficients, a_o and a_1 are given in Table 1.

Table 1. Regression coefficients a_o and a_1[a]

Range of r_d	a_o	a_1
$0 \le r_d \le 1.082$	0	0
$1.082 < r_d < 3.02$	0.04615	-0.04264
$3.02 \le r_d$	-0.0825	0

[a]The coefficients are based on all rural highway types combined, but are used for urban highways as well, because of a lack of more definitive data.

Equations 4, 5, and 6 combine to form the basic equation:

$$r = f_w\left[b_o + b_1 r_d + (a_o + a_1 r_d)(S - \bar{S})\right] + f_d r_d \,. \tag{7}$$

Figures 4 and 5, based on the preceding equations, illustrate overall accident rates as functions of skid number and dry-pavement accident rate for climates that produce wet highways 10% and 30% of the time. The effects of countermeasures on accident rates, discussed in the previous section, can be visualized in these figures. The figures show how wet-pavement exposure and skid number can impact the effectiveness of geometric and traffic control countermeasures that act directly, but not exclusively, on the dry-pavement accident rate. When a geometric or traffic control countermeasure is applied, the improvement is reflected by a displacement along a line of constant skid number to a lower accident rate. The model contains a correction factor, based on Equation 7, to correct for this effect. Resurfacing countermeasures involve an improvement in skid number. When the skid number is increased, the improvement is reflected by a vertical displacement to a lower total accident rate (presumably, at a constant dry-pavement accident rate, although some countermeasures may involve both effects).

Figure 4. Overall Rural Accident Rate Versus Dry-Pavement Accident Rate and Skid Number, When Pavement is Wet 10% of Time.

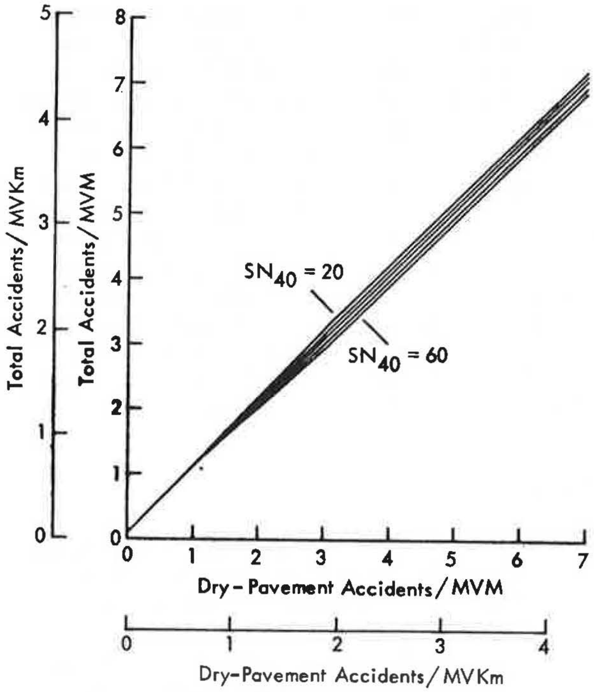
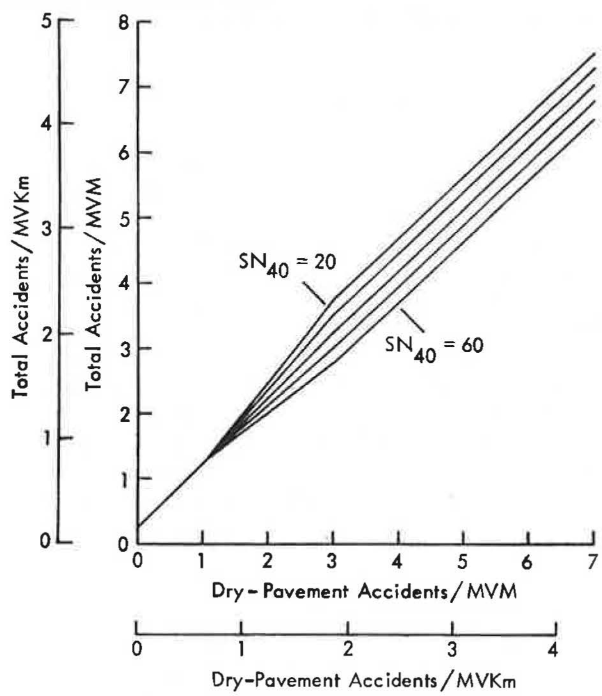


Figure 5. Overall Rural Accident Rate Versus Dry-Pavement Accident Rate and Skid Number, When Pavement is Wet 30% of Time.



The change in overall accident rate with skid number is given by the partial derivative:

$$\frac{\partial r}{\partial S} = (a_o + a_1 r_d) f_w \ . \qquad (8)$$

In the model, an incremental change in skid number (ΔS) produces an incremental change in overall accident rate (Δr),

$$\Delta r = \frac{\partial r}{\partial S} \Delta S \qquad (9)$$

The form for $\partial r/\partial S$ is based on Equations 4 through 8 and is calculated as:

$$\frac{\partial r}{\partial S} = 0 \ . \quad \text{if} \quad r \leq r_1 \ . \qquad (10)$$

where $r_1 = f_w \left[b_o + 1.082 \ (b_1 - 1) \right]$ (11)

$+1.082$.

