How Best to Rank Sites with Promise

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The starting point for a program of local safety improvements is the preparation of a list of sites with promise at which to conduct a detailed engineering study, by which cost-effective projects can be identified. Inclusion on the list depends on the criteria used for ranking sites. Five alternative ranking criteria were compared by the cost-effectiveness of the projects to which they lead. It was found that sites at which most accidents or most severity-weighed accidents are expected lead to most cost-effective projects.

A site with promise (SWiP) is a site at which safety can be improved cost-effectively. The screening for SWiPs is the first step of the site safety improvement process (*1*, p. 28). The product of screening is a ranked list of SWiPs. The second step of the process is to conduct a detailed engineering study (DES) at the sites ranked highest. The goal for the DES is to define effective projects to enhance safety.

Several alternative ranking criteria are used in screening. Ranking can be by accident frequency or by excess accident frequency, by accident rate or its excess, by severity-weighed versions of these, and by other criteria. Each criterion produces a different ranked list of SWiPs. The question is, Which list is best? That is, which of the alternative ranking criteria points to SWiPs at which the most cost-effective safety projects can be found? This question was examined by Hummer et al. (*1*).

The approach to answering this question was outlined earlier (*2*, pp. 27–28). The four steps of the approach are as follows:

1. Compare the performance of two ranking criteria, and apply both criteria to the same set of sites to generate two ranked lists of SWiPs.
2. At those top-ranked SWiPs that are not common to both lists, perform a DES.
3. The DESs will point to projects to enhance safety. Estimate the anticipated costs and safety benefits for each project.
4. The ranking criterion that is shown to lead to more cost-beneficial projects will be deemed better.

This general approach was implemented on rural two-lane roads in Colorado. The design of this study, its execution, analysis, and conclusions are described here.

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STUDY DESIGN

Five different criteria were used to produce five ranked lists of SWiPs for rural two-lane roads in Colorado's mountainous terrain. Four lists were produced by using Profile & Peak (P&P) software. This software was coded in Visual Basic according to the principles given by Hauer et al. (*2*) and is described in a series of downloadable working papers (*3*). In general, the process involves the calibration of a regression model that provides, for any annual average daily traffic (AADT), an estimate of what is normal. This is combined with the accident count of each site into an empirical Bayes estimate of expected accidents, and the highest peak meeting some statistical reliability criterion is identified.

Sites were ranked by P&P in accord with four criteria:

Criterion 1. Sites where most accidents are expected;
Criterion 2. Sites where most severity-weighed accidents are expected;
Criterion 3. Sites where most excess accidents are expected; and
Criterion 4. Sites where most severity-weighed excess accidents are expected.

The rankings are given in Table 1, which shows the first 20 SWiPs when ranking is by Criterion 1. Thus, by Criterion 1, the highest-ranking site (26) is on Segment G of Highway 6, which begins at Milepost 264 [Beginning milepost (Bmp = 264)] and ends at Milepost 266.42 [Ending milepost (Emp = 266.42)]. The SWiP (the peak) is that part of this segment that begins $^{16}\!/_{10}$ mi ($L = 16$) from the beginning milepost, that is, at Milepost 265.6; the SWiP ends at the right edge of $^{17}\!/_{10}$ mi ($R = 17$) from the beginning milepost, that is, at $1.7 + 0.1 = 1.8$ mi from 264, at Milepost 265.8.

Note that because in Table 1 the ranking is by Criterion 1, the rank in Column 14 is the arithmetic series 1, 2, 3, . . . , 39, 40. Were one to rank by Criterion 2, the rank order would be that shown in Column 15. The highest rank by Criterion 2 would also be on Segment G of Highway 6, but the SWiP now begins at 264.0 + 0.1 and ends at 264.0 + 2.5 + 0.1. Were one to rank by Criterion 3, the highest-ranking site is 23, which is also on Segment G of Highway 6 but is now between Milestones 258 and 259.95. The peak is just 0.1 mi long and begins at 258 + 1.3 = 258.3.

The fifth criterion, score, was used to produce an additional ranked list. The score column is the product of the accidents per mile per year and the number of standard deviations above what would be normal for such a site (%SD DEV). Accordingly,

Criterion 5. Sites at which the product (accidents/mile-year) × (excess accidents/mile-year in standard deviations) is highest.

