Cost-Effectiveness of Driveway Slope Improvements

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In the development of roadside safety improvement programs, many types of obstacles have been identified as being hazardous. However, little attention has been given to the hazard of driveway slopes along noncontrolled and limited-access roadways. It was the purpose of this study to assess the hazard posed by such driveway slopes and to determine the cost-effectiveness of flattening them. The degree of hazard was measured in terms of the expected number of injury (fatal or nonfatal) accidents per year resulting from a vehicle traversing the slope. The probability of injury in a run-off-the-road encroachment of a driveway slope, which was used to compute the degree of hazard, was derived from severity indexes computed from results obtained from the highway vehicle object simulation model to simulate a standard-sized automobile traversing driveway slopes under encroachment conditions of 92-km/h (55-mph) speed and 10° encroachment angle in a free-wheeling steering mode. The results of this study indicate that (a) driveways are a roadside hazard, (b) the most cost-effective driveway slope design standard is 8:1, and (c) flattening to an 8:1 slope is the most cost-effective driveway slope improvement. The cost-effectiveness methodology used in this study provides a common basis for comparing driveway slope improvements with other types of improvements in the management of roadside safety improvement programs.

During the past two decades a considerable amount of attention has been devoted to improving roadside safety by removing, relocating, or reducing the impact severity of obstacles along roadsides. Many types of obstacles have been identified as being hazardous, and, as a result, comprehensive safety improvement programs have been undertaken. However, very little attention has been given either to the hazard of driveway slopes along the roadside of noncontrolled or limited-access roadways or to the cost-effectiveness of improving driveway slopes.

The purpose of this study was threefold. First, the degree of hazardousness of a typical driveway slope configuration along the roadside of a modern noncontrolled access, or limited-access, roadway facility was assessed. Second, the most cost-effective design standard for driveway slopes was determined. And, third, the cost effectiveness of improving driveway slopes from 3:1 to flatter slopes was evaluated.

The probability of injury in a run-off-the-road encroachment of a driveway slope must be determinable in order to conduct a cost-effectiveness analysis. The severity of such an event can be expressed as the ratio of the resulting automobile accelerations to the resulting accelerations "tolerable" to an unrestrained occupant. This ratio, commonly referred to as a severity index, was computed from the results obtained by a mathematical computer model simulation program named the highway vehicle object simulation model (HVOSM). The methodology used to express severity indexes in terms of probability of injuries is also discussed in this paper.

DESCRIPTION OF DRIVEWAY SITE

The driveway used in this study was chosen as a typical rural-suburban example. It is located along a four-lane divided rural highway section that is in a rural-urban transition area. The driveway site is shown in Figure 1.

The speed limit posted in the area of the driveway is the current national standard of 92 km/h (55 mph). The design speed of the highway section is 108 km/h (65 mph), and the horizontal and vertical alignments through the study area are both tangent. The topography traversed is flat and level.

The section has a variable width median, two 7.3-m (24-ft) lanes in each direction surfaced with portland cement concrete, a 3.7-m (12-ft) shoulder section on the outside with a 3.0-m (10-ft) wide surface of asphalt concrete. The foreslope is 6:1 to a minimum of 9.1 m (30 ft) from edge of pavement. Beyond 9.1 m, the foreslope is 4:1 to the 3.0-m flat-bottom ditch. The backslope is uniformly 4:1 from ditch bottom to original terrain elevation.

The actual driveway geometrics include 3:1 fill slopes with an 18.3-m (60-ft) wide grading top, for future intersection development, and an essentially tangential grade line from the shoulder point to the original terrain. The driveway used for this research did have drainage; however, based on prior research on flared end-sections and bar grates, no special consideration was given to this area; the main thrust of the research was directed to the driveway fill slopes. The geometric connection of driveway embankment to roadway embankment is basically defined by intersecting planes with a variable but limited amount of rounding.

COMPUTER SIMULATION MODEL

HVOSM was used to study the dynamic motion of an automobile traversing the ditch and driveway configurations described in the preceding section. HVOSM was developed by McHenry (1, 2) of the Cornell Aeronautical Laboratories and modified for specific field applications by the Texas Transportation Institute (3).

