Table 5. Evaluation of geometric consistency of divided-highway transition case study.

Feature	Divided-Highway Transition, Two-Lanes to Four-Lanes	Bridge, Full Width, No Shoulders	Horizontal Curve $2^\circ, 15^\circ$	Railroad Bridge Overpass	Crest Vertical Curve	Divided-Highway Transition, Four-Lanes to Two-Lanes
	Calculations of Geometric Features in Southbound Direction of State-16					
Station	701+10	727+90	734+90	740+00	776+50	780+00
R_f	2.0	2.5	0.9	0.8	1.2	3.0
V_{85} (km/h)	105	105	105	105	100	100
Sight distance (m)	600	321	606	545	909	144
Separation distance (m)	636	812	212	155	1106	106
R_f	2.0	2.5	0.9	0.8	1.2	3.0
S	0.69	0.90	0.69	0.69	0.69	1.80
E	1.00	1.00	1.00	1.00	1.00	1.00
U	0.80	0.80	0.80	0.80	0.80	0.80
C	0.00	0.00	0.68	0.73	0.00	0.90
WL_ℓ	0.0	1.1	1.8	1.7	1.7	0.7
WL_n	1.1	1.8	1.7	1.7	0.7	5.0
LOC_n	B	B	B	B	A	E

Note: 1 m = 3.3 ft; 1 km/h = 0.62 mph.

would suggest that conditions are good except near the southbound terminus of the four-lane section where the crest vertical curve severely limits the sight distance to the divided highway transition for the existing operating speeds. The route is classified as a rural minor arterial since it is a major state highway and, therefore, the U factor is 0.8.

Table 5 presents a summary of the initial geometric feature data, resulting calculations, and level-of-consistency evaluations. The calculations solve the work-load equation. Level-of-consistency evaluations are determined based on the criteria presented in the preceding table. As indicated in the last line in Table 5, the four-lane roadway is very consistent (i.e., the level of consistency is B, B, B, B, A, E) over much of the four-lane section except at the southern (last) divided-highway transition. To solve this problem the divided-highway transition should be moved farther away from the crest of the vertical curve until the sight distance is again unrestricted.

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Abridgment

Use of Total Benefit Analysis for Optimizing Lane Width, Shoulder Width, and Shoulder Surface Type on Two-Lane Rural Highways

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The relationships between safety and design for lane width, shoulder width, shoulder surface type, and accidents have been developed. The objective of this paper is to demonstrate how these and other relationships may be employed to obtain optimal design specifications for lane width, shoulder width, and shoulder surface type. A manual procedure is presented for basic design problems. As the complexity of the problem increases, some computerized optimization procedure, such as dynamic programming, is recommended.

The primary purpose for conducting research to establish the relationships between the various roadway design features and accidents (frequency and severity) is to enable safer roadways to be constructed under the current funding limitations faced by the states. A critical element in the policy-determination process is often omitted, which leaves valuable research with no means for practical application. This is the step of translating established relationships into quantitative economic models that can be used for optimizing roadway designs. The objective of this paper is to present one such model for consideration for general use.

We will assume that a reliable set of relationships can be obtained through standard research procedures. A detailed review of past research efforts has been conducted (1). Further, a set of relationships, developed especially for this type of optimization process, has been developed for lane width, shoulder width, and shoulder surface type for the National Cooperative Highway Research Program (NCHRP) project 3-25 (1). Although the development of such relationships is not new (2), the special procedures employed in this project to account for interactions between design features makes these relationships particularly appropriate for an optimization design process.

The use of a total benefit approach to the allocation of high-hazard funds for spot roadway improvements was documented as early as 1973 (3). This technique was adopted as an ongoing operating procedure within Alabama (4), and the computer software employed has been well documented (5,6). In addition, these procedures have been published in two independent technical journals (6,7), and a simultaneous implementation was made in Kentucky (8).

The total benefit approach, as implemented by using dynamic programming for optimization, has generally been accepted as (9) "the best procedure identified as currently being used in any state." Although the same concept of maximizing the total benefit obtained subject to budgetary constraints is employed, the procedure discussed here varies from those described above in two important respects: (a) it applies primarily to new construction and major reconstruction as opposed to spot improvements and (b) it employs a manual procedure for optimization.