The next task was to select from the five ranked lists a limited set of sites at which to perform a DES. These had to be so chosen that the cost-effectiveness of projects defined by one criterion could be

TABLE 1 SWiP Rankings by Criterion 1

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
					Criterion 1		Criterion 2		Criterion 3		Criterion 4		Rank			
Site	Hwy	Segment	Bmp	Emp	L	R	L	R	L	R	L	R	1	2	3	4
26	6	G	264	266.42	16	17	1	25	16	16	16	16	1	1	2	1
23	6	G	258	259.95	12	14	1	19	13	13	13	13	2	2	1	2
289	40	A	244.2	245.58	4	8	0	0	5	6	4	8	3	16	3	4
763	285	D	240.8	241.23	1	4	0	0	0	0	0	0	4	14	42	42
570	119	A	30.66	36.42	19	23	9	29	22	22	21	22	5	3	4	3
432	74	A	14.56	17.53	25	29	7	30	25	26	27	29	6	5	6	9
272	36	B	10.8	11.83	1	6	0	0	2	2	2	3	7	18	5	5
290	40	A	246.19	247.48	1	12	0	0	0	0	0	0	8	15	41	41
573	119	A	39.03	40.4	5	11	0	0	0	0	0	0	9	17	26	26
429	74	A	10.8	14	17	24	4	24	11	13	17	23	10	4	12	10
572	119	A	36.81	38.93	11	20	0	0	0	0	0	0	11	25	27	27
403	72	A	12.77	17.47	11	21	11	44	18	20	6	44	12	6	9	14
532	119	A	4.59	6.09	2	15	0	0	0	0	0	0	13	26	29	29
480	91	A	19	22.1	5	15	0	0	5	8	3	7	14	28	14	6
25	6	G	260.32	263.32	17	24	0	0	0	0	0	0	15	29	35	35
264	34	A	80.19	83.27	8	24	0	0	0	0	0	0	16	19	54	54
	24	A	279.71	281.97	4	20	0	0	0	0	0	0	17	34	47	47
732	285	D	201	203.28	1	17	0	0	1	2	1	2	18	36	11	8
790	550	B	32.4	35.35	2	20	0	0	0	0	0	0	19	37	37	37
783	550	B	27.61	29.73	1	21	0	0	0	0	0	0	20	20	44	44
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efficiently compared to the cost-effectiveness of projects selected by all other criteria. To illustrate the process, Table 2 shows the top 10 SWiPs ranked by Criteria 1 and 2. The sites in the shaded cells are included in both rankings. Nothing can be learned about the relative performance of these two ranking criteria by examining the cost-effectiveness of projects at the common sites. To discriminate between Criterion 1 and Criterion 2, one must contrast the cost-effectiveness of projects at sites {289, 763, 272, 290, 573} chosen by Criterion 1 but not by Criterion 2 with that of projects at sites {403, 172, 144, 147, 41} chosen by Criterion 2 but not by Criterion 1. The full set of contrast comparisons is in Table 2. To perform these, a DES was needed at 22 sites.

CONDUCT OF DESs

The DESs were performed by the first three authors at the Colorado Department of Transportation (CDOT) offices in Denver. In preparation, an abbreviated report was written for every segment containing a SWiP. Each such report consists of about 10 pages of tables and figures describing the accident history of the segments in comparison with similar roads. Appended to each report was a geographic information system (GIS) graph showing the horizontal alignment of the segment, the mileposts (marked by an x), and the location of accidents for the 1986–1999 period on a bar perpendicular to the alignment: a circle for a property-damage-only (PDO) accident, a

