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ROLLOVER POTENTIAL OF VEHICLES ON EMBANKMENTS, SIDESLOPES, AND OTHER ROADSIDE FEATURES

Vol. I. Executive Summary

August 1986

Final Report

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16. Abstract

The objective of this research program was to study the interaction of vehicles with various roadside features to determine critical roadside-feature design crit[illegible] based on the [illegible] inducing [illegible]le rollover. Results of a review of accident data analyses reported in the literature are presented to indicate the general state of knowledge of rollover accidents. Among the findings are that: (1) different classes of vehicles based on use and/or size exhibit distinct differences in rollover tendencies, and (2) the existing accident data base lacks the information necessary to define the roadside-feature geometry and other conditions that caused vehicle rollover. Full-scale tests with an instrumented automobile were performed to verify the HVOSM (Highway-Vehicle-Object Simulation Model) as modified to improve its utility for studying vehicle off-road traversals. The HVOSM was then used to predict the dynamic responses of representative small and large cars encountering different roadside-feature configurations, including both tracking and nontracking departures from the roadway. It is concluded that the sideslope of fill embankments should be no steeper than 3:1, and preferably flatter, for fill heights greater than 3 ft (0.9 m), to reduce the likelihood of small-car rollover. It is recommended that consideration be given to revising the present AASHTO design criteria for barrier warrants accordingly. It is also shown that the rounding of slope breaks currently recommended by AASHTO further reduces the rollover hazard.

This report consists of two volumes. The other volume is Volume II, Technical Report, Report No. FHWA/RD-86/164.

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FOREWORD

This report presents results of a study of the interaction of vehicles with various roadside features to determine critical roadside-feature design criteria based on the potential for inducing vehicle rollover. It should be of interest to organizations involved in research concerned with the safety aspects of roadside design and others using the HVOSM (Highway-Vehicle-Object Simulation Model) computer program.

The authors gratefully acknowledge the contributions of Dr. K.W. Terhune of Calspan Corporation, who aided in the literature review and accident data analysis portion of the study.

This report has been provided to the National Technical Information Service for distribution.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac

MASS (weight)

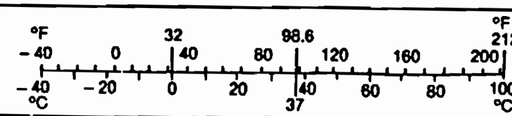
Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

1. INTRODUCTION

Accident studies have revealed that rollover of vehicles that accidentally leave the roadway is not only a frequent event, particularly in single-vehicle accidents, but also the most hazardous in terms of the frequency and severity of injuries to vehicle occupants. In addition, these studies show that small, lightweight automobiles are more prone to overturn in an accident than are large, heavy cars. In view of these facts, the trend toward increasing use of small, lightweight vehicles in recent years gives rise to concerns regarding whether the existing guidelines for the design of roadside features are appropriate or require modification to reduce the rollover potential of these newer-type vehicles during encroachments on the roadside.

The objective of this research program was to study the interaction of vehicles with various roadside features to determine critical roadside-feature design criteria based on the potential for inducing vehicle rollover. The HVOSM (Highway-Vehicle-Object Simulation Model) computer program was used to determine the dynamic responses of representative small and large cars traversing various sideslope, fill-embankment, and ditch configurations. Both tracking and nontracking departures from the roadway were simulated. Prior to the simulation study, full-scale tests with an instrumented Volkswagen Rabbit automobile were performed to verify the HVOSM, which had been modified to incorporate several revisions and extensions developed by McHenry Consultants, Inc. (MCI) to improve the application of HVOSM to rollover situations.

2. LITERATURE REVIEW AND ACCIDENT DATA ANALYSIS

Existing literature and available data were reviewed and analyzed to determine the general state of knowledge of rollover accidents, particularly with regard to the frequency of occurrence for various classes of vehicles, the severity of such accidents in producing injuries to the vehicle occupants, and the identification of possible causative factors related to roadside features encountered by the vehicles as well as conditions at which vehicles depart from the roadway. Summarized below are the principal findings from this review of pertinent literature and accident data analyses.

• Classifications of vehicles based on their use and/or size exhibit distinct differences in the frequency of rollover. For example, results of a Calspan analysis of single-vehicle accidents (SVAs) recorded in the 1979 through 1981 NASS accident data files are shown in table 1. Note that, for passenger cars, the frequency of rollovers decreases with increasing vehicle weight and that about 25% of all off-roadway accidents resulted in rollover.

Table 1. Incidence of any rollover, regardless of whether first harmful event (% SVAs).

Vehicle type	Location of first harmful event				% R.O. on and off roadway combined
	On roadway		Off roadway		
	No. SVAs	% R.O.	No. SVAs	% R.O.	
Utility Vehicles	24	79.2	65	60.0	65.2
Pickup Trucks	76	34.2	430	40.7	39.7
Vans	33	18.2	86	34.9	30.3
Station Wagons	143	6.3	668	23.2	20.2
Passenger Cars	302	7.6	1,346	24.6	21.5
2,000 lb or less	33	24.2	105	49.5	43.5
2,100-2,500 lb	31	22.6	204	35.3	33.6
2,600-3,000 lb	30	13.3	227	30.8	28.8
3,100-3,500 lb	69	2.9	323	21.1	17.9
3,600-4,000 lb	67	3.0	264	15.2	12.7
4,100-4,500 lb	51	0.0	167	12.6	9.6
4,600 lb or more	21	0.0	56	14.3	10.4
All Vehicle Types	578	14.4	2,595	28.1	25.6

1 lb = 0.4535 kg

• The vast majority of rollovers occur within 30 ft (9.1 m) of the roadway, and relatively few occur or are initiated on the shoulder.

• Embankments, ditches, and culverts are the roadside terrain features cited as being most frequently involved in overturn accidents, though detailed information on the geometry of the terrain and/or whether rollover was caused by vaulting or by the wheels contacting a small obstacle or digging into soft soil so as to trip the vehicle is generally lacking in accident data files.

• The likelihood of rollover increases with the steepness and height of embankments and the depth of ditches. Limited available data indicate that rollover frequency increases sharply for fill/ditch heights/depths greater than 3 ft (0.9 m).

• In most (50 to 80%) of the rollover accidents, the vehicles were skidding out of control at a large yaw angle prior to overturning.

- About half of all accidental departures from the roadway occurred at path angles greater than 15 degrees, and the majority of vehicles were estimated to have been traveling at speeds less than 40 to 50 mi/h (64 to 80 km/h).

- Rollover accidents are severe in terms of the frequency and severity of injuries to the vehicle occupants. The fatality rate of occupants of rollover vehicles is approximately twice that for occupants of vehicles in nonrollover impacts. Ejection is the leading cause of serious and fatal injuries, accounting for more than half of the fatalities incurred in rollover accidents.