STATEMENT OF PROBLEM

Briefly stated, the problem is that of allocating a limited budget to roadway construction in such a way that safety is not compromised. Stated another way, the objective is to balance the various costs of increased design parameters so that the total safety benefit is maximized. Budgetary resources are assumed to be limited; however, no assumption is made that they are known from the outset. That is, the problem is complicated slightly inasmuch as the designer is generally not given a specific amount of money to allocate to the roadway under consideration. Usually the design is used to determine the cost or funding request. Thus, the procedure devised for solving this problem must have enough flexibility to enable an easy consideration of last-minute changes in funding.

In order to further limit the scope of the problem at hand, we will assume that the relationships between the design specification variations and accidents (frequency and severity) have been estimated with some degree of confidence. We will also assume that the construction cost variation is known for the variations in the design specifications under consideration. Considerable additional work is required in these two areas, but they will be considered only briefly below because they fall outside the scope of primary consideration. Note, however, that the economic evaluation methodology considered here could contribute heavily toward both the direction and the increased application of future research efforts.

Table 1. Example subset of alternatives for example tangent section.

Pavement Width (ft)	Shoulder Width (ft)	Shoulder Surface Type	Segment Cost[a] ($000s)	Accident Cost ($000s)
20	4	Unpaved	102	163
	6	Unpaved	106	150
	8	Unpaved	109	137
	4	Paved	110	159[b]
	6	Paved	121	146[b]
	8	Paved	129	132
22	4	Unpaved	149	147[b]
	8	Unpaved	153	137[b]
	10	Unpaved	156	118
	4	Paved	157	144[b]
	8	Paved	168	129[b]
	10	Paved	176	114
24	4	Unpaved	199	131[b]
	8	Unpaved	203	115[b]
	10	Unpaved	206	99
	4	Paved	207	128[b]
	8	Paved	218	112[b]
	10	Paved	227	96

[a]Accident costs were obtained from the relationships developed in NCHRP Report 197 (1).
[b]Eliminated from further analysis due to increasing accident costs.

SOLUTION TECHNIQUE

The solution technique will be called a total benefit technique because the objective function is to maximize the total benefit from a safety point of view. This technique will be exemplified in terms of trade-offs among allocations to lane width, shoulder width, and shoulder surface type. Four major phases are associated with the total benefit methodology:

Phase 1: Determine construction costs,
Phase 2: Determine accident costs,
Phase 3: Determine candidate designs, and
Phase 4: Select the final design.

The first two phases of developing construction and accident costs can be performed concurrently and independently of each other, and they are beyond the scope of this paper. Once this is accomplished, the last two phases can be performed as discussed below.

Determination of Candidate Designs

The first two phases involve calculation of the construction and accident costs for any alternative design. This application is concerned with the combination of pavement width, shoulder width, and shoulder surface type. Because of the large number of possible combinations of these alternatives, the designer must select only those alternatives (or combinations) that are practical in terms of highway agency policy, route continuity, and other nonsafety factors related to the project. After these designs have been selected, construction and accident costs over the service life of the project are calculated for each.

These alternatives are next arrayed by increasing construction costs. Table 1 (1-6,10,11) illustrates a typical array based on example costs output from phases 1 and 2. Note that an ascending construction cost does not necessarily lead to decreasing accident costs. For example, the alternative for 20-ft pavement and 4-ft paved shoulders has an estimated accident cost of $159 000, which is more than the accident cost for the preceding alternative at a lower construction cost. Since an increase in construction costs accompanied by an increase in accident costs could not possibly be a cost-safety-effective design, these alternatives should be eliminated from further analysis.

The candidate design alternatives in Table 1 are for roadway segments within the project limits that have horizontal curvature of less than 3°. Another group of candidate design alternatives must be selected for segments that have 3° or greater horizontal curvature. Practical alternatives from each curvature group are then combined into candidates for the total project design specifications.

Table 2. Cost/benefit data for alternatives.