TABLE 2 Contrast Comparisons

Comparison	Site in by Criterion X and not by Y	Site in by Criterion Y and not by X
1	In by 1 and not in by 2: {272, 289, 290, 573, 763}	In by 2 and not in by 1:{41, 144, 172, 403, 147}
2	In by 1 and not in by 3: {147, 290, 429, 432, 573, 763}	In by 3 and not in by 1: {3, 21, 403, 668}
3	In by 1 and not in by 4: {147, 290, 432, 573, 763}	In by 4 and not in by 1: {480, 668, 732}
4	In by 1 and not in by 5: {147, 272, 289, 290, 429, 432, 763}	In by 5 and not in by 1: {326, 480, 514, 567, 572, 770}
5	In by 2 and not in by 3: {41, 144, 147, 429, 432}	In by 3 and not in by 2: {3, 21, 272, 289, 668}
6	In by 2 and not in by 4: {41, 144, 147, 172, 403, 432}	In by 4 and not in by 2: {272, 289, 480, 668, 732}
7	In by 2 and not in by 5: {41, 44, 147, 172, 403, 429, 432}	In by 5 and not in by 2: {326, 480, 514, 567, 572, 573, 770}
8	In by 3 and not in by 4: {3, 21, 403}	In by 4 and not in by 3: {429, 480, 732}
9	In by 3 and not in by 5: {3, 21, 272, 289, 403, 668}	In by 5 and not in by 3: {326, 480, 514, 567, 572, 573, 770}
10	In by 4 and not in by 5: {272, 289, 429, 668, 732}	In by 5 and not in 4: {326, 514, 567, 572, 573, 2770}

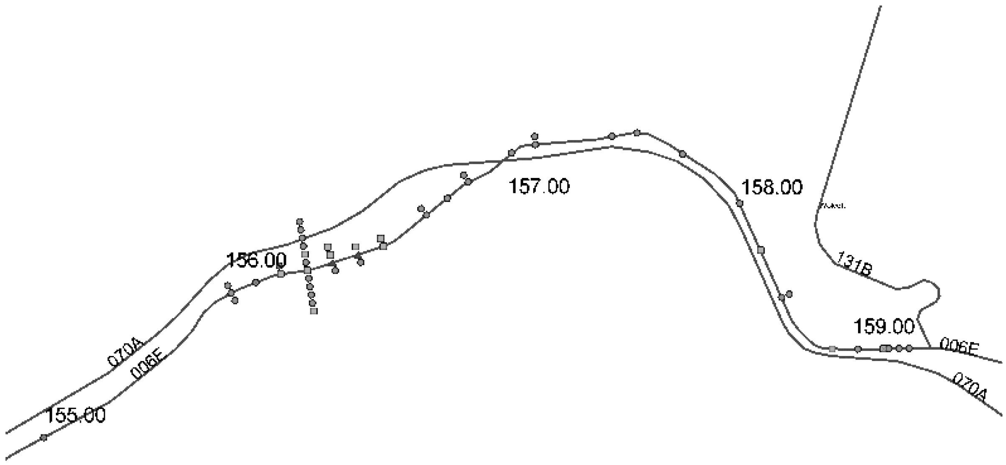

FIGURE 1 Alignment and accident history for Site 3 (Highway 6, Segment E, Mileposts 155.00 to 159.13).

square for an injury accident, and a triangle for a fatal accident. The graph for Site 3 is shown as Figure 1.

In addition to these, an accident data spreadsheet was prepared, containing all coded accident information for the site of interest, one row per accident. An extract of a few rows and columns from the spreadsheet for Site 3 is given in Table 3.

The conduct of a DES entailed a number of steps. The first was to peruse the abbreviated report. Next, the SWiP was identified by its mileposts on the GIS graph, and the location and accident pattern were examined visually. Then, the accident data spreadsheet for the segment was used to analyze the accident information of the SWiP. By using the filter facility of the spreadsheet, a quantitative mental picture was developed of the accident characteristics: how many off-road and on-road accidents occurred, which side of the road was involved, what objects were struck, whether there were many opposite-direction accidents, whether more accidents than usual tended to occur during inclement weather, on icy, snowy, or slushy roads, at night, and so forth. After this detailed information from the accident data spreadsheet had been assimilated, the videolog tape of the site was driven through a few times. Occasionally, it was necessary to retrieve the hard copy of some accidents to clarify the circumstances of their occurrence. The accident-data spreadsheet and the videolog viewer were compared until a consensus was reached about what actions (projects) could be considered at this SWiP. Thus, for example, at Site 3 two actions were chosen: add a cable guardrail on the south side from Milepost 156.1 to 156.3 and perform local grading of the shoulder and eliminate the ditch near the crest.