3. HVOSM MODIFICATIONS AND VERIFICATION

HVOSM MODIFICATIONS

Summary

The simulation aspect of this research project required several analytical refinements and computer-program extensions to improve the application of HVOSM to rollover situations. McHenry Consultants, Inc. (MCI), retained as a consultant throughout this project, had incorporated several specific program modifications in a proprietary (MCI) version of HVOSM to achieve more realistic simulations of actual rollover accidents. Those MCI modifications, and additional modifications, were implemented in the HVOSM program at Calspan for use in this study.

Portions of this revised version of HVOSM are still in developmental stages. Many of the new enhancements were developed in response to needs that arose during previous research efforts. As a result of this functional implementation, the program code is essentially a "working copy" and, hence, contains variables redefined from previous options and dummy variables for uncompleted extensions. Certain options previously available in the HVOSM-RD2 version have been removed; these include the sprung-mass/barrier-impact simulation and the road-roughness simulation.[1]

The revised version of HVOSM includes: (1) a deformable-soil model, (2) modifications to the tire model, (3) a sprung-mass ground contact model, (4) a tire-sidewall contact model, (5) a driver control model, and (6) improved treatment of terrain-table angled boundary specification. Only the first three of these were utilized in the simulations performed in this research program, and they are briefly described below.

Deformable-Soil Model

The deformable-soil model provides the capability to simulate tire forces that result from plowing of the soil when the tires create ruts which can result in tripped rollover. The model is based on analytical relationships developed by Bekker for the sinkage and motion resistance of a tracking wheel.[2,3] The effect of a sideslipping tire is accounted for by assuming that the motion resistance increases in proportion to the increase of the projected vertical tire/soil interface area in the direction of motion. The components of this resultant soil plow force in the X and Y directions of the wheel coordinate system are computed and are added to the rigid-surface circumferential and side forces of the tire, respectively.

Tire-Model Modifications

Three aspects of the analytical treatment of the tires were revised: (1) energy dissipation of the "hardening" spring phase of radial loading is now accomplished by logic that applies the rate-increasing factor (λ_T) only during compression of the tire to simulate energy dissipated in deforming the rim of the wheel; (2) calculation of the tire load perpendicular to the local terrain was changed to make the load independent of the side force, since the

1. Segal, D.J., "Highway-Vehicle-Object Simulation Model--1976," Volumes 1 through 4, Report No. FHWA-RD-76-162, -163, -164, and -165, February 1976.
2. Bekker, M.G., Off-the-Road Locomotion, University of Michigan Press, Ann Arbor, MI, 1960.
3. Bekker, M.G., Introduction to Terrain-Vehicle Systems, University of Michigan Press, Ann Arbor, MI, 1969.

original formulation could result in unrealistically large values when the side force is negative and the camber angle approaches 90 degrees; and (3) the procedure for calculating side forces in the tire/ground contact patch was modified to assure that overloaded tires would achieve full side-force saturation at 60 degrees of sideslip.

Sprung-Mass Ground Contact Model

To simulate terrain contacts by the sprung mass, the terrain-table interpolation routine used for tire contacts was adapted to detect ground interference of up to 39 points on the sprung mass that may be specified. Deflections of the vehicle structure are assumed to occur in directions that are perpendicular to the local (rigid) terrain at the locations of the individual contacts. The resultant velocities tangential to the terrain contacts are calculated for the individual points, and friction forces opposing the motions are applied. Load-deflection properties of the points can be either uniform or individually specified.

HVOSM VERIFICATION

Full-scale tests were performed with an instrumented 1979 VW Rabbit automobile to provide data for evaluating the validity of the modified computer program. The first series of tests was performed on flat, rigid pavement to better enable checking that the vehicle characteristics in general were satisfactorily represented by the simulation model input data set. In the second series of tests, the vehicle traversed natural roadside terrains to assess the predictive capability of HVOSM employing the deformable-soil model. These included measurement of the motion-resistance force as the car was dragged over a sod field, spinout on level turf, and traversals of a fill-embankment end transition and of the front slope of a wide ditch.

Figure 1 presents comparisons of the HVOSM and measured vehicle responses in the traversal of the front slope of a 3ft(0.9m)-deep, wide-bottom ditch at 42.3 mi/hr (68.1 km/hr). Despite the severity of the conditions, correlation between the simulated and measured responses of the car was very good except for the yaw response. As a result, the path of the