A standard-sized automobile was used in this study. The properties of the selected automobile were defined in previous research work conducted by Ross and Post (4, 5) and Weaver, Marquis, and Olson (6) on sloping grates in medians and roadside embankment slopes.

The roadway, shoulder, and soil were assigned friction coefficient values of 0.8, 0.6, and 0.2, respectively, and the soil was assigned a stiffness value of 580 kPa (4000 lbf/in^2). Terrain contact was only monitored at the two corners of both the front and rear bumpers.

No attempt was made to steer and brake the automobile during any of the driveway simulations. This free-wheeling condition would be representative of an inattentive driver.

PROBABILITY OF INJURY

The criteria used in the majority of the research work conducted during the past decade for evaluating the safety aspects of roadside hazard improvements were based on levels of vehicle deceleration that would be tolerable to an unrestrained occupant. An attempt was made in this study to expand the existing technology to include the probability of occurrence of injury accidents. This task was required in order to determine the cost-effectiveness of making driveway slope improvements.

Figure 1. Driveway site.

Severity Index Concept

The severity index concept attempts to take into consideration the combined and simultaneous effects of the longitudinal (x-axis), lateral (y-axis), and vertical (z-axis) accelerations of the automobile at its center of mass. The severity index is computed as the ratio of the measured or computed resulting automobile acceleration to the resulting tolerable automobile acceleration that defines an ellipsoidal surface. This ratio can be expressed mathematically by Equation 1. An in-depth discussion on the development of Equation 1 has been presented elsewhere (6, 7).

$$SI = \sqrt{(G_{LONG}/G_{XL})^2 + (G_{LAT}/G_{YL})^2 + (G_{VERT}/G_{ZL})^2} \quad (1)$$

The relationship between the accelerations experienced by an occupant and the accelerations of an automobile at its center of mass during a run-off-the-road collision or maneuver are largely dependent on the degree of restraint. In other words, the greater the degree of restraint the more similar are the accelerations experienced by an occupant and the accelerations of the automobile. At the present time, however, accident data show that in the majority of the accidents occupants were unrestrained. The tolerable accelerations suggested (6) for use in the severity index equation are presented in the table below.

	Acceleration (g)		
Degree of Occupant Restraint	G_{YL}	G_{XL}	G_{ZL}
Unrestrained	5	7	6
Lap belt only	9	12	10
Lap belt and shoulder harness	15	20	17

The severity index computations in what follows will be based on accelerations tolerable to an unrestrained occupant, and the automobile accelerations will be averaged over a time duration of 50 ms.

Severity Index and Injury Probability

In 1967, Michalski (8) of the National Safety Council statistically established, from the results of a study involving 951 automobile traffic accidents, that the incidence of occupant injury was directly related to the position of impact and the corresponding magnitude of vehicle damage. The severity of damage to a vehicle was rated on a seven-point photographic scale (9) by police officers and researchers at the scene of an accident.

The work of Michalski was applied and extended by Olson and Post (10) to include vehicle decelerations. Selecting vehicles damaged in full-scale tests conducted by California, New York, and the Texas Transportation Institute, Olson had research engineers rate the severity of vehicle damage using the National Safety Council's seven-point photographic scales. The corresponding average vehicle decelerations could then be computed knowing the impact conditions of the tests, vehicle dimensions, and the types of objects hit. The results of that study are shown in Figures 2 and 3.

An insight into establishing a relationship between severity index and injury probability can be obtained based on the combined work of Michalski (8) and Olson (10) for an angle-type collision such as a traffic barrier. In this type of collision in which vehicle snagging was minimized, it was determined that the average longitudinal vehicle decelerations (G_{long}) were equal to

$$G_{long} = \mu G_{lat} = \mu(10\ P) \quad (2)$$

where

μ = coefficient of friction between vehicle body and traffic barrier,
G_{lat} = average lateral decelerations = 10 P (Figure 2), and
P = injury probability.