Once the actions (projects) for a SWiP were agreed on, the cost and safety effect of each action was estimated. The cost of an action was estimated on the basis of CDOT's experience with similar projects. The target accidents for each action were jointly identified. Thus, for example, the target accidents for Action 1 (addition of a cable guardrail on one side of a curve) were the off-the-road accidents occurring on the south side of the road between 156.1 and 156.3. These were later counted, by severity, by again using the accident data spreadsheet. (This was done by setting the milepost filter to 156.1–156.3, setting the location filter to off-right when the direction filter was set to earthbound, and setting the location filter to off-left when the direction filter was set to westbound.) Finally, the effect of each action on the target accidents for percent reduction was estimated on the basis of what is usually used by CDOT staff in their analyses.

A considerable amount of judgement is involved in the DES. For the purposes of this study, the overriding consideration was consistency. That is, an attempt was made to ensure that for each

TABLE 3 Accident Data Spreadsheet

Hwy	Mile-post	Severity	Location	Vehicles	Contour	Condition	Lighting	Weather	Event_1	
006E	156.10	INJ	OFF RIGHT	1	CURVE ON-LEVEL	ICY	DAYLIGHT	NONE	DELINEATOR POST	...
006E	156.10	PDO	OFF LEFT	1	STRAIGHT ON-GRADE	ICY	DAYLIGHT	NONE	LARGE BOULDER	...
006E	156.20	INJ	OFF LEFT	1	CURVE ON-LEVEL	DRY	DAWN OR DUSK	NONE	OVERTURNING	...
006E	156.20		ON	2	CURVE ON-GRADE	ICY	DAYLIGHT	NONE	SIDESWIPE SAME DIRECTION	...
006E	156.20		OFF RIGHT	1	CURVE ON-GRADE	ICY	DAYLIGHT	NONE	OVERTURNING	...
006E	156.20	INJ	OFF LEFT	1	CURVE ON-GRADE	ICY	DAYLIGHT	NONE	OVERTURNING	...
...	...	...	...	...	...	...	...	...	...	...

site the same kinds of judgments are made about what actions may be appropriate, the cost of the proposed action, the target accidents of the action, and what safety effect the action is likely to have. Although it is important to make a good guess about the cost and safety effect of an action, for the purposes of this study, it was more important to be consistent in the guesses across all actions.

ANALYSIS AND RESULTS

The information from the DES and some preparatory computation were entered in a spreadsheet, parts of which are given in Table 4.

The first two columns of Table 4 are self-explanatory. The third column gives the ranking criterion by which this site was identified. The next two columns refer to the number and type of action recommended at a site. Thus, for example, at Site 3 two actions were recommended. Each action has its costs and project life. For compatibility, all costs were converted to an annual cost. In Table 4 the interest rate (I) of 10% was used for this computation. With $I = 10\%$, capital expenditure of \$20,000 is equivalent to 20 equal annual installments of \$2,349 (assuming no salvage value). In some cases there was no capital cost (e.g., when a site had to be pretreated each year with sodium chloride to reduce the hazard of slippery road surface conditions), and the annual cost of the action was entered directly (see Site 144, Action 1).

The 9th, 10th, and 11th columns of Table 4 give the number of fatal, injury, and PDO target accidents that occurred at the project sites during the 14-year period of 1986 to 1999. Target accidents are those whose occurrence could be affected by the recommended project. As noted earlier, at Site 3 the first recommended action was the installation of a cable guardrail on one side of the curve. Accordingly, given are the one fatal, five injury, and four property-damage-only off-the-road accidents that occurred on the affected side of the road. The accident modification factor used by CDOT for this type of guardrail is a reduction of PDO accidents by 20% and of fatal and nonfatal injury accidents by 60%. These values are given in the 12th, 13th, and 14th columns of Table 4.

The expected annual saving in (raw) fatal accidents can be estimated as $1 \times 0.60/14$ years $= 0.043$. Similarly, $5 \times 0.60/14 = 0.214$ is the estimate of the expected annual reduction injury accidents and $4 \times 0.2/14 = 0.057$ of the reduction in PDO accidents. By using \$1,000,000, \$35,000, and \$6,500 as the costs of fatal, nonfatal injury, and PDO accidents, respectively, the annual saving is $1{,}000{,}000 \times 0.043 + 35{,}000 \times 0.214 + 6{,}500 \times 0.057 = \$50{,}729$. Because the annual cost of Action 1 at Site 3 is \$2,349, the benefit–cost ratio here is \$50,729/\$2,349 = 21.6.