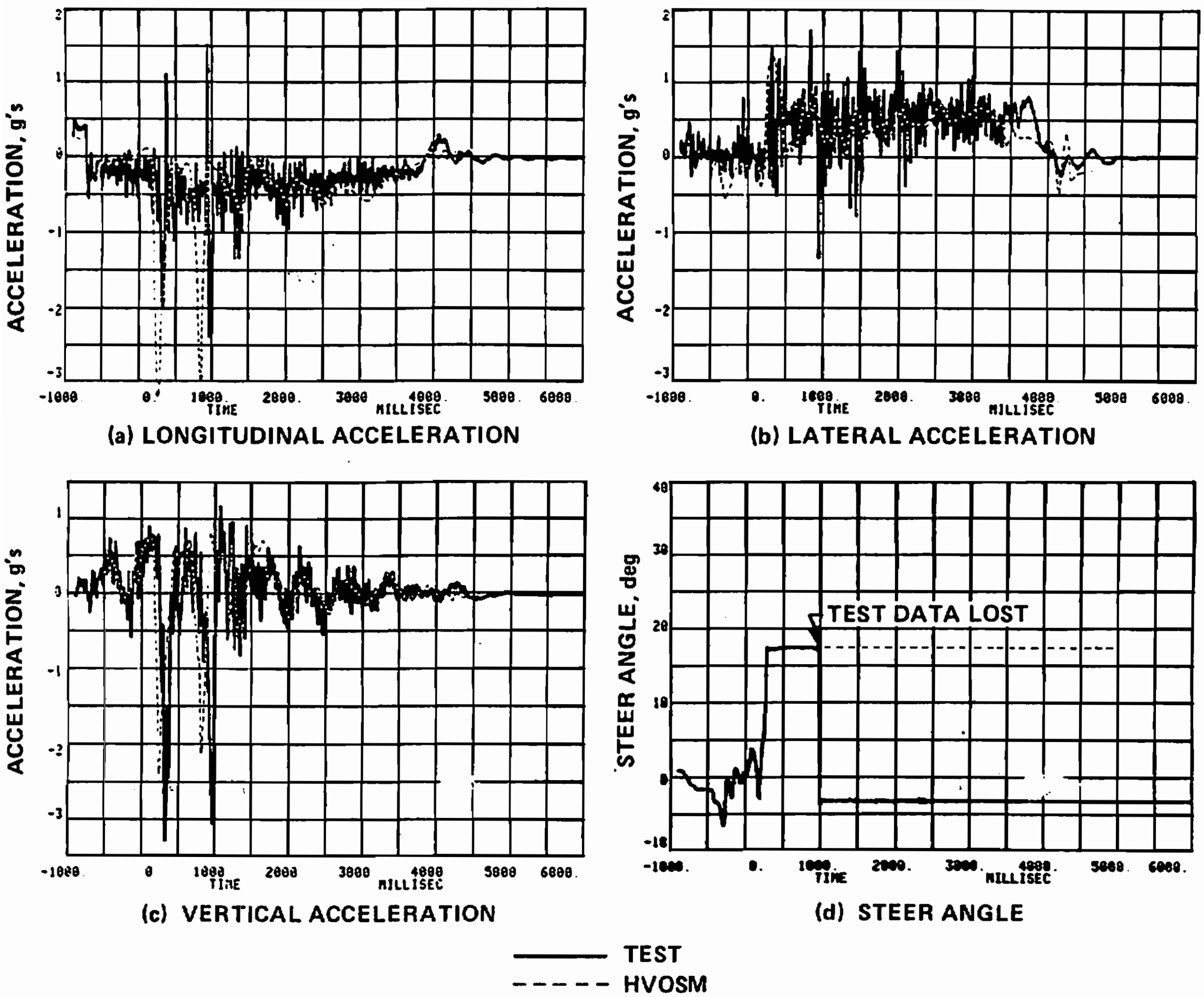


Figure 1. Comparison of HVOSM and measured vehicle responses in ditch-embankment test.

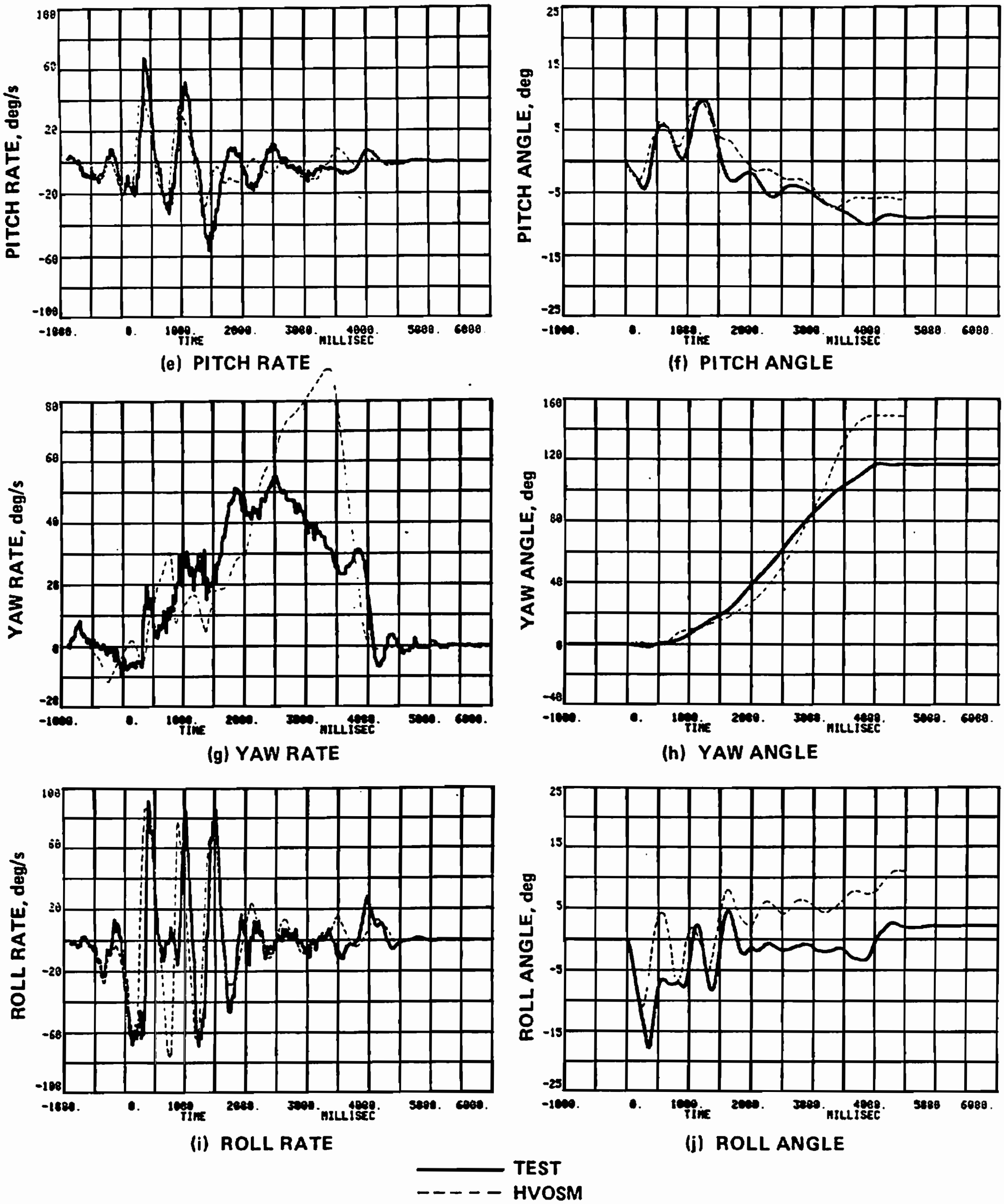


Figure 1. Comparison of HVOSM and measured vehicle responses in ditch-embankment test. (continued)

simulated vehicle after exit from the ditch deviated from the actual trajectory. For the less severe conditions of the other tests, the agreement between the model and test results was even better.

On the whole, the deformable-soil model of the modified HVOSM computer program improved the accuracy of the simulations of the tests on the various roadside terrains. However, this study did not thoroughly establish the extent to which the model accounts for all of the various real-world conditions that contribute to vehicle rollover. A more extensive and rigorous validation of the analytical approach might be obtained through measurements of the sinkage and motion resistance forces of tires operating on soil for various tire loads, sideslip angles from 0 to 90 degrees, and soil conditions.