On substituting Equation 2 into the severity index equation (Equation 1) and assuming that (a) the vertical accelerations are negligible, (b) the occupants are unrestrained, and (c) the friction coefficient is 0.3, one obtains the following relationship:

$$SI = \sqrt{(G_{long}/G_{xl})^2 + (G_{lat}/G_{yl})^2} = \sqrt{(10\mu P/7)^2 + (10P/5)^2} = 2.0P \quad (3)$$

Further insight into the relationship between severity indexes and injury probability can be obtained by combining the later work of Young, Post, and Ross (11) with that of Michalski (8) and Olson (10). In 1971, Young conducted a research study on the rigid Texas concrete median barrier, which is similar in design to the General Motors (GM) (12) traffic barrier that has inclined surfaces. HVOSM was used in that study, and several full-scale tests were conducted for validation purposes. Severity indexes were computed to compare the severity of one test, or simulation, with another and to serve as an aid in making decisions concerning roadside modifications that should effect a reduction in occupant injury and loss of life.

The combined work of Michalski, Olson, and Young is presented in Figure 4. In addition, Michalski statistically established the angle impact relationships shown in Figure 4 between mean vehicle damage ratings (R) and those accidents in which (a) R = 1.99 and vehicles were drivable, (b) R = 4.08 and vehicles were not drivable, (c) R = 2.49 and no injuries occurred, and (d) R = 4.73 and injuries occurred.

The average lateral vehicle decelerations, G_{lat}, that correspond to these mean damage ratings were obtained from Figure 2. The deceleration levels, in turn, were expressed as a function of the impact speed and angle using an equation contained in Olson's work. Referring to Figure 4, the following conclusions were reached:

1. The severity index curves exhibit the same characteristic shape as the deceleration level curves generated independently by Olson.
2. The no-injury prediction by Michalski and Olson agrees well with the tests run on the GM traffic barrier using a live driver who received no injuries and remained in complete control of his vehicle during 83-km/h (50-mph) and 8° collisions. It must be kept in mind, however, that even during this type of collision resulting in low levels of deceleration there exists a low probability for injury.
3. The injury prediction by Michalski and Olson corresponds to a severity index of 1.3 and an injury proba-

Figure 2. Curve relating lateral deceleration, proportion of injuries, and damage-rating scale.

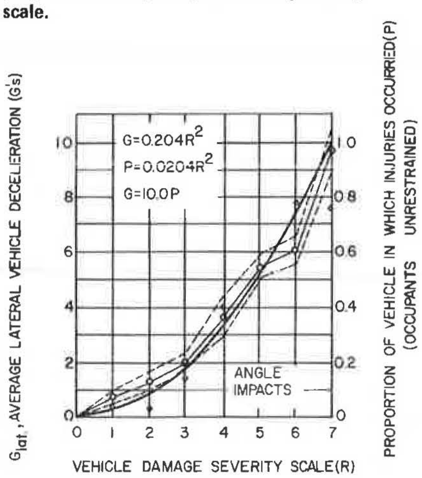
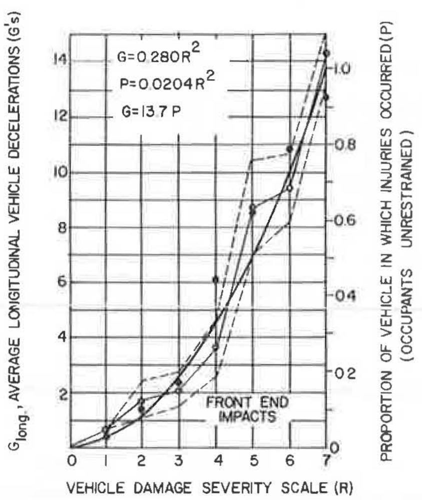


Figure 3. Curve relating longitudinal deceleration, proportion of injuries, and damage-rating scale.



