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Benefits of Slope Flattening

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Abstract
The benefits of slope flattening were investigated by simulating accident costs with updated foreslope severities based on real-world accident data collected over a 7-year period in the State of Ohio. Functional classes considered were freeways, rural and urban arterials, and rural and urban local highways. Highways were modeled using the Roadside Safety Analysis Program (RSAP). Highway parameters considered in RSAP were slope steepness, roadway curvature, percent grade, longitudinal length, fill height, and lateral offset to the slope break point. Simulated accident costs were incorporated into a Microsoft Excel spreadsheet, where future users can specify installation costs, which tend to vary significantly from one location to another for slope flattening applications. Each functional class demonstrated slope flattening trends. On freeways and urban arterial highways, slopes should be no steeper than 1V:3H, and the benefit of flatter slopes was minimal. On rural arterial highways, the slope should be no steeper than 1V:4H, and the benefit of flatter slopes was also minimal. On local highways, the steepest slope should be 1V:3H, but the slope should be made as flat as possible because accident costs continued to decrease as the slope was flattened.

Keywords: roadside safety, benefit-cost analysis, RSAP, severity index, roadside slopes, embankments

1. Introduction

Historically, engineering judgment has been used to design roadside slopes. As a result, foreslope designs were very inconsistent. Plus, crash severity for different slopes with varying steepness has been very subjective because they have been based on judgment rather than analytical and/or experimental studies.

To make this subject even more complex, determination of the best slope design has to take into consideration not only safety but also costs so that the selection be based on a benefit–cost (B/C) analysis. Programs such as the Roadside Safety Analysis Program (RSAP) (Mak & Sicking, 2002) have been used to conduct B/C analyses of highway safety improvement options, but it is still cumbersome to apply it to every possible highway scenario and difficult to implement among engineers statewide. This can be attributed to the fact that costs to retrofit existing slopes with flatter slopes can be significantly different from case to case. Implementation costs may be influenced by soil availability, transportation distances, and the cost to purchase right-of-way alongside the road. Not only that, but also societal cost estimates have increased significantly since 1991 (Miller et al., 1991) and will likely continued to do so. With shrinking budgets, it has become expedient to develop a systematic approach to designing roadside geometries and safety appurtenances that economically create a safe environment.

In particular, single-vehicle run-off-road (SVROR) accidents were treated in this research. These accidents accounted for approximately 15% of all crashes and nearly one third of all fatal crashes in 2010 (National Highway Traffic Safety Administration [NHTSA], 2010). Embankments alone accounted for approximately 0.9% of all crashes, but nearly 3% of all fatal crashes (NHTSA, 2010). As an attempt to mitigate this problem, this study focused on the benefits of treating roadside slopes by flattening them. The slope of the roadside was defined by a rise-over-run designation, with the rise always equal to 1 unit. For example, a slope with a vertical (V) rise of 1 unit and a horizontal (H) run of 2 units would be designated as 1V:2H.

2. Literature Review

Past research studies have investigated the impact of roadside slopes on crash severity. In the 1970s, Glennon (1974) and Post (1977) conducted studies to determine how variations in slope steepness impacted crash severity. They collected and analyzed SVROR accident data. The safety effect of sideslopes with different steepness was examined. Crash severities from road with 1V:6H, 1V:4H, and other steeper sideslopes were compared. Different highway classifications were adopted as well. The SVROR data was collected in multiple states in the Midwest region.

In the study conducted by Glennon (1974), B/C analyses were conducted to provide guidelines for where and when to adopt a specific sideslope. From these B/C analyses, it was found that the decisions on roadside design should be flexible. That is, they should change according to roadway, roadside, and traffic characteristics. Thus, roadside design policies (i.e., adoption of allowable slope steepness) should be adjusted for each highway section group with similar characteristics. For instance, it was found that the use of

6:1 slopes can be more cost-effective than 4:1 slopes at traffic volumes between 2,000 and 4,000 vehicles per day (vpd). In a study conducted by Post (1977) at the University of Nebraska—Lincoln the probability of injury accidents was found to significantly decrease by flattening driveway slopes from 3:1 to 8:1. This study also showed that the most cost-effective improvement was a driveway slope from 6:1 to 8:1, while flattening a driveway slope from 8:1 to 10:1 was not cost-effective (Post, 1977).