4. SIMULATION ANALYSIS OF ROADSIDE FEATURES

SUMMARY

Over 200 HVOSM computer runs were made in examining the rollover tendencies of vehicles traversing various sideslope, fill-embankment, and ditch configurations. The roadside cross sections included an 8ft(2.44m)-wide shoulder and a 4-ft (1.22-m) rounding of the shoulder/front-slope break line. The rounding profiles defined by the equations given by AASHTO (called "optimum" rounding herein) were also used in some of the sideslope simulations.(4) The ground beyond the shoulder was assumed to be deformable, with characteristics defined by the soil constants for sod given by Bekker.(2)

Two small cars and one large, heavy car were simulated. One of the small cars was represented by the HVOSM input data set developed for the VW Rabbit used in the full-scale tests, which weighed 2,410 lb (1,093 kg) including the driver. The other small car weighed 1,800 lb (816 kg) and was identical to the first except for values of those parameters (moments of inertia, C.G. location, etc.) affected by the different weight. Model inputs

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4. "Guide for Selecting, Locating, and Designing Traffic Barriers," American Association of State Highway and Transportation Officials, 1977.

for these cars were defined based on data from several sources.[5,6,7] The third vehicle was assumed to weigh 4,450 lb (2,018 kg) and represented the large, heavy class of cars at the opposite end of the size and weight spectrum. Again, available data were used to define typical physical characteristics for that vehicle class.[8,9]

Both tracking and nontracking vehicle departures from the roadway were considered. The departure conditions used are shown in table 2. A back-to-the-road steer maneuver was also simulated in all computer runs.

Table 2. Departure conditions considered.

Variable	Departure No. 1	Departure No. 2
Speed, mi/h	60	45
Path Angle, degrees	15	25
Sideslip Angle, degrees	0	30

60 mi/h = 96.5 km/h; 45 mi/h = 72.4 km/h

SIDESLOPES

The [illegible] behavio[illegible] of th[illegible] v[illegible] [illegible]perating on [illegible] 3:1, and 4:1 slopes with both 4-ft (1.22-m) and optimum shoulder roundings was investigated in the first group of computer simulations. A value of the tire/ground friction coefficient (μ) of 0.6 was assumed for these runs. The results indicated that the tendency to roll over was greater for the nontracking departure and, as expected, increased with increasing steepness of the sideslope. Both small cars rolled over on the 2:1 slope, and the 2,410-lb (1,093-kg) car also rolled over on the 3:1 slope. However, rollover of these vehicles did not occur on

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5. Howerter, E.D., Hinch, J.A., and Owings, R.P., "Sensitivity Analysis of Subcompact Vehicle Performance Due to an Impact with a Breakaway Luminaire Support," ENSCO, Inc., Report No. FHWA-83-02, 15 April 1983.
6. Personal communication from Lloyd E. Carlson, Mobility Systems and Equipment Company, to Charles F. McDevitt of FHWA.
7. Riede, P.M., Leffert, R.L., and Cobb, W.A., "Typical Vehicle Parameters for Dynamic Studies Revised for the 1980's," Society of Automotive Engineers, Inc., Technical Paper No. 840561, March 1984.
8. Personal communication from Robert J. Keenan, Johns Hopkins University Applied Research Laboratory, IHVHP computer program input data listing for 1976 Ford LTD vehicle, 25 September 1984.
9. Basso, G.L., "Functional Derivation of Vehicle Parameters for Dynamics Studies," National Research Council Canada, Report No. LTR-ST 747, September 1974.

the slopes with optimum rounding, which shows the importance of that design parameter in maintaining vehicle stability. The large, heavy car did not roll over on any of the slopes and had less tendency to spin out than the smaller cars. No rollovers occurred in any of the simulations of the tracking departure, though each of the vehicles came very close to overturning on the 2:1 slope with 4-ft (1.22-m) rounding. The finding that the small, lightweight cars rolled over more readily than the large, heavy car is in keeping with the finding from the analysis of accident data.

Additional simulations were performed in which the friction coefficient of the ground was varied to identify the minimum values that would result in vehicle rollover on each sideslope. It was thought that, in this way, these values might serve as a metric providing insight as to how much the rollover potential differed among the various sideslopes. The results obtained in the simulations of the small, lightweight cars are summarized in tables 3 and 4 and depicted graphically in figure 2.

For the skidding departures, these results show a consistent trend of increased μ required for rollover with decreasing steepness of the slope. In contrast, for tracking departures, the threshold values of μ for rollover were found to be nearly the same for all sideslopes. The reason for the difference in the relationship between the sideslope and the friction coefficient needed to produce rollover for the two different departure conditions is not clear. In the case of the sideslipping departure, the car is initially nearly broadside to the slope, so the inclination of the slope contributes to the vehicle roll; hence, the magnitude of the tire side forces needed to trip the vehicle is reduced as the steepness of the slope is increased. For the tracking departure, the interactions of factors affecting the roll dynamics are much more complex, but it appears that the yaw velocity achieved by the vehicle during spinout is a primary factor influencing whether the lateral accelerations developed are high enough and sustained for a sufficiently long period to induce rollover.

The results of the 2,410-lb (1,093-kg) car simulations of the 2:1 and 3:1 sideslopes, for which the friction coefficient was varied over a wide range (between 0.6 and 1.7), show some unexpected findings that further

Table 3. Threshold of ground friction coefficient for rollover of 1,800-lb (816-kg) car.