Alternative Total Construction Costs ($000s)	Marginal Construction Costs ($000s)	Reduced Accident Costs ($000s)	Cumulative Increased Construction Costs ($000s)	Cumulative Reduced Accident Costs ($000s)
2366.9	Minimum cost to construct roadway section			
2375.9	9.0	2.1	9.0	2.1
2382.9	7.0	7.0	16.0	9.1
2391.9	9.0	1.6	25.0	10.7
2447.9	56.0	5.3	81.0	16.0
2463.9	16.0	8.5	97.0	24.5
2510.8	46.9	43.5	143.9	68.0
2519.8	9.0	1.6	152.9	69.6
2527.1	7.3	3.3	160.2	72.9
2536.1	9.0	1.2	169.2	74.1
2591.8	55.7	5.3	224.9	79.4
2608.1	16.3	4.5	241.2	83.9
2657.9	49.8	20.4	291.0	104.3
2666.9	9.0	1.2	300.0	105.5
2674.4	7.5	2.4	307.5	107.9
2683.4	9.0	1.2	316.5	109.1
2738.9	55.5	4.2	372.0	113.3
2755.4	16.5	3.6	388.5	116.9
2805.9	50.5	14.5	439.0	131.4
2814.9	9.0	1.2	448.0	132.6
2831.1	16.2	0.6	464.2	133.2
2886.9	55.8	7.1	520.0	140.3
2903.1	16.2	0.6	536.2	140.9
3033.4	130.3	4.0	666.5	144.9

Selection of Final Design

The final design is selected from the alternatives identified in phase 3. No rigid procedure is specified to force a design on the descision maker. Rather, the methodology of phase 3 produces all of the information required for cost/benefit, marginal cost/benefit, and break-even analyses. At this point the designer must take into account other design characteristics that affect the final selection of pavement width, shoulder width, and shoulder type. The final design selected must represent the agency's highway improvement policy in terms of these design features, as well as the most cost-safety-effective design.

Table 2 summarizes the marginal safety benefits and the total safety benefits from an actual appliction of the NCHRP research made to a road section in Alabama. The marginal cost is the additional construction expenditure, and the marginal safety benefit is the reduction in accident cost when the corresponding construction expenditure is made. All feasible combinations that involve both curved and tangent alternatives over the roadway were considered. The total safety benefit is the cumulative total of reduced accident costs, and the cumulative increased construction cost is the increased construction costs over the lowest-cost alternative. As more funds are expended, their capability to purchase safety benefits is generally reduced. The first $2 366 900 is considered the basic expenditure. It is required to construct the project to a minimal safety level. From that point on, the additional investments are viewed as contributing additional safety benefits.

From the marginal benefits shown in Table 2, for an additional $9000 from the minimum cost of $2 366 900, an additional $2100 in safety benefits can be realized. If an additional $7000 is expended for the next alternative, the additional benefit was estimated to be $7000—equal to the additional investment. However, the cumulative additional construction cost is $16 000 for total additional reduced accident costs of $9000.

On the basis of marginal benefits, expenditures in excess of the minimum design do not return equivalent benefits. This result is only for the example given here and not a general conclusion of this research. Each construction project must be evaluated on its own merits. Also, because the construction-accident trade-off is so dependent on estimated costs of accidents by severity, it is not recommended that this be the sole criterion for selection of the construction expenditure. Rather, each of the policies specified is optimal for the corresponding construction expenditure because all suboptimal alternatives were eliminated. High-level judgment must be made at this point in light of alternative uses of funds by using similar results of other project analyses. The final design must represent the agency's highway improvement policy in terms of specific design features as well as the most cost-safety-effective design.

CONCLUSIONS

One criticism that has been leveled against cost-effectiveness techniques applied to safety is that "dollars are being traded against lives." The technique presented circumvents this problem by changing the analysis from a comparison of costs and benefits to a maximization of benefits given a fixed budget. This is a more practical approach that can lead to greater overall roadway system safety.

Use of the total benefit methodology will permit an agency to select designs of pavement width, shoulder width, and shoulder type that are optimum from a safety standpoint. That is not to imply that it leads to the lowest possible accident costs but rather that it produces the lowest accident costs for the expenditure of funds that is to be made. Depending on other design criteria that may offset the final alternative selected, this concept of tailoring the design for each project will result in lower construction costs than would have been required without it. Any reduction in construction costs for a given project can be applied to the improvement of additional miles of highway that would not have been possible without the availability of these additional monies.

Effective use of the methodology presented above will provide safety benefits in excess of those that would be obtained without its use. Although safety benefits are not maximized for each project, total safety benefits are increased by the improvement of more miles of facilities, rather than a few miles of improvements that are built to designs that are not cost effective.