Zegeer (1988) studied the accident benefits of various roadside improvements. Detailed crash and roadside data were gathered from 4,951 miles of two-lane rural roads in multiple states. Roadside data included field sideslope measurements. Data analysis revealed that flattening slopes from 1V:3H to 1V:7H lowered rates of single-vehicle accidents (Zegeer, 1988). However, only a 2% reduction in single-vehicle accidents was found for a 1V:3H sideslope compared to a 1V:2H sideslope.

Past research has also established the strong relationship between slope steepness and rollover propensity, which tends to increase injury propensity and severity. Deleys and Parada (1986), investigated the likelihood of rollovers on different slope configurations. They concluded that the sideslope of fill embankments should be no steeper than 1V:3H, and preferably flatter, for fill heights greater than 3 ft (0.9 m) to reduce rollover likelihood.

3. Problem Statement

Even though past research has investigated the relationship between accident severity and slope steepness, they have been based on inaccurate severity indexes (SIs). That is, SIs of slope/embankment crashes have been primarily based on judgment rather than scientific investigation. In addition, B/C procedures use these indexes resulting in outputs that cannot be reliable to say the least. These indexes are likely to be overestimated because one may argue that overestimation of SIs tend to be more "conservative." However, one cannot say that conservatism implies more funding on safety alternatives that cannot produce the highest benefit. To correct these indexes and conduct more reliable B/C analyses, engineers need to calibrate indexes used in B/C procedures based on real-world accident data and estimate the safety benefit of slope flattening.

4. Objectives

The objectives of this research are twofold: (1) calibrate the SIs contained in RSAP with real-world crash data and (2) provide guidance on the benefits associated with slope flattening.

5. Research Approach

To accomplish the objectives of this research study, the SIs used by RSAP were updated according to real-world accident data. A parametric analysis was performed to identify the parameters used in RSAP that significantly influenced accident costs. Then, safety alternatives were selected from available features in RSAP, which included flattening the slope to varying steepnesses or doing nothing. RSAP models were generated and simulated for more than 50,000 scenarios. Once the simulations were complete, accident costs were extracted from the data and used to develop a relationship between average daily traffic (ADT) and accident cost for each of the simulated scenarios. Finally, recommendations were provided based on findings.

6. Calibration of Severity Indexes in RSAP

Accident data from the State of Ohio between 2000 and 2006 was used to correlate accident severity with slope embankments. This was done by adjusting the severity index (SI) in RSAP until the output matched the accident data. RSAP output is given on an annual basis and in terms of the number accidents, traffic volume, and posted speed limit. First, the data was filtered to include only accidents involving SVROR events and severe (A) or fatal (K) injuries. Filtering continued by including only accidents in which the first harmful event or most harmful event was a traversal of an embankment (i.e., impacts with fixed objects, like trees, were excluded). This filtering resulted in a total of 816 crash events.

Next, slopes were defined according to their steepness and height. These definitions coincided with default options in RSAP and included slope rates of 1V:2H, 1V:3H, 1V:4H, and 1V:6H and embankment heights of 1, 7, and 13 ft (0.3, 2.1, and 4.0m). Then, a program called Global Mapper was used to read Light and Detection and Ranging (LiDAR) files, which contain topographical data of the entire state of Ohio. This alone provided incentive to utilize data from Ohio, considering most states do not have accident data and LiDAR files. Using the topographical tool, the slope steepness and height could be measured at any location, including the roadside immediately adjacent to accident locations. These measurements were done at each of the 816 accident locations, and the accident was categorized into one of the slope-height categories.