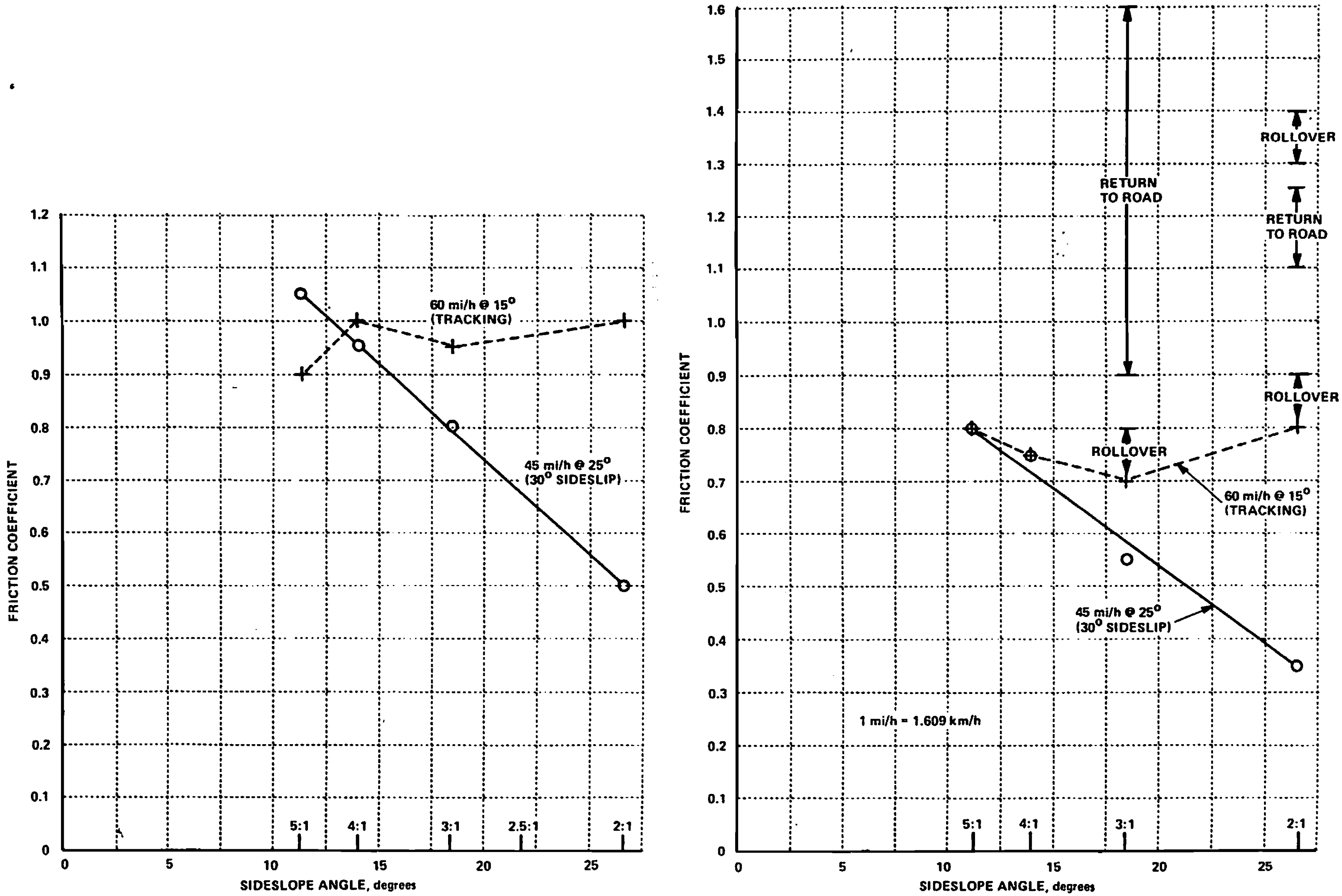
Sideslope ratio	Friction coefficient	Maximum roll angle, degrees	Comments
45-mi/h and 25-degree (30-degree Sideslip) Departure			
2:1	0.45	45.2	Car spins out and slides down sideslope.
2:1	0.50	Rollover	Rollover 25.6 ft from EOP.
3:1	0.75	32.1	Car begins return to road, stops on sideslope; maximum lateral distance 26.2 ft from EOP.
3:1	0.80	Rollover	Rollover 21.5 ft from EOP.
4:1	0.90	24.7	Car returns to road at high angle; maximum lateral distance 19.3 ft from EOP.
4:1	0.95	Rollover	Rollover 18.3 ft from EOP.
5:1	1.0	24.3	Car returns to road at high angle; maximum lateral distance 16.6 ft from EOP.
5:1	1.05	Rollover	Rollover 12.6 ft from EOP on return path to road.
60-mi/h and 15-degree (Tracking) Departure			
2:1	0.95	43.5	Car spins out on sideslope.
2:1	1.0	Rollover	Rollover 50.7 ft from EOP.
3:1	0.90	24.9	Car begins return to road, spins out.
3:1	0.95	Rollover	Rollover 27.9 ft from EOP on return path to road.
4:1	0.95	20.8	Car begins return to road, spins out.
4:1	1.0	Rollover	Rollover 14.6 ft from EOP on return path to road.
5:1	0.85	16.8	Car begins return to road, spins out.
5:1	0.90	Rollover	Rollover 16.2 ft from EOP on return path to road.

1 mi/h = 1.609 km/h
1 ft = 0.3048 m

Table 4. Threshold of ground friction coefficient for rollover of 2,410-lb (1,093-kg) car.

Sideslope ratio	Friction coefficient	Maximum roll angle, degrees	Comments
45-mi/h and 25-degree (30-degree Sideslip) Departure			
2:1	0.30	49.6	Car spins out and slides down sideslope.
2:1	0.35	Rollover	Rollover 21.3 ft from EOP.
3:1	0.50	29.2	Car spins out and backs down sideslope.
3:1	0.55	Rollover	Rollover 39.3 ft from EOP.
4:1	0.70	26.8	Car begins return to road and spins out on sideslope.
4:1	0.75	Rollover	Rollover 21.2 ft from EOP.
5:1	0.75	22.8	Car returns to road; maximum lateral distance 20.2 ft from EOP.
5:1	0.80	Rollover	Rollover 19.0 ft from EOP.
60-mi/h and 15-degree (Tracking) Departure			
2:1	0.75	46.4	Car slides on return path to road.
2:1	0.80	Rollover	Rollover 76.1 ft from EOP on return path to road.
2:1	1.25	46.8	Car on stable return path to road.
2:1	1.30	Rollover	Rollover 55.1 from EOP.
3:1	0.65	26.5	Car spins out on sideslope.
3:1	0.70	Rollover	Rollover 46.4 ft from EOP.
4:1	0.70	17.9	Car begins return to road, spins out.
4:1	0.75	Rollover	Rollover 30.2 ft from EOP on return path to road.
5:1	0.75	18.0	Car begins return to road, spins out.
5:1	0.80	Rollover	Rollover 16.5 ft from EOP on return path to road.

1 mi/h = 1.609 km/h
1 ft = 0.3048 m



a. 1,800-lb (816-kg) car

b. 2,410-lb (1,093-kg) car

Figure 2. Friction-coefficient threshold for rollover.

illustrate the complexity of the rollover phenomena. In the case of the 2:1 sideslope, spinout of the vehicle occurred for values of friction coefficient of 0.75 and lower. The car rolled over in runs performed with friction coefficients of 0.8 and 0.9 but followed a stable return path toward the road for coefficients in the range between 1.1 and 1.25. Further increases of the friction coefficient to 1.3 and 1.4 again resulted in rollover of the vehicle. Similarly, on the 3:1 sideslope, rollover occurred only for the narrow range of friction coefficients between 0.7 and 0.8. Below this range, the car spun out on the slope; for higher values (up to 1.7), it was steered on a stable trajectory back to the road without rolling over.

Rollover of the 4,450-lb (2,018-kg) car occurred on the 2:1 sideslope for the sideslipping departure condition with friction coefficients of 0.8 or higher. However, the vehicle otherwise did not roll over, even for values of the friction coefficient as high as 1.6. For the tracking departure, the vehicle spun out on the slope for friction coefficients up to 1.2 and returned to the road with further increases of the coefficient.

The reason for the difference in the friction coefficients required to cause rollover of the cars of different size and weight is not clear. However, two factors that appear to provide a partial explanation were identified. These are: (1) differences in the value of the roll static stability factor, $\frac{T}{2h}$ (i.e., the ratio of the half-track to the height of C.G.) and (2) differences in the suspension characteristics that affect the development of suspension jacking forces.