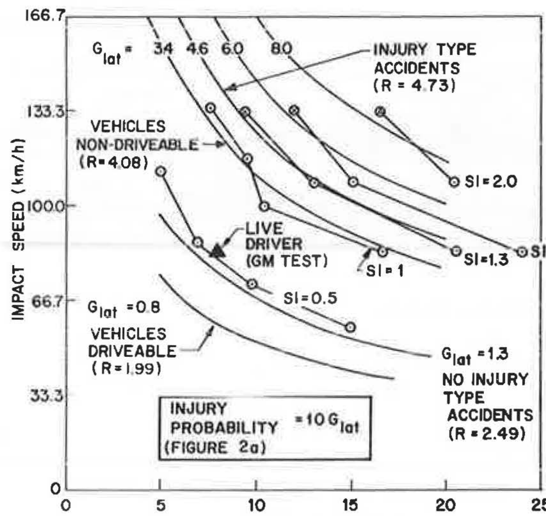
bility of about 50 percent. No attempt was made by Michalski to classify the severity of an injury. However, it is our opinion that this condition may approximately define the division between minor and serious injuries.

4. The not-drivable prediction by Michalski and Olson corresponds to an injury probability of about 35 percent and a severity index of 1.0, which was defined by Weaver, Marquis, and Olson (6) as representing a safe run-off-the-road maneuver or a collision.

5. The relationship between severity index and injury probability defined by Equation 3 agrees reasonably well with the results presented in Figure 4.

Based on the findings discussed above and realizing the complexity of the problem at hand, we reached a decision to define injury probabilities for fatal and nonfatal accidents over six broad categories of severity index. This relationship, shown in the table below, will be used in the subsequent cost-effectiveness evaluation.

Figure 4. Relations among impact conditions and vehicle lateral accelerations, severity index, and probability of injury during collision with Texas concrete median barrier.



Note: 1 km/h = 1.61 mph.

Severity Index	Probability of Injury Accident
SI ≤ 0.5	0.1
0.5 < SI ≤ 1.0	0.3
1.0 < SI ≤ 1.5	0.5
1.5 < SI ≤ 2.0	0.7
2.0 < SI ≤ 2.5	0.8
2.5 < SI	1.0

SIMULATION RESULTS

Twenty-seven computer simulation runs were made in this study on driveway slopes of 3:1, 4:1, 6:1, and 8:1. The automobile was assumed to encroach on the roadside from the center of the outside lane at a speed and angle of 92 km/h (55 mph) and 10°. Simulations were made across the entire width of the driveway slope in increments of roughly 3.0 m (10 ft), which was considered adequate for making a cost-effectiveness analysis. The paths of the center of gravity of an automobile traversing 3:1 and 8:1 driveway slopes are shown in Figures 5 and 6.

The position of a vehicle along its path where the severity index was computed is marked by an "x". In the majority of the runs this occurred near the intersection of the ditch slope and driveway front slope, before the automobile was abruptly airborne, and at or slightly beyond the point where the automobile touched down.

The dotted portion along a vehicle's path defines the area and distance over which the automobile was airborne. Similarly, a large single dot along the vehicle's path defines the position where the roll angle was approximately 90° and rollover was imminent. Other than being reflected in the severity index, no attempt was made to evaluate the significance of the automobile being airborne for the driver's response.

COST-EFFECTIVENESS ANALYSIS

The cost-effectiveness analysis conducted in this study was based on the cost-effectiveness approach formulated by Glennon (13) and implemented in Texas for managing roadside safety improvement programs on both noncontrolled roadways and freeways (14). The cost-effectiveness measure used in this approach was annual cost that eliminated one injury (fatal or nonfatal)

Figure 5. Driveway 3:1 slope computer simulations of automobile center-of-gravity paths.