RSAP requires a length scale (e.g., length of the embankment in the model). Therefore, to correlate real-world accident data to SI via RSAP, the statewide length of each of the slope-height categories had to be estimated. This was done by randomly selecting 150 segments across the state and measuring each segment every 100 ft (30.5 m), for a total of 5,300 feet (1,615 m), or approximately one mile. These random locations were chosen by tabulating the roadway description inventory reports for the highway network in Ohio. By doing so, segments in the table were defined by various features, such as mileposts or intersections with other roads. A random number generator was used to select 150 of these segments. Then, an additional random number was used to select a starting milepost within that segment. Using these measurements, the estimated mileage of 1V:2H, 1V:3H, 1V:4H, and 1V:6H slopes was determined. Each measurement was assumed to represent the midpoint of the interval, such that the single-point measurement applied to the entire 100-ft (30.5-m) region.

A complication arose on steeper slopes. Originally, the severity estimates (number of accidents per mile) of the flatter slopes (1V:4H and 1V:6H) was higher than for the steep slopes (1V:2H and 1V:3H). This was contributed to the more-frequent use of longitudinal barriers on steep slopes, per guidance in the *Roadside Design Guide* (AASHTO, 2006). Therefore, steep locations from the 150 random segments were located using Google satellite images, and the presence of longitudinal barriers was noted. Then, the total mileage of the steep slopes was reduced to represent an unshielded length. By doing so, the severity estimates of the steeper slopes exceeded the severity estimates of the flatter slopes.

Finally, the estimated lengths were applied to the accident data, which was sorted according to functional class, traffic volume, and speed limit (all of which was contained in the accident database supplied by Ohio). For each functional class, the number of accidents as normalized to 10,000 vpd, which was used as a constant input parameter in RSAP. Then, the severity estimate was increased or decreased according to the distribution of posted speed limits for each functional class. The baseline speed was 55 mph (88.5 km/h), and was used as a constant input parameter in RSAP. If the average speed for a functional class was above this baseline, then the severity estimate was increased, and vice versa. The number of A+K accidents that RSAP was expected to match are shown in Table 1.

Table 1. Expected number of A+K (severe + fatal) accidents from real-world data.

	Height (ft)				*Height (ft)*		
Slope	*1*	*7*	*13*	*Slope*	*1*	*7*	*13*
	Freeway				*Rural Arterial*		
1 to 2	0.0018	0.0012	0.0073	1 to 2	0.0012	0.0245	0.0203
1 to 3	0.0000	0.0008	0.0013	1 to 3	0.0101	0.0068	0.0205
1 to 4	0.0000	0.0013		1 to 4	0.0021	0.0038	0.0021
1 to 6	0.0004			1 to 6	0.0026		
	Urban Arterial				*Local*		
1 to 2	0.0031	0.0043	0.0117	1 to 2	0.0803	0.2534	0.1070
1 to 3	0.0013	0.0003	0.0000	1 to 3	0.0448	0.0254	0.1291
1 to 4	0.0003	0.0007		1 to 4	0.0074	0.0132	
1 to 6	0.0007			1 to 6	0.0257		

Table 2. Modification factors for severity index of foreslopes in the Roadside Safety Analysis Program

	Height (ft)				*Height (ft)*		
Slope	1	7	13	Slope	1	7	13
	Freeway				*Rural Arterial*		
1 to 2	0.38	0.26	0.33	1 to 2	0.4	0.55	0.48
1 to 3	0.37	0.33	0.34	1 to 3	0.75	0.53	0.67
1 to 4	0.46	0.47		1 to 4	0.66	0.64	
1 to 6	0.64			1 to 6	0.92		
	Urban Arterial				*Local*		
1 to 2	0.53	0.41	0.47	1 to 2	1.11	1.28	0.82
1 to 3	0.54	0.51	0.23	1 to 3	1.13	0.77	1.24
1 to 4	0.53	0.53		1 to 4	0.88	0.88	
1 to 6	0.79			1 to 6	1.56		

To calibrate RSAP for each functional class, fill height, and slope steepness, outputs were adjusted by trial and error until the RSAP output matched the results shown in Table 1. The resulting modification factors for SI values of foreslopes are shown in Table 2.