An interesting observation noted in analyzing the results of all of the simulation runs is that, when the vehicles did not roll over, the maximum roll angles were always much less than the critical roll angle, particularly for the shallower slopes, and changed only slightly with changes of the friction coefficient. Yet, a small increase to the critical value suddenly produced a very large change of the roll response that resulted in rollover. This suggests that, when unknown combinations of a host of other variables (e.g., speed, orientation, linear and angular velocities, suspension deflections and velocities, and driver control inputs) are such as to create nearly threshold conditions for rollover, nonuniformities of real-world terrains which may cause only small variations of the effective friction coefficient can spell the difference between whether a vehicle safely traverses a sideslope or is triggered into a rollover.

FILL EMBANKMENTS

The simulations of vehicles traversing fill embankments were aimed at verifying the current AASHTO criteria for determining the need for protective barrier systems on roadway fill sections which are shown in figure 3.[4] Of primary interest was that portion of the curve for fill heights less than about 17 ft (5.2 m), where, depending on the height, unrounded slopes as steep as 1½:1 are permissible without barrier protection.

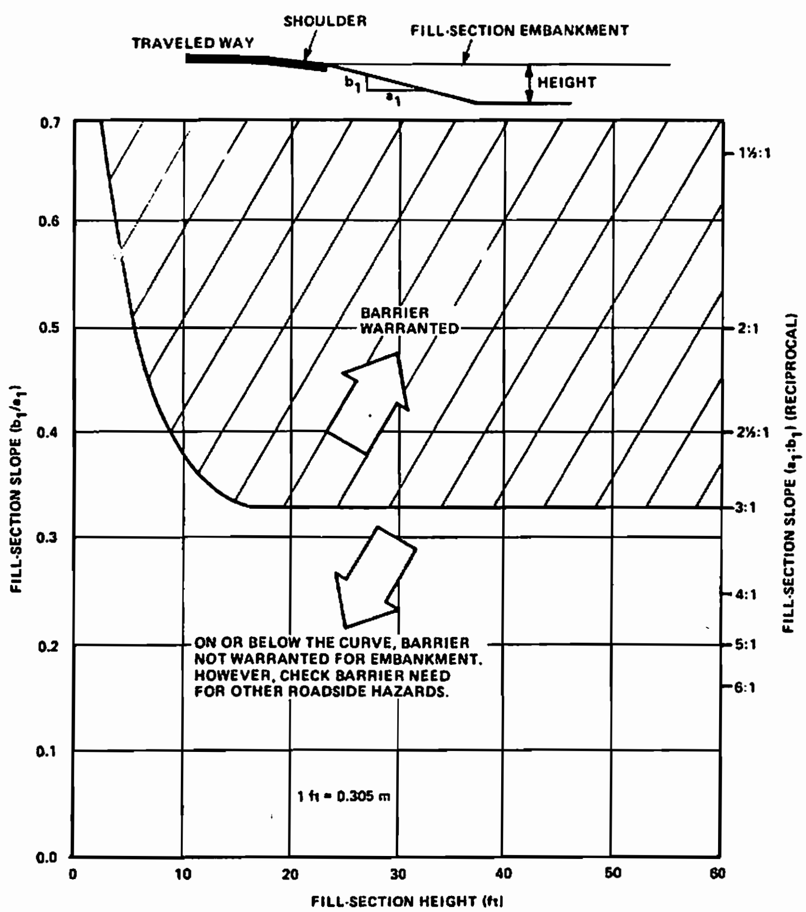


Figure 3. Warrants for fill-section embankments.[4]

Embankments with 2:1, 3:1, and 4:1 slopes and varying in height from 3 ft (0.9 m) to 17.5 ft (5.3 m) were considered. A value of 0.6 for the friction coefficient of the ground was used, and rounding of the toe was provided based on the rate of 0.3 ft (0.09 m) per degree change of slope recommended by DeLeys for avoiding bumper impact with the ground.[10]

The results of the simulated traversals of the various embankment configurations are summarized in table 5. The vehicle was not steered in several of the runs because the earlier study of sideslopes had shown that, with the assumed steer maneuver, the car would either return to the road or spin out on the slope before reaching the toe of the embankment. Rollover of the vehicles occurred for the nontracking departure on the 2:1 embankment with a height of only 3.2 ft (0.98 m), which is the minimum fill-section height possible with the assumed roundings at the shoulder and toe. As would be expected, rollover also resulted when the height of the embankment was increased to 5.5 ft (1.68 m), which is about the maximum height allowed by the current criteria before a barrier is warranted. Note, however, that rollover was avoided when the transition from the shoulder to the sideslope was more gradual, as provided by the optimum rounding. The vehicle also did not overturn on these embankments for the case of the tracking departure.

Rollover was also induced after the vehicle had successfully negotiated the 10ft(3.0m)-high embankment with a 2:1 slope while tracking. In this instance, rollover was precipitated by the high lateral acceleration developed while in a rapid spin as the vehicle was moving back up the embankment.

Roll stability was maintained in all of the simulations of the 1,800-lb (816-kg) car traversing the embankments with a 3:1 front slope, and the maximum roll angle was essentially independent of the height of the embankment. For the sideslipping departure condition, the car either returned to the road or spun out on the slope. Note that the vehicle did not encroach much beyond the toe of the embankment in many of the runs.

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10. DeLeys, N.J., "Safety Aspects of Roadside Cross-Section Design," Report No. FHWA-RD-75-41, February 1975.

Table 5. Summary of fill-embankment simulations.