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Strategy for Selection of Bridges for Safety Improvement

JARVIS D. MICHIE

In order to upgrade traffic safety of existing bridges in a systematic and cost-effective manner, we must have a clear understanding of how safety is measured and controlled. Safety is not an absolute but a relative condition that balances the risk of an event and society's acceptance of that risk. Something is considered safe if its risks are acceptable. Risk is measured by the probability of the occurrence of an adverse event (i.e., bridge accident) and the event's consequences (i.e., collision severity). Based on length alone, a bridge is 50 times more hazardous than the roadway in general. The large number of bridge accidents is attributed to narrow bridges and to obsolete approach guardrail and bridge rail installations. To improve bridge traffic safety, the ideal solution would be to widen all narrow bridges and upgrade barrier installations on all other bridges. Because of cost, this approach is not practical. As an alternative, bridge selection for safety improvement can be based on degree of risk and available funds concentrated on the high-risk bridges. This procedure, which is also applicable to other roadside safety problems, advocates uniform standards for degree of risk rather than uniform standards for design. In fact, design standards will be varied according to site requirements to achieve the acceptable level of risk. Two techniques are presented to identify bridges that have a high degree of risk: (a) adverse accident experience and (b) high traffic volume coupled with substandard highway features. The extent and type of safety improvements are presented.

The term safety is currently a very popular word, judging by its use as a topic in newspapers, books, magazines, and other media. The term safety carries a heavy emotional and political load. There is considerable public confusion about safety, and this confusion is not helping the highway community improve its system.

A simplistic and misleading definition of safe is "free from harm or risk." However, nothing can be absolutely free of risk. Because nothing can be absolutely free of risk, nothing can be said to be absolutely safe. There are degrees of risk, and, consequently, there are degrees of safety (Figure 1). Safety, then, is a judgment of the acceptability of risk; and risk, in turn, is defined as a measure of the probability and severity of harm to human health (1). In other words, something is safe if its risks are judged to be acceptable. Even with a specific measure of risk, the acceptability judgment, which is a value decision made by all or a segment of society, may vary with time and place.

Degree of risk is measured by the probability of an event multiplied by consequences or severity of the event:

$$\text{Degree of risk} = \text{probability of occurrence} \times \text{probability of consequences} \quad (1)$$

The degree of risk can be lowered by causing a decrease in the number of events or collisions or a reduction in the severity of the collisions when they occur. Unfortunately, it costs money to make these changes, so one should be sure the improvement in safety (reduction in risk) is worth the cost.

HIGHWAY SAFETY EFFORT

Traditionally, highways have been constructed or upgraded according to state or federal design standards. For example, highway features (such as typical cross sections, lane widths, maximum horizontal curvatures, maximum shoulder slopes, and minimum roadside clear zones) are consistently high on the Interstate system. Low fatality rates on the Interstate system have proved the effectiveness of the high-design standards. On the other hand, some believe that much of the Interstate system has been unnecessarily built to these high and costly design standards. Thus, safety funds have been spent on highway segments where the degree of risk and, therefore, the potential for reducing fatalities are low.

As the safety upgrading attention is directed away from the Interstate system to the remaining 6 200 000 km (3 838 000 miles) of highways, highway agencies are forced to be more prudent with expenditures.

An alternative to the upgrading of highways to one or more specified uniform design standards is the upgrading of highways to a uniform standard for degree of risk. Such a standard can be quantified in terms of kilometers of highway per run-off-the-road type of fatality. An initial goal can be set at, say, 800 km (500 miles) and then increased as additional safety funds become available. This approach implies a variable design standard that is determined by the degree of risk at a local site and is in contrast to the uniform standard design approach used on the Interstate system. This uniform risk approach is the only strategy that is both effective and affordable. To select a uniform design standard will be either grossly wasteful of public funds or ineffective in reducing fatalities.

The application of risk management to the assessment and implementation of safety is an emerging technique in highway technology. The number of spot safety improvement programs is increasing. The multiple-service-level bridge railing selection procedure, which is based on risk measurement and assessment (2), is another example of the emerging technology. Moreover, considerable research activity is under way in this area. Although it will be a few years before a comprehensive technology is developed, some things can be done now.

THE BRIDGE SAFETY PROBLEM

The table below is based on 1975 data (3,4) (1 km = 0.62 mile).

Category	Length (km)	Fatalities	Kilometers per Fatality
Roadway	6 175 000	11 300	546.5
Bridges	12 400	1 120	11.1

In 1975, 45 850 people were killed; 11 300 of them were involved in a single-vehicle, ran-off-the-road, hit-fixed-object type of collision (5). Moreover, we know that the fixed object involved with at least 1120 of these