7. Sensitivity Analysis

Using RSAP, the accident cost of a divided rural arterial highway with four lanes was determined. This represented the baseline model that was used to measure the sensitivity of the parameters shown in Table 3.

Each of the eleven parameters was altered according to the third column, titled “Change,” on an individual basis. The change in accident cost relative to the baseline model was recorded for each variation. This sensitivity analysis was conducted to reduce the total number of simulations required to sufficiently represent most highways. No guidance was available to determine a minimum percent difference in accident cost that would determine the significance of a parameter. Therefore, it was decided to include only the parameters above the “Number of Lanes” parameter shown in Table 3. This decision was made based on the fact that not all functional classes have four lanes of traffic, making this parameter obsolete for some analyses. Beyond the number of lanes, percent differences never exceeded 7% and were considered negligible. From the results of the sensitivity analysis, parameters above the “Number of Lanes” in Table 3 were varied to create an exhaustive simulation matrix. The remaining parameters were constants.

Table 3. Results of the sensitivity analysis

Parameter	*Baseline*	*Change*	*Estimated Average Crash Cost (US$)*	*Annual Percent Change*
Baseline	Baseline	None	$21,199.67	—
Degree of curvature	0	8 Left	$50,245.39	94%
		8 Right	$32,193.86	
Length of feature, ft[a]	800	100	$3,820.44	84%
		1,500	$39,353.44	
Average daily traffic, vehicles per day	50,000	10,000	$7,937.52	56%
		90,000	$31,568.47	
Grade, %	0	−6	$31,779.03	51%
		+6	$32,129.55	
Fill height, ft[a]	7	1	$7,390.78	44%
		13	$26,186.20	
Lateral offset, ft[a]	8	4	$27,441.54	27%
		12	$16,063.66	
Number of lanes	4	2	$17,206.76	13%
		6	$22,883.78	
Lane width, ft[a]	12	10	$22,965.74	7%
		14	$19,836.64	
Traffic growth rate, %	2	1.5	$20,079.64	5%
		2.5	$22,387.09	
Shoulder width, ft[a]	4	2	$20,506.61	3%
		6	$20,547.96	
Percent trucks, %	16	5	$21,088.98	1%
		40	$21,385.30	

a. 1 ft = 0.305 m.

8. RSAP Modeling

8.1. Design Alternatives

8.1.1. Do Nothing.

Alternatives were compared to a baseline option known as the “do nothing” condition. This option left the foreslope untreated because the direct costs of flattening the slope were too expensive. For all highways, 1V:2H was the steepest slope used. However, NCHRP Report No. 638 recommended a slope of 1V:3H or flatter on all functional classes except rural local highways (Sicking et al., 2009). In this project, 1V:2H slopes were used on all functional classes in the event that an existing roadway incorporated that cross-section.

8.1.2. Slope Flattening.

Slope flattening can be implemented as a safety treatment for roadside areas containing foreslopes that may be too steep and, as a result, may be considered a hazard for errant motorists. However, flattening may involve many costs that may influence the economic feasibility of this safety alternative. To implement slope flattening, soil must be transported to the site, if proper soil is not available on or near construction site, and compacted in place. The cost of soil transportation would depend on the distance between the source of the soil and its destination. In some cases, there may be an excavation project nearby, and the cost of fill material would be almost nothing. In contrast, if soil must be transported over a great distance, the cost would have a large negative effect on this alternative's viability.

In addition to the cost of the fill material, the cost to purchase the land immediately adjacent to the roadway must be ascertained. Perhaps the state already owns the land, and the cost of the right-of-way (ROW) would be zero; or maybe the adjacent area includes buildings, cultural importance, or environment concerns, which could make the ROW a very costly purchase. Because of the wide variation of the costs associated with this alternative, B/C ratios could not be estimated. Instead, only the numerator of the B/C ratio was determined.