Two assumptions are made in this computation. First, the applicable interest rate is 10%; the sensitivity of the results to this assumption will be examined later. Second, the expected number of accidents can be estimated by the average of the recorded number of accidents. Although a 14-year-long accident record has been used, the numbers are usually small and therefore given to random variation. This may introduce a large noise into the results, particularly when the widely disparate cost weights are applied to small accident counts by their severity. In addition, because the SWiPs for the conduct of the DES were selected on the basis of the same 14-year accident history (even if not of the specific target accidents), there is danger of the regression-to-mean bias. To remedy this, similar computations will be done by using the empirical Bayes estimates of expected accidents by severity.

Comparisons That Use Raw Accident Counts

The question originally posed concerned which of the five ranking criteria yields the most cost-effective projects. The answer is provided through pairwise comparisons, starting with a comparison of the cost-effectiveness of actions selected by using Criterion 1 (ranking by expected frequency) and Criterion 2 (ranking by expected severity-weighed accident frequency). The criterion leading to superior results will be retained for further comparisons, and the criterion leading to inferior results will be dropped from further consideration.

To prepare the comparisons, the rows in Table 5 were sorted first by the Criterion column and then by the Annual Benefit/Cost column. Because there are often several actions at the same site, it was necessary to account for the possible overlap of their effect. Thus, for example, Action 2 at Site 432 is expected to reduce on-the-road accidents (1 fatal, 26 injury, and 22 PDO) by 20% with a benefit–cost ratio of 257/1. Action 1 at the same site applies to all accidents (off and on the road) but has a lower benefit–cost ratio. Therefore, Action 2 takes precedence over Action 1. To avoid double counting, the accident reduction that is due to Action 2 (which applies to on-the-road accidents) must be accounted for before computation of the benefit that is due to the implementation of Action 1. Accordingly, after Action 2 is implemented, one should expect $1 - 1 \times 0.2 = 0.8$ fatal, $41 - 26 \times 0.2 = 35.8$ injury, and $53 - 22 \times 0.2 = 48.6$ PDO on-the-road accidents. Only these are subject to the further effect of Action 1. Similar adjustments were made to all accident counts. After these adjustments, the data were resorted, within each ranking criterion, in the decreasing order by the estimated annual benefit–cost ratio, as shown in Table 5.

The results are best presented as cumulative annual costs and benefits. Figure 2 compares the costs and benefits of projects at Sites 272, 289, 290, and 763, identified by Criterion 1 and not Criterion 2 (black squares), and of projects at Sites 41, 144, 172, and 403, identified by Criterion 2 and not Criterion 1 (circles). In comparing the squares and circles, two things matter. First, when the squares suggest a curve that is above the curve suggested by the circles, then, for any cumulative cost chosen, actions selected by Criterion 1 (black squares, expected accident frequency) have higher safety benefits than actions selected by Criterion 2 (circles, severity-weighed expected accident frequency). Second, the slope of the suggested curve (either the squares or the circles) at any cumulative cost measures the benefit–cost ratio at that point.

In Figure 2, the sites selected by Criterion 1 (and not Criterion 2) have more profitable actions (projects) than sites selected by Criterion 2 (and not Criterion 1). Although the difference is not large, its direction is unexpected. One could expect better results when ranking is by Criterion 2, in which accident savings of fatal, injury, and PDO accidents are given different weights, than when ranking is by Criterion 1 and accident severity is not accounted for. One could expect better results than when ranking is by Criterion 1 and severity is not accounted for.

It was noted earlier that the computations depend on the interest rate used to convert capital into annual costs. So far, $I = 10\%$ has been used. The computations were repeated with $I = 5\%$ and $I = 15\%$. The effect of use of a different interest rate amounts (approximately) to a rescaling of the horizontal axis in Figure 2. Since the ordinates of all point remains the same, while the abscissa expands or contracts with the choice of the interest rate, the relative position of the squares and the circles remains the same. Thus, the comparison of the cost-effect performance of two criteria is by and large independent of the interest rate used.