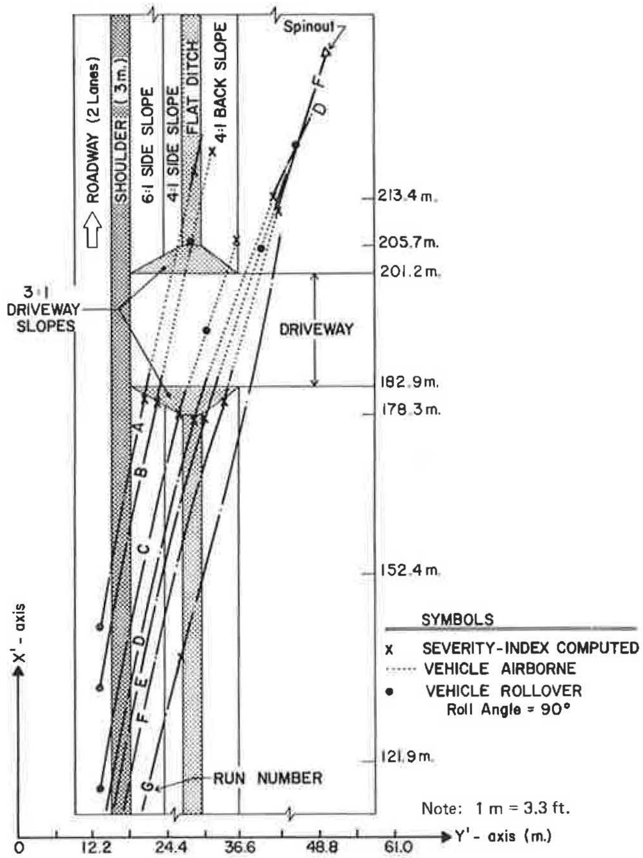
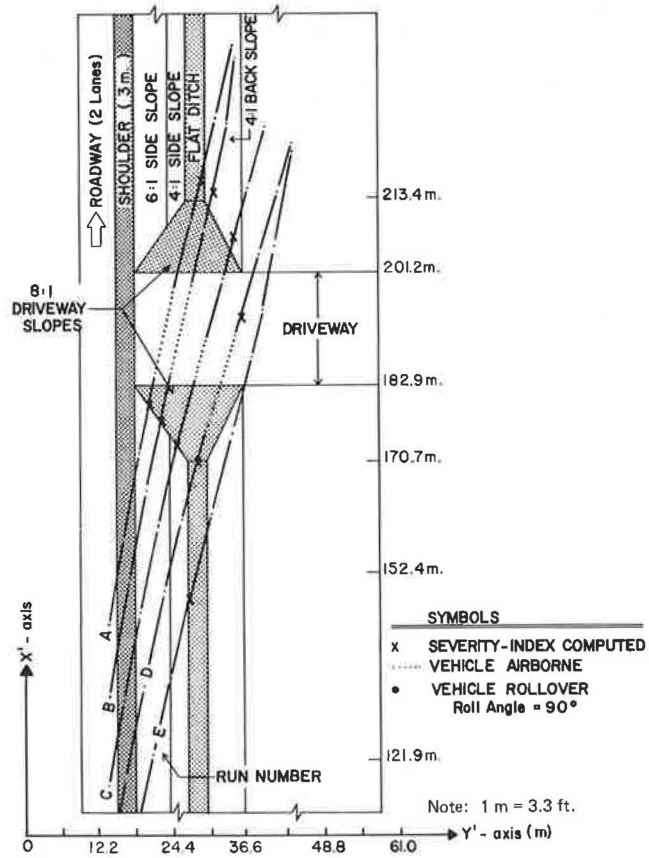


Figure 6. Driveway 8:1 slope computer simulations of automobile center-of-gravity paths.



accident per year. The measure of effectiveness was defined as the difference between the hazard indexes before and after an improvement expressed in terms of number of fatal and nonfatal accidents per year. Thus, in order to apply the cost-effectiveness approach, it was necessary to compute the hazard index for each driveway slope alternative and its annual cost.

Hazard Index

The hazard index was computed for each driveway slope alternative using the following equation:

$$H_i = E_f[P(C/E)]\,[P(I/C)_i] \qquad (4)$$

where

- H_i = hazard index for driveway slope i or expected number of injury (fatal or nonfatal) accidents per year (i = 3:1, 4:1, 6:1, 8:1, 10:1),
- E_f = encroachment frequency or number of encroachments per 1.6 km (1 mile) per year,
- $P(C/E)$ = probability that a driveway slope will be traversed given that an encroachment has occurred, and
- $P(I/C)_i$ = probability of an injury (fatal or nonfatal) accident given that a driveway slope i has been traversed.