Even though slope flattening may be associated with significant costs, flattening may produce remarkable accident cost reduction, which is the benefit considered in a B/C analysis. Consider a vehicle that goes over an embankment, its center of gravity acts through a point outside of the geometric center of the vehicle. Steeper slopes caused the center of gravity to move farther out relative to the vehicle than on flatter slopes. Therefore, as the slope gets steeper, the likelihood of a rollover increases because the lateral component of the weight of the vehicle gets larger. For an illustration of this concept, Figure 1 is given. In this figure, a 1V:2H slope and 1V:6H slope are compared. The lateral component of the weight on the 1V:2H slope is

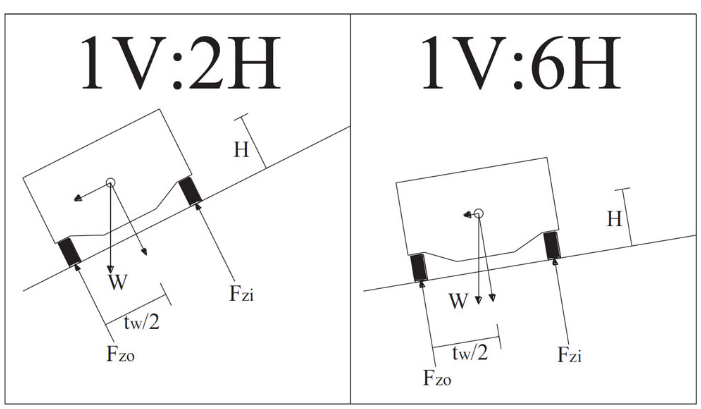

Fig. 1. Effect of slope on the lateral component of the vehicle's weight.

2.72 times larger than the 1V:6H counterpart. Flatter slopes reduced the severity of each accident because the frequency of vehicular instability was reduced. As a result, the cost per accident decreased. For this study, only the slopes that have been preprogrammed into RSAP were used. Those slopes were 1V:2H, 1V:3H, 1V:4H, and 1V:6H.

8.3. Input Parameters

8.3.1. Functional Class.

This research utilized the following three functional class categories: (1) local, (2) principal arterial, and (3) freeway. Freeways were arterials with full control access. Typically, they supported efficient flow of traffic and high traffic volumes, and in this research, values up to 100,000 vpd were used. Freeways were considered as rural highways with volumes greater than 30,000 vpd, but the speed and angle distribution used by RSAP was identical for rural and urban settings. As a result, the conclusions made with regard to freeways can be used in both land usages.

Arterials provided high-speed travel between major points, such as cities. This functional class typically makes up the largest portion of a State's highway infrastructure. As a result, many different types of highways, including freeways, can be included in this class. For this research, freeways were considered separately. For notational purposes, principal arterial highways were designated as arterial highways. Volumes on arterials up to 30,000 vpd were used in this project. In addition, RSAP assigns principal and minor arterials the same speed and angle distributions; therefore, conclusions made with regard to arterials apply to principal and minor arterial highways. However, the urban arterials and rural arterials utilized different speed and angle distributions and were considered separately.

Local highways were all roads that were not considered to be freeways, arterials, or collector highways. They support traffic over relatively short distances and serve the land adjacent to collector networks. In RSAP, the speed and angle distributions differ for a rural and urban local highway. As a result, they were considered separately. Also, local highways tend to have small traffic volumes. For this research, rural local highways had volumes up to 1,000 vpd, and urban local highways had volumes up to 5,000 vpd.

Collector highways fall between arterial and local highways. Their modeling parameters, such as ADT, were not as clear as the other functional classes. As a result, a collector highway was classified as an arterial or a local highway, based on the traffic volume.

For a more detailed description of these functional classes, including volume descriptions, the reader is referred to the American Association of Highway Transportation Officials (AASHTO; 2004) *Geometric Design of Highways and Streets*.