Vehicle weight, lb	Departure, mi/h @ degrees	Side-slope ratio	Fill height, ft	Toe dist. from EOP, ft	Max. roll, degrees	Max. Lat. encroach., ft	Comments
1,800	60 @ 15	2:1	3.2	15.4	26.8/-13.0	35.4	Airborne after crossing rounding at shoulder, impacts beyond toe rounding. Returns to road during spinout.
1,800	45 @ 25	2:1	3.2	15.4	Rollover	18.9	Rollover on toe rounding.
2,410	45 @ 25	2:1	3.2	15.4	Rollover	17.9	Rollover on toe rounding.
1,800	60 @ 15*	2:1	5.5	20.0	37.6/-18.5	>140	Car airborne after crossing rounding at shoulder, impacts on toe rounding, spins out on flat.
1,800	60 @ 15	2:1	5.5	20.0	38.4/-16.5	41.9	Same as above, except steer causes car to return to road during spinout.
1,800	45 @ 25*	2:1	5.5	20.0	Rollover	23.5	Rollover on toe rounding.
2,410	45 @ 25	2:1†	6.5	27.9	29.9	29.9	Returns to road, no spinout.
4,450	60 @ 15	2:1†	6.5	27.9	28.3	39.3	Returns to road, no spinout.
1,800	60 @ 15	2:1	10.0	29.0	Rollover	40.9	Rollover during spinout after recrossing toe on return path to road.
1,800	60 @ 15	3:1	3.0	17.5	22.5/-12.1	32.9	Car begins return to road, spins out on flat.
1,800	45 @ 25	3:1	3.0	17.5	26.6/-1.4	22.3	Car returns to road, very stable, LF wheel does not go beyond toe rounding.
1,800	60 @ 15	3:1	5.0	23.5	24.6	33.5	Car returns to road in spin at high yaw and sideslip angles.
1,800	45 @ 25	3:1	5.0	23.5	26.3	26.5	Stable return to road. Left-side wheels do not go beyond toe rouning.
2,410	45 @ 25	3:1	5.0	23.5	Rollover	25.2	Rollover on toe rounding.
1,800	60 @ 15	3:1	10.0	38.5	24.5	41.9	Stable return to road. Left-side wheels do not go beyond toe rounding.
1,800	45 @ 25	3:1	10.0	38.5	26.3	35.6	Car stable on return path to road, remains on sideslope.
1,800	60 @ 15*	3:1	17.0	59.5	23.5/-6.2	>136	Car stable on slight curved path away from road.
1,800	45 @ 25*	3:1	17.0	59.5	26.3/-13.5	41.6	Car spins out on sideslope.
1,800	60 @ 15*	4:1	17.0	76.0	17.0/-5.8	>133	Car stable on slightly curved path away from road.
1,800	45 @ 25*	4:1	17.0	76.0	19.6/-9.9	27.8	Car begins return to road, spins out.

1 mi/h = 1.609 km/h
1 ft = 0.3048 m
1 lb = 0.454 kg

Notes: * simulations with zero steer input
† simulations with optimum shoulder/sideslope rounding

The 2,410-lb (1,093-kg) small car rolled over in the case of the skidding departure on the 5ft(1.5m)-high, 3:1 embankment. As noted earlier, that car was found to overturn more readily than the one weighing only 1,800 lb (816 kg).

The results of this study of embankments show that fill sections with a front slope of 2:1 are hazardous, regardless of the height of the embankment. It also appears that a 3:1 embankment slope is marginally safe, since rollover of one of the small cars was shown to occur on embankments 5 ft (1.5 m) or more in height. This is evidenced further by the results of recent full-scale tests of a 15ft(4.6m)-high embankment for which the steepness of the main portion of the sideslope was nominally 3:1.(11) In those tests, a pickup truck, a van, and a minisize automobile weighing 1,938 lb (879 kg) were each remotely controlled so as to depart from the roadway at 50 mi/h (80.5 km/h) and at a 15-degree angle (tracking). After leaving the road, a steer input was initiated to maneuver the vehicle back toward the road. Both the pickup truck and the van successfully traversed the embankment and followed a stable return path to the road; the maximum roll angle of each vehicle was approximately [illegible] degrees. However, in the test with the small automobile, the rear of the vehicle began to slide around (counterclockwise yaw) shortly after the left-steer maneuver was begun. As the vehicle continued down the embankment, the tires on the right side began to plow into the sod ground, and the vehicle subsequently rolled over near the bottom of the embankment.

In view of all of these findings, it may be concluded that roadside barriers are warranted for any embankment having a front slope steeper than 3:1 to protect against rollover of small, lightweight vehicles.

DITCHES

Among the important factors that need to be considered in the design of ditches that can be safely traversed are the steepness of the front and back slopes and the depth and shape of the bottom of the ditch. Thus, compared to

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11. Buth, C.E. and Campise, W.L., "Performance Limits of Longitudinal Barrier Systems, Volume IV - Appendix C, Details of Embankment Traversal Tests," Texas Transportation Institute, Contract No. DTFH61-82-C-00051, May 1985.

fill embankments, ditches involve at least two additional geometric variables. Criteria for combinations of front and back slopes that provide acceptable cross sections for ditches with various shapes of the bottom are defined by AASHTO and are depicted in figure 4.[4]

The effects of ditch design variables on vehicle rollover tendencies were investigated in only a few simulations of three selected ditch configurations. Two of these ditches had combinations of front and back slopes that were within the envelopes for preferred cross sections. One was a 17ft(5.2m)-deep vee ditch with front and back slopes of 4:1 and 6:1, respectively; the other was a 3ft(0.9m)-deep round bottom ditch with an 8-ft (2.4-m) rounding between 4:1 front and back slopes. The third ditch considered was also a vee shape with a 3:1 front slope and a 4:1 back slope which, as may be seen from figure 4, is a slope combination that is outside the boundary for preferred ditch cross sections. A ditch depth of 3 ft (0.9 m) was also chosen to ensure that the vehicle would encounter the back slope for the nontracking departure condition. The roadside terrain for each ditch configuration included an 8ft(2.4m)-wide shoulder with 4-ft (1.2-m) rounding tangent to the front slope.

The responses of the simulated 1,800-lb (816-kg) small car in traversing the various ditches are summarized in table 6. Because of the larger lateral distance from the edge of the road to the bottom of the 17ft(5.2m)-deep vee ditch, only the 60-mi/h (96.5-km/h) at 15-degree tracking departure was simulated. The car easily traversed the ditch and, as may be seen, the maximum roll angle was in the counterclockwise direction. From a comparison with a similar simulation of a 17ft(5.2m)-high fill embankment having a 4:1 sideslope (refer to table 5), it may be noted that the effect of the change from zero to a 6:1 backslope was to increase the maximum negative roll angle from -5.8 degrees to -23.7 degrees.

The vehicle responses in the simulation of the other vee ditch with steeper front and back slopes were very violent and resulted in overturning of the car in the case of the tracking departure. The very large radial tire forces developed when the right-front wheel impacted the back slope caused a "flip" type of rollover in the counterclockwise direction. The vehicle also

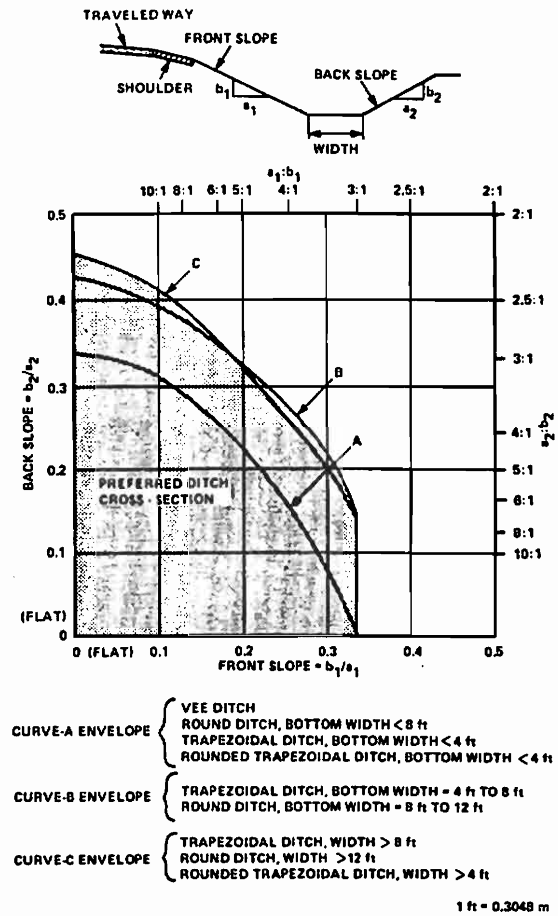

Figure 4. Envelopes of front and back slope combinations for preferred ditch sections.[4]

Table 6. Summary of ditch simulations.