A brief discussion of how each of the independent variables in this equation was computed follows.

Encroachment Frequency

Knowledge of the frequency with which vehicles encroach on the roadside of noncontrolled facilities is extremely limited. Therefore, the encroachment frequency used by Glennon (13) was assumed to be applicable for the purposes of this analysis.

Probability of Traversing Driveway

The probability that a driveway slope will be traversed given that an encroachment has occurred is proportional to the longitudinal length of the roadway within which the path of an encroaching vehicle would intersect a driveway slope. For the conditions simulated in this study (encroachment angle of 10°), it was determined that this length was about 61 m (200 ft) per driveway. Due to the lack of data on the effects of roadway conditions on the frequency and nature of encroachments, it was assumed that the longitudinal distribution of encroachments was uniform.

Probability of Injury Accident

The probability of an injury accident given that a driveway slope has been traversed was computed for each driveway slope using the following procedure:

1. For each driveway slope, the maximum severity index and potential for rollover were determined from the simulation results on each of five encroachment paths (A, B, C, D, and E).
2. For each driveway slope, the probability of an

injury accident was determined for each encroachment path as follows: (a) if rollover occurred, a probability of one was assigned; (b) if rollover did not occur, a probability was assigned on the basis of the maximum severity index experienced on the encroachment path using the relationship presented in the second table.

3. For each of the five encroachment paths, the probability that it would be the path of an encroaching vehicle was derived from the distribution of lateral displacements of encroaching vehicles generated by Glennon (13). These encroachment path probabilities were determined as follows: (a) for each encroachment path, the lateral distances between the edge of the traveled way and the point at which the path intersects each driveway slope were calculated, and the range of these values was determined, (b) the probabilities of the lateral displacements of vehicle encroachments being within each of these ranges were determined.

4. The expected probability of an injury accident for each driveway slope was calculated by using the following equation:

$$P(I/C)_i = \sum_{j=A}^{E} P(j)\,[P(I/j)] \qquad (5)$$

where

$P(I/C)_i$ = probability of an injury accident given that driveway slope i has been traversed,
$P(j)$ = probability that encroaching vehicle will follow encroachment path j (j = A, B, C, D, E), and
$P(I/j)$ = probability of an injury (fatal or nonfatal) accident given that the encroaching vehicle follows path j.

The results of this step are presented below.

Driveway Slope	Probability of Injury Accident
3:1	0.9
4:1	0.8
6:1	0.7
8:1	0.3
10:1	0.3

Table 1. Driveway construction costs.

Driveway Slope	Driveway Type Costs ($): With No Underdrainage	With One 0.6-m-Diameter Underdrain	With Two 0.6-m-Diameter Underdrains
3:1	320	1890	3460
4:1	340	2060	3790
6:1	380	2400	4420
8:1	420	2730	5040
10:1	460	3070	5670

Note: 1 m = 3.3 ft.

Table 2. Driveway slope improvement costs.

Slope Improved To	Slope Improvement Cost ($): From 3:1 C[a]	E[b]	C/E[c]	From 4:1 C[a]	E[b]	C/E[c]	From 6:1 C[a]	E[b]	C/E[c]	From 8:1 C[a]	E[b]	C/E[c]
4:1	100	250	400	-	-	-	-	-	-	-	-	-
6:1	240	690	1140	140	440	740	-	-	-	-	-	-
8:1	380	1120	1860	280	870	1460	140	430	720	-	-	-
10:1	530	1560	2600	430	1310	2200	290	870	1460	150	440	740

[a]C = with no underdrainage.
[b]E = with one 0.6-m (2-ft) diameter underdrain.
[c]C/E = with two 0.6-m (2-ft) diameter underdrains.

Table 3. Cost-effectiveness of alternate driveway slope design standards with no underdrainage.