8.3.2. Roadway Geometry.

Parameters characterized by a low sensitivity were assigned a constant value throughout all analyses. Freeways and divided arterials were modeled with four lanes, whereas undivided arterials and local highways were modeled with two lanes. A shoulder width of 8 ft (2.4 m) was used on all highways except freeways. This width was chosen to give law enforcement enough room to pull over to the side of the road, to give maintenance workers enough space, and to provide enough room for motorists to avoid accidents. The shoulder width on a freeway was increased to 12 ft (3.7 m) to account for increased traffic volumes (AASHTO, 2005: Labra & Mak, 1980). The location of the slope under examination was assumed to be on the right side of the roadway. Default values of 25 years and 4% were used for the design life and interest rate, respectively. The traffic growth rate was estimated to be 2% and the percent of trucks was set at a constant 16% (Wisconsin Department of Transportation, 2010).

Features and values used in the detailed study were summarized in Table 4. Lateral offset distances and feature lengths were chosen to represent a range of practical values. Embankment heights were chosen from available settings in RSAP. These three parameters were used for each functional class. In contrast, the percent grades and degrees of curvature were chosen based on minimum design standards published in NCHRP Report No. 638, and they varied depending on the functional class of the highway (Sicking et al., 2009). Downgrades and left-hand curves were chosen over their counterparts because they represented the more critical scenario and provided conservative recommendations.

Table 4. The Roadside Safety Analysis Program input values

	Freeway	*Urban Arterial*	*Rural Arterial*	*Urban Local*	*Rural Local*
Grade (%)	0	0		0	
	−2	−3		−6	
	−3	−6		−12	
Degree of curvature	0	0	0	0	0
	2	4	3	3	4
	3	8	6	6	8
Length of feature (ft)	200				
	800				
	1,400				
Height (ft)	1				
	7				
	13				
Offset (ft)	2				
	7				
	12				

9. Benefit–Cost Analysis

9.1. Direct Costs

Direct costs can vary significantly from one project to another. These costs may include material, labor, mobilization, ROW acquisition, and other components. The combined total cost of the project represented a principal cost, which was then annualized over the design life of the feature. It was recommended to use a 25-year design life and an interest rate of 4%, even though most slopes are functional far beyond 25 years. The annualization of the principal cost is shown in Equation 1,

$$DC = P \cdot \left[\frac{i\,(1+i)^n}{(1+i)^n - 1} \right] \tag{1}$$

where,

DC = Direct cost
P = Principal cost
n = Design life in years
i = Interest rate in decimal form.

9.2. Accident Cost Reductions

In general, flattening slopes resulted in dramatic reductions in accident costs, as shown in Table 5. This reduction can exceed 90% in some cases. For each functional class and foreslope, the accident costs were averaged over varying ADTs, lateral offsets, embankment heights, longitudinal lengths, percent grades, and roadway curvatures. Then, the averages were compared in matrix form. The intersection of each row and column represented a comparison between the two slope steepnesses. For example, on a freeway, there was a 13% reduction in accident cost when flattening a 1V:4H slope to a 1V:6H slope (row 4, column 4 of the Freeway results). Negative percentages indicated an increase in accident cost. This was apparent on freeways and urban arterials when flattening a 1V:3H slope to a 1V:4H slope. However, this anomaly was only 6% and simply indicated that the severity of the two slopes was approximately equal, according to the accident data used to update SIs. The same conclusion could be drawn from the positive 4% on undivided urban arterials. An interesting result was seen on local highways when flattening a 1V:4H slope to a 1V:6H slope. Unlike other functional classes, local highways appeared to have an optimal slope design of 1V:4H, which is discussed in section 7.