If $r > r_1$,

$$\frac{\partial r}{\partial S} = -0.0825 \ f_w \qquad (12)$$

or

$$\frac{\partial r}{\partial S} = f_w \ (r - r_1) a_1 / \left\{ f_w \left[b_1 + a_1 \ (S_o - S) \right] + (1 - f_w) \right\} , \qquad (13)$$

whichever is algebraically larger. In Equation 13, S_o represents the skid number for the time immediately before $\partial r/\partial S$ is evaluated. The coefficients for Equations 10 through 13 depend only on area type and highway type as shown in Table 2. Equations 10 through 13 are employed in the model to calculate $\partial r/\partial S$ and, then, the accident rate is adjusted for changes in skid number according to Equation 9.

Table 2. Summary of Coefficients for Equations Employed in Model

Area Type	Highway Type	$\bar{S}$	a_1	b_o	b_1
Rural	Two-lane	46.0	-0.64264	0.8066	0.8281
Rural	Multilane uncontrolled access	46.0	-0.64264	0.8066	0.8281
Rural	Multilane controlled access	46.0	-0.64264	0.8066	0.8281
Urban	Two-lane	39.7	-0.64264	0.8066	0.8281
Urban	Multilane uncontrolled access	39.7	-0.64264	0.8066	1.4873
Urban	Multilane uncontrolled access	39.7	-0.64264	0.8066	1.4873

Spot-site accident rates can also be analyzed. The model assumes that analyzed spots have been identified as high-accident locations and that, therefore, such spots have above average accident rates corresponding to the upper end of the fan of lines in Figures 4 and 5. The change in accident rate due to skid number for spot-sites is then assumed to be proportional to the change that would be observed for highway sections, and is evaluated using Equations 10 through 13.

Costs Employed in the Model

The four types of costs employed in the model are: (1) capital costs, (2) accident costs, (3) user costs, and (4) maintenance and operating costs. Each type of cost is discussed below.

Capital Costs

The initial capital outlay and final capital worth (salvage value) for each countermeasure are obtained by the program from the support system files maintained by the user. The capital costs are converted by the model to equivalent uniform annual cash flows, for comparison with the other costs and benefits. The user can override the support system values in specific instances where atypical costs are desired.

Accident Costs

The following accident costs, developed by the National Highway Traffic Safety Administration (10), are supplied with the model:

Definition	Cost
Cost per vehicle involved in a property-damage-only accident	\$300
Cost per injury	\$7,300
Cost per fatality	\$200,700

The average cost of a fatal accident is calculated in the model as:

$$C_{FA} = (C_F)(W_F)(P_F)$$

where C_{FA} = Average cost of a fatal accident
C_F = Average cost of a fatality = \$200,700
W_F = Weight factor for fatal accident costs supplied by user (default value = 1.0)
P_F = Average number of fatalities per fatal accident

The user can change the value of C_F as needed by updating the support system files. The user can also adjust the standard fatal accident cost for a particular analysis by selecting a value other than 1.0 for W_F. The value of P_F as a function of highway type and area type has been determined from accident data for a 4-year period supplied by the states of California, Michigan and Washington. Costs for injury and property-damage-only accidents are determined analogously.

The model determines the expected accident rate for each year of the analysis period taking into account the effects of changing skid number and traffic volume. The costs described above are used to define the total accident cost for each year, and these costs are then expressed as equivalent uniform annual accident costs for calculation of the benefit/cost ratio.

User Costs

The only user costs incorporated in the model are costs due to delays and excess fuel consumption arising from countermeasure construction. These costs may be incurred in the year when a countermeasure is first installed and/or in a subsequent year when the countermeasure is replaced. Other user costs, such as normal fuel consumption and operating costs, are not included in the model because the effect of any countermeasure on these costs has not been well quantified.

Maintenance and Operating Costs

The support system files maintained by the user contain typical maintenance and operating expenses per unit length of highway as a function of area type and highway type. In addition, the support system files contain, and the model uses, the additional maintenance and operating costs associated with each countermeasure. The maintenance and operating cost for a given site with a given countermeasure installed can vary as a function of time. For example, the model logic permits decreased maintenance and operating costs immediately following the installation of resurfacing or surface treatment countermeasures, if that is the experience of the using agency.

Status of the Computerized Model

The final programming and encoding of the benefit-cost model, as well as the support system and the computer control instructions, are the responsibility of the Data Systems Division of the Federal Highway Administration. A preliminary version of the model has been programmed and tested. The complete and tested version should be available shortly from the Federal Highway Administration.

The model is being programmed in Fortran IV and is adaptable to a large number of computer systems being operated in the U.S. and elsewhere.

The computerized model should be a useful tool for agencies that need a comprehensive and quantified basis for planning and budgeting their safety programs.

Acknowledgments

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