Slope Improved To	Slope Improvement: From 3:1 C[a] ($)	E[b]	C/E[c] ($)	From 4:1 C[a] ($)	E[b]	C/E[c] ($)	From 6:1 C[a] ($)	E[b]	C/E[c] ($)	From 8:1 C[a] ($)	E[b]	C/E[c] ($)
4:1	2	0.03	70	-	-	-	-	-	-	-	-	-
6:1	6	0.05	120	4	0.02	200	-	-	-	-	-	-
8:1	6	0.15	70	8	0.12	70	4	0.10	40	-	-	-
10:1	14	0.15	90	12	0.12	100	8	0.10	80	4	0	Infinite

[a]C = annualized cost of improvement using 8 percent interest rate, 20-year service life, and zero salvage value.
[b]E = difference between the hazard indexes before and after improvement.
[c]C/E = cost to eliminate one injury (fatal or nonfatal) accident.

Table 4. Cost-effectiveness of alternate driveway slope improvements with no underdrainage.

Slope Improved To	Slope Improvement: From 3:1 C[a] ($)	E[b]	C/E[c] ($)	From 4:1 C[a] ($)	E[b]	C/E[c] ($)	From 6:1 C[a] ($)	E[b]	C/E[c] ($)	From 8:1 C[a] ($)	E[b]	C/E[c] ($)
4:1	10	0.03	330	-	-	-	-	-	-	-	-	-
6:1	24	0.05	480	14	0.02	700	-	-	-	-	-	-
8:1	38	0.15	250	28	0.12	230	14	0.10	140	-	-	-
10:1	53	0.15	350	43	0.12	360	29	0.10	290	15	0	Infinite

[a]C = annualized cost of improvement using 8 percent interest rate, 20-year service life, and zero salvage value.
[b]E = difference between the hazard indexes before and after improvement.
[c]C/E = cost to eliminate one injury (fatal or nonfatal) accident.

Cost

Construction costs and slope improvement costs of the driveways studied were estimated by using 1977 average unit cost data obtained from the Nebraska Department of Roads. In each case, three cost estimates were made to reflect the effects of different drainage requirements. The estimated construction costs and slope improvement costs are shown in Tables 1 and 2 respectively.

Analysis

An incremental cost-effectiveness analysis was conducted to identify (a) the most cost-effective driveway slope design standard and (b) the most cost-effective driveway slope improvement. In the design-standard evaluation, the cost of the flatter slope provided by a higher standard was assumed to be equal to the difference in the driveway construction costs given in Table 1 for the two slopes involved and the particular drainage requirements under consideration. In the analysis of driveway slope improvements, the costs shown in Table 2 were used. The costs were made annual by using an 8 percent interest rate, 20-year service life, and zero salvage value.

The hazard indexes were computed by using Equation 4 and the probabilities of an injury accident given previously. An average daily traffic count of 3000 was assumed, which corresponds to an annual encroachment frequency of six per 1.6 km (1 mile).

Results

The results of the incremental cost-effectiveness analyses of driveway slope design standards and driveway slope improvements for driveways with no underdrainage are presented in Tables 3 and 4 respectively, also based on the 3000 annual daily traffic and six encroachments per year per 1.6 km (1 mile). For both design standards and improvements, the alternative with the lowest cost to eliminate one injury accident per year was the 8:1 driveway slope. Although the costs to eliminate one injury accident per year were higher for driveways with one or two 0.6-m (2-ft) diameter underdrains, the results were similar to those of driveways without underdrainage. Thus, in every case, the most cost-effective driveway slope design standard was 8:1 and the most cost-effective driveway slope improvement was 8:1.

CONCLUSIONS

The results of this study indicate the following:

1. Driveway slopes do present a roadside hazard,
2. The most cost-effective driveway slope design standard is 8:1, and
3. The most cost-effective driveway slope improvement is to flatten the slope to 8:1.

Of course, the higher the ADT of the roadway, the greater the degree of hazard and the more cost effective the 8:1 slope becomes.

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