9.3. Benefit–Cost Equation

A B/C ratio, calculated using Equation 2, was an indication of the viability of changing the existing or baseline design. A value of 1.0 meant the benefits

Table 5. Accident cost reductions in percentages

	1V:3H	1V:4H	1V:6H		1V:3H	1V:4H	1V:6H
		Freeway					
1V:2H	45%	41%	49%				
1V:3H	x	−6%	8%				
1V:4H	x	x	13%				
1V:6H	x	x	x				
		Divided Rural Arterial				*Undivided Rural Arterial*	
1V:2H	18%	66%	68%	1V:2H	19%	66%	68%
1V:3H	x	58%	61%	1V:3H	x	58%	61%
1V:4H	x	x	5%	1V:4H	x	x	6%
1V:6H	x	x	x	1V:6H	x	x	x
		Divided Urban Arterial				*Undivided Urban Arterial*	
1V:2H	58%	56%	68%	1V:2H	62%	63%	68%
1V:3H	x	−6%	24%	1V:3H	x	4%	18%
1V:4H	x	x	28%	1V:4H	x	x	14%
1V:6H	x	x	x	1V:6H	x	x	x
		Rural Local				*Urban Local*	
1V:2H	59%	92%	84%	1V:2H	52%	90%	79%
1V:3H	x	80%	61%	1V:3H	x	78%	57%
1V:4H	x	x	−96%	1V:4H	x	x	−99%
1V:6H	x	x	x	1V:6H	x	x	x

balanced out the costs over the design life. Typically, this is not a favorable investment practice. States often use minimum ratios of 2.0 and preferable ratios of 4.0 or higher to justify modifying the baseline design.

$$B/C_{2-1} = \frac{(AC_1 - AC_2)}{(DC_2 - DC_1)} \tag{2}$$

where,

B/C_{2-1} = Benefit−cost ratio comparing the baseline design to the alternative design
AC_1 = Annualized accident cost of the baseline design
AC_2 = Annualized accident cost of the design alternative
DC_1 = Annualized direct cost of the baseline design
DC_2 = Annualized direct cost of the design alternative.

10. Summary, Discussions, and Conclusions

To mitigate inconsistent foreslope designs, B/C analyses should be used to generate a systematic approach to roadside geometric design. RSAP was one tool available to engineers to accomplish this task. A sufficiently large simulation matrix was created to represent as many highway configurations as possible. Using updated SIs based on real-world accident data, accident costs were simulated. These accident costs can be used to conduct B/C analyses where direct costs, roadway parameters, ADT, inflation, design life, and interest rate could be specified by the analyst. The full list of all accident costs produced can be found at Schrum et al. (2011).

Each functional class utilized a baseline slope of 1V:2H. The average accident cost reductions, shown in Table 5, indicated that flattening this baseline slope always decreased accident costs, and in some cases, that reduction exceeded 90%. This supported the RDG critical classification of a 1V:2H slope (AASHTO, 2006).

Freeways and urban arterials behaved similar to one another. The benefit of flattening the slope to 1V:3H was approximately the same as flattening the slope to 1V:4H or 1V:6H. This promotes a general recommendation that the foreslope on these highways should not be steeper than 1V:3H. Additional inspection of these accident cost-reduction matrixes showed that flattening a 1V:3H slope to a 1V:4H slope yielded approximately no benefit, and flattening to a 1V:6H yielded only a slight benefit.

Rural arterials demonstrated unique results. Flattening a 1V:2H slope to a 1V:3H slope resulted in accident cost reductions of less than 20%. However, as the slope was flattened to 1V:4H or flatter, the reduction was greater than 65%. Interestingly, the benefit of flattening a 1V:4H to a 1V:6H slope was minimal. As a result, the general recommendation is to flatten 1V:2H or 1V:3H slopes on rural arterials highways to 1V:4H slopes.