TABLE 4 Data for Analysis

Row	Site #	Ranking Criterion	Action #	Action Type	Capital Cost	Project Life	I=10% Annual Cost	Raw Target Accidents Fatal	Raw Target Accidents Injury	Raw Target Accidents PDO	% Reduction Fatal	% Reduction Injury	% Reduction PDO	Annual Accidents Fatal	Annual Accidents Injury	Annual Accidents PDO	Annual $ Saved	Annual Benefit/Cost
1	3	3	1	Cable Guardrail	20000	20	2349	1	5	4	60	60	20	0.043	0.214	0.057	50,729	21.6
2	3	3	2	Shoulder Grade	10000	30	1061	1	5	7	20	20	20	0.014	0.071	0.100	17,436	16.4
3	21	3	1	Widen & Separate	30000	20	3524	0	4	6	30	30	30	0.000	0.086	0.129	3,836	1.1
4	21	3	2	Signage, Rumble	3000	10	488	0	2	6	5	5	5	0.000	0.007	0.021	389	0.8
5	41	2	1	Shoulder Pave 2'	295000	20	34651	2	47	42	25	25	25	0.036	0.839	0.750	69,964	2.0
6	144	2	1	Pretreat	NA	1	4000	0	18	19	30	30	30	0.000	0.386	0.407	16,146	4.0
7	144	2	2	Shoulder Pave 4'	353000	20	41463	2	14	29	30	30	30	0.043	0.300	0.621	57,396	1.4
8	147A	2	1	Sign, Stripe, & Delin.	11000	4	3470	0	18	19	15	15	15	0.000	0.193	0.204	8,073	2.3
9	147A	2	2	Edge Rumble	11400	10	1855	2	18	20	20	20	20	0.029	0.257	0.286	39,429	21.3
10	147B	1	1	Sign, Stripe, & Delin.	8400	4	2650	1	10	25	15	15	15	0.011	0.107	0.268	16,205	6.1
. . .																		

TABLE 5 Sorted and Modified Data for Criterion 1

Row	Site #	Ranking Criterion	Action #	Action Type	Annual Cost	Raw Target Accidents			Annual $ Saved	Annual Benefit/ Cost
						Fatal	Injury	PDO		
41	432	1	2	Median Rumble	114	1	26	22	29329	257.4
40	432	1	1	Reduce to 11'	88	0.8	35.8	48.6	16921	192.1
35	429	1	1	Cable Guardrail	235	0	7	0	10500	44.7
11	147	1	2	Edge Rumble	1465	1	12	16	21771	14.9
27	290	1	3	Cable Guardrail	4698	1	9	9	57193	12.2
22	289	1	1	Cable Guardrail	6225	1	13	24	64586	10.4
59	763	1	2	Widen & Separate	1175	0	9	21	9675	8.2
16	272	1	3	Warn. etc.	2208	1	33	32	16879	7.6
25	290	1	1	Grade and Delineate	587	0	6	11	3016	5.1
10	147	1	1	Sign &Strip &Del.	2650	0.8	9	23.8	13604	5.1
58	763	1	1	Upgr. & Extend Guardr.	4111	1	6	8	19900	4.8
14	272	1	1	Cable Guardrail	1175	0	3.6	1.53	5542	4.7
26	290	1	2	Widen & Separate	1175	0	4	9	4254	3.6
15	272	1	2	Reg. Guardrail	1175	0	3.6	5.4	3600	3.1
17	272	1	4	Reduce to 11'	235	0	0	3	139	0.6

Figure 3 is a comparison of Criterion 1 (expected accident frequency) and Criterion 3 (expected excess accident frequency). Criterion 1 appears to decisively outperform Criterion 3. The comparison of Criterion 1 (expected accident frequency) and Criteria 4 (expected severity-weighed excess accident frequency) and 5 lead to the same clear conclusion.

On the basis of these comparisons, it appears that identifying sites by expected accident frequency (Criterion 1) leads to most cost-effective projects.