Departure, mi/h @ degrees	Slopes, front/back	Depth, ft	℄ Dist. from EOP, ft	Bottom rounding, ft	Max. roll, deg	Max. Lat. encroach., ft	Comments
Vee Ditches							
60 @ 15*	4:1/6:1	17.0	76.0	0	17.0/-23.7	>133	Car stable on slightly curved path away from road.
60 @ 15	3:1/4:1	3.0	17.5	0	Rollover(-)	21.0	Severe impact with back slope caused "flip"-type rollover.
45 @ 25	3:1/4:1	3.0	17.5	0	48.8/-22.2	20.4	Airborne after impacting backslope. Sprung-mass right-front corner impact with back slope prevented rollover.
Round Bottom Ditch							
60 @ 15	4:1/4:1	3.0	20.0	8	20.9/-11.6	28.1	Car returned to road, very stable.
45 @ 25	4:1/4:1	3.0	20.0	8	19.6	22.5	Car returned to road, did not contact back slope.

1 mi/h = 1.609 km/h
1 ft = 0.3048 m

*Simulation with zero steer input.

nearly rolled over (attained 90% of the critical roll angle) in the nontracking departure from the road. In this instance, however, note that the maximum roll was in the clockwise direction, because of the high lateral forces that were generated by the tires prior to and upon impact with the back slope. As noted in the table, forces resulting from contact of the right end of the front bumper with the back slope prevented the vehicle from rolling over.

From the responses of the vehicles observed in the few simulations of ditches performed in this study, it appears that the existing guidelines for the design of preferred ditch sections, which are primarily based on vehicle linear acceleration limit criteria for avoiding injuries to occupants, provide for designs that also are safe from the standpoint of offering low vehicle rollover potential.

5. CONCLUSIONS AND RECOMMENDATIONS

Based on the findings of this study, the following conclusions and recommendations are made:

1. The sideslope of a fill embankment should be no steeper than 3:1, and preferably flatter, to reduce the likelihood of rollover. Results of tests and computer simulations show that 3:1 slopes are marginally safe for traversal by small, lightweight automobiles, which are known, from the preponderance of evidence from accident data analyses, to be more likely to roll over than large, heavy vehicles. The slopes should also be firm and smooth to minimize the likelihood of the vehicle's tires digging into the ground or striking a surface irregularity which could trip the vehicle into a rollover.

It is recommended, therefore, that consideration be given to revising the current AASHTO design criteria for barrier warrants on sideslopes and embankments so as to indicate that safety barriers are warranted for all slopes steeper than 3:1, for fill heights greater than 3 ft (0.9 m). This would make the criteria for barrier placement on embankments more consistent with the AASHTO criteria for the design of ditches shown in figure 4. (Note that, for ditches having zero backslope (i.e., with a cross section like that of an embankment), the front slope should be no steeper than 3:1.) The simulations of this study were limited to fill heights of 3 ft (0.9 m) or greater in order to accommodate the roundings of the slope breaks.

2. Current AASHTO criteria for the design of preferred ditch sections, which limit the front slope to no steeper than 3:1, appear to define ditch configurations that are relatively safe with respect to vehicle rollover potential. However, because of the small difference between two of the criteria applicable to different ranges of ditch bottom width (see figure 4, curves B and C), it is recommended that those criteria be replaced by a single faired curve that follows curve C of figure 4 for front slopes steeper than 5:1 and that follows curve B of the figure for shallower front slopes to provide a greater margin of safety.

3. All slope breaks of roadside terrain should be rounded as much as possible to reduce the potential for vehicles to be caused to roll over due to tripping on sag vertical curves. The need for adequate rounding of crest vertical curves, such as the break line of shoulder and side slopes, also cannot be over[illegible]sized. Such r[illegible] only afford drivers greater opportunity to maintain or regain control of their vehicle but also decrease the likelihood of rollover by preventing the vehicle from achieving large values of angular momentum about the roll axis.

4. The modified HVOSM has been demonstrated to be capable of predicting the response of vehicles operating on off-road terrains with reasonable accuracy. The development and incorporation of the deformable-soil model in HVOSM is considered an important improvement since it allows simulation of the effects of tire sinkage in soil, which has been identified as one of the leading causes of rollover. However, evidence of the validity of the deformable-soil model is clearly still very limited. It is recommended, therefore, that tests be performed to measure the sinkage and motion-resistance forces of tires in soft soil for various tire loads and for sideslip angles from zero to 90 degrees, which would provide data needed for a more rigorous validation of the analytical approach.

5. The relatively few simulations that resulted in vehicle rollover in this study point to the dynamic nature of the rollover phenomenon, which is sensitive to the complex interactions of many factors whose effects are nonindependent. Adequate vehicle parametric data for the severe operating regime associated with the rollover response are generally lacking. Among the most important of these are definitive data for tire properties under the high tire load and large slip and camber angle conditions that prevail in most rollover events. To alleviate this deficiency of the model data base, it is strongly recommended that a test program be conducted to determine typical force characteristics of tires for slip and camber angles ranging up to 90 degrees and for loads including extreme overload.

6. Ultimately, the vehicle rollover potential associated with roadside features is reflected by real-world accident experience. From the literature review performed as a part of this study, it is apparent that the existing accident data base lacks the comprehensive and detailed information necessary to define the conditions that lead to rollover for the different vehicle types. For example, data contained in accident files such as NASS and FARS usually provide little or no information regarding the geometrics of the accident site (e.g., steepness of slopes, embankment height, and roundings), whether the vehicles were tripped by a surface irregularity or as a result of tire ruts in soft soil, where rollovers were initiated with respect to the terrain feature (sideslope, backslope, toe of embankment, etc.), vehicle trajectory, etc.

To alleviate such shortcomings of the existing accident data base, it is recommended that a data-collection effort be made that is specifically directed toward providing the information necessary to evaluate, using statistical analysis techniques, the suitability of roadside-feature design criteria for the current and projected mix of vehicle types.

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