Local highways demonstrated the greatest benefit in slope flattening. They also demonstrated the greatest degree of variability in the results. Counter intuitively, by flattening a 1V:4H slope to a 1V:6H slope, the accident cost nearly doubled. This was the product of the methodology of updating SIs. The number of severe and fatal accidents per mile was calibrated in RSAP using real-world accident data from the State of Ohio between years 2000 and 2006. On local highways, the frequency of these accidents was nearly twice as much on 1V:6H slopes as the frequency on 1V:4H slopes. Despite the curious lack of accidents on 1V:4H slopes, the results still indicated a high reduction in accident costs when flattening the baseline slope to any of the considered retrofit slopes. Therefore, on local highways, the slope should be made as flat as possible.

In conclusion, the benefit of slope flattening was quantified using reliable SIs, which were based on real-world crash data. The results should help engineer answer the question: how flat can a slope be graded and still be economical. Accident cost reductions can indicate potential slope designs that could provide a cost-effective design. When used in combination with direct costs, B/C analyses can be conducted using Equation 2. The results of this analysis would provide a design recommendation based on the benefits of slope flattening. It is also important to stress that the slopes were assumed to have no fixed objects on them and at their bottom. Also, it was assumed that the roadside terrain, beyond the slope, was flat.

11. Recommendations

The results of this research depended on real-world accident data. As more data is collected, RSAP can be recalibrated to match the current performance of various slopes, and the simulations used in this research can be redone, providing accurate accident costs with respect to the time period of the accident data.

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References

American Association of Highway Transportation Officials. (2004). *Geometric design of highways and streets*. Washington, DC: American Association of Highway Transportation Officials.

American Association of State Highway Transportation Officials. (2005). *A policy on design standards – Interstate system* (5th ed.). Washington, DC: American Association of State Highway Transportation Officials.

American Association of State Highway and Transportation Officials. (2006). *Roadside design guide*. Washington, DC: American Association of State Highway and Transportation Officials.

Deleys, N. J., & Parada, L. O. (1986, August). *Rollover potential of vehicles on embankments, sideslopes and other roadside features* (Research Report Number FHWA/RD-86/164). Buffalo, NY: Calspan Corporation.

Glennon, J. C. (1974). *Roadside safety improvement programs on freeways — A cost-effective priority approach* (NCHRP Report 148). Washington, DC: Transportation Research Board.

Labra, J. J., & Mak, K. K. (1980, November). *Development of reconstruction procedure for pole accidents*. Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration, Southwest Research Institute.

Mak, K. K., & Sicking, D. L. (2002, June). *Roadside Safety Analysis Program (RSAP) user's manual* (NCHRP Project No. 22–9). Washington, DC: Transportation Research Board.

Miller, T., Viner, J., Rossman, S., Pindus, N., Gellert, W., Douglass, J., Dillingham, A., ... G. Blomquist, G. (1991, October). *The costs of highway crashes* (Research Report Number FHWARD- 91-055). Washington, DC: The Urban Institute.

National Highway Traffic Safety Administration. (2010). *Traffic safety facts 2010*. Washington, DC.

Post, E. R. (1977). *Cost-effectiveness of driveway slope improvements* (Research Report No. TRP- 03-001-77). Lincoln, NE: University of Nebraska-Lincoln, Civil Engineering Department.

Schrum, K. D., Albuquerque, F. D. B., Sicking, D. L., Faller, R. K., & Reid, J. D. (2011, December 19). *Roadside grading guidance – Phase I* (Transportation Research Report No. TRP-03-251- 11, Project No. TPF-5(193) Supplement #13). Lincoln, NE: University of Nebraska-Lincoln, Midwest Roadside Safety Facility.

Sicking, D. L., Lechtenberg, K.A., & Peterson, S. M. (2009). *Guidelines for guardrail implementation* (NCHRP Report No. 638). Washington, DC: Transportation Research Board.

Wisconsin Department of Transportation. (2010). *Plans and projects: I-90 Corridor Roadside Facilities Study Need*. Retrieved from http://www.dot.wisconsin.gov/projects/d5/i90study/docs/volumes.pdf

Zegeer, C. V. (1988). *Accident effects of sideslope and other roadside features on two-lane roads* (Transportation Research Record No. 1195). Washington, DC: Transportation Research Board, National Research Council.