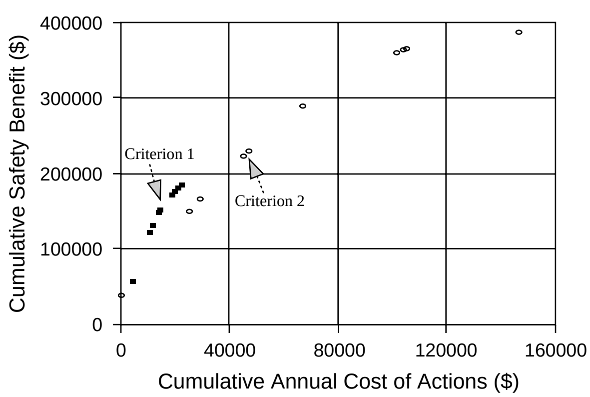

FIGURE 2 Comparison of Criteria 1 and 2.

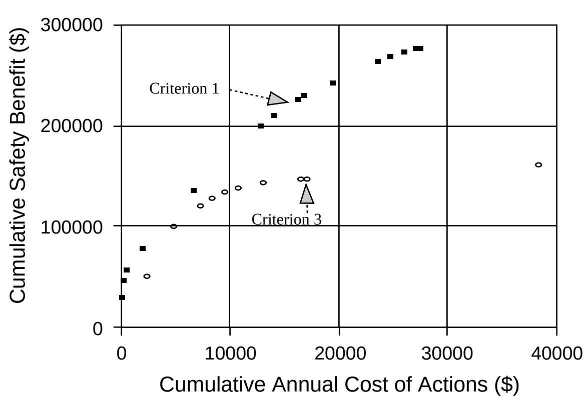

FIGURE 3 Comparison of Criteria 1 and 3.

In this section, the safety effect was estimated by the product: (count of past accidents, by severity) × (estimated % reduction, by severity). This has the advantage of simplicity. However, there are two potentially serious drawbacks: the exaggeration of random noise by the severity weighing of fatal accidents and the potential for regression-to-mean bias. In the next section, an attempt is made to avoid these drawbacks by using the empirical Bayes approach to estimation.

Comparisons by Using Empirical Bayes Estimates

In this section, the terminology and procedures of Hauer are used (*4*). To produce an empirical Bayes estimate, an estimate of the number of accidents expected on similar entities and an estimate of the overdispersion parameter are needed. Whereas models for mountainous two-lane roads in Colorado were estimated, these predict only total and injury accidents, and AADT is the only explanatory variable. There are no current models that can predict, say, off-road accidents or on-road accidents, nighttime or daytime accidents, accidents when the road surface is icy, snowy, or slushy, and so forth. However, this study's actions (projects) are oriented toward target accidents under such specific conditions. To make up models for these specific conditions, the ad hoc device of multiplying the prediction for total accidents by the corresponding proportion has been used. Thus, for example, the proportion of on-the-road accidents on rural two-lane roads in the mountainous terrain of Colorado is 0.3879. Accordingly, to predict the number of on-road accidents on similar roads, 0.3879 was used to multiply the model prediction for total accidents. This is an imperfect remedy since different accident types show different dependence on AADT. Even this ad hoc remedy is often insufficient. Thus, for example, many actions are aimed at reducing accident occurrence on tight horizontal curves, segments with large grades, and so forth. The information needed to adjust estimates to these conditions is not available. Although the empirical Bayes estimate can, in theory, correct for some flaws, it does so only when the sites to which it is applied are drawn at random from a reference population defined by similarity of traits. In the present case, roads that are genuinely similar to those identified for action are in many cases roads with sharp curves and steep grades, whereas all the roads for which there are models are rural two-lane roads in mountainous terrain in Colorado. These include segments with sharp curves as well as relatively straight segments and roads on steep as well as mild grades. Therefore, there can

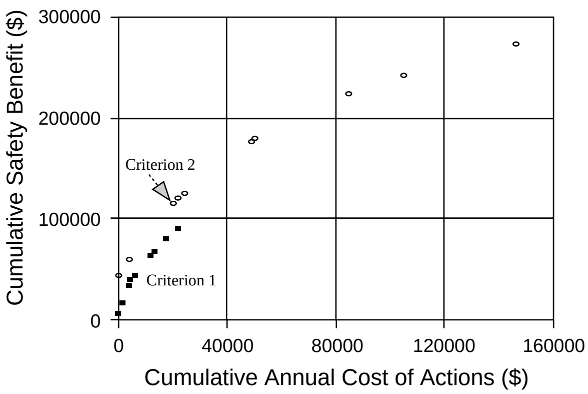

FIGURE 4 Empirical Bayes comparison of Criteria 1 and 2.

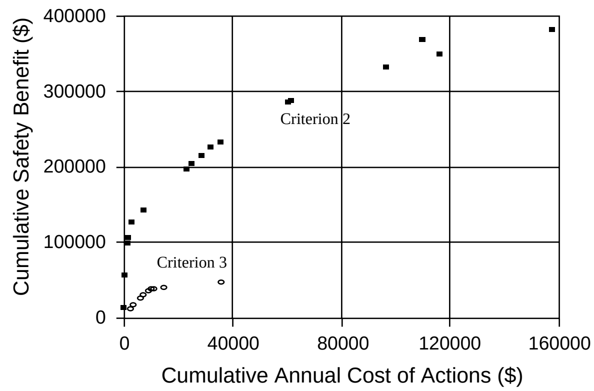

FIGURE 5 Empirical Bayes comparison of Criteria 2 and 3.

be legitimate doubt about the correspondence between the segments to which the empirical Bayes estimate is applied and the reference population used. Under such conditions, the general tendency of the empirical Bayes estimate is to overcorrect, to produce estimates that are smaller then what they should be.

Starting again with the comparison of Criteria 1 and 2, this time by using empirical Bayes estimates, the result is as shown in Figure 4. The difference between the performances of these two criteria is small. However, the sense of the comparison is now reversed. As originally anticipated, Criterion 2 (severity-weighed expected accident frequency) is seen to perform slightly better than Criterion 1 (expected accident frequency). Therefore, Criterion 2 is retained for further comparisons.

The comparison between Criterion 2 and Criterion 3 is shown in Figure 5. Criterion 2 (severity-weighed accident frequency) clearly dominates Criterion 3 (excess of accident frequency) and survives to the next round.

The comparison between Criterion 2 and Criteria 4 and 5 confirmed the primacy of Criterion 2 even more conclusively. Thus, when empirical Bayes estimates are used, ranking of SWiPs by Criterion 2 (severity-weighed expected accident frequency) leads to more cost-beneficial projects than the four other ranking criteria examined.

SUMMARY, CONCLUSION, AND DISCUSSION

Five criteria were used to rank SWiPs for rural two-lane roads in the mountainous terrain of Colorado. At 22 of the top-ranking sites chosen by the five criteria, a detailed engineering analysis was performed to estimate the costs and safety benefits of 61 actions (projects). When cumulative annual costs and benefits were compared, Criterion 1 (ranking by accident frequency) and Criterion 2 (ranking by severity-weighed expected accident frequency) performed better than Criteria 3, 4, and 5, which make use of excess accident frequency.

This result is to some extent preordained. To estimate the annual safety effect of some action, normal procedure is to use the product (expected number of accidents of some kind/year) × (% reduction in such accidents/100). Note that the factor "% reduction in such accidents/100" (or related indices, such as accident modification factors) is what all research into the safety effect of countermeasures produces. The safety effect of some action is never estimated by the product: (number of excess accidents of some kind/year) × (% reduction in such excess accidents/100). This could not be done even if desired, because the factor "% reduction of excess accidents" is never estimated by research and is therefore not known. Thus, it should be a surprise that Screening Criteria 1 and 2, which are based on accident frequency, outperform Screening Criteria 3, 4, and 5, which are based on excess accident frequency. If one assumes that the reduction in accident frequency is proportional to accident frequency, then it follows almost necessarily that ranking SWiPs by accident frequency will lead to projects showing the larger benefits. Were one to assume that the safety benefit of some action is proportional to the excess accident frequency, the result could be different. Such speculation is not worthwhile because accident modification factors related to excess accident frequency do not exist.

Although the result is reasonable, this study is not definitive. The number of sites at which a DES has been done is not large, the conduct of a DES requires judgment that may vary from one person to the next, the accident modification factors used may not be precise, and neither estimates based on the raw accident data nor empirical Bayes estimates are free of bias. As always, replication by others is necessary.

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