EMBANKMENT WIDENING AND SLOPES FOR ENERGY ABSORBING END TERMINALS

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### Abstract (Limit: 200 words)

Full-scale crash testing has shown that W-beam guardrails do not perform well when installed on even modest roadside slopes. In order to provide the maximum clear recovery area, guardrails are installed as far as possible from the traveled way. This practice causes guardrail terminals to be placed adjacent to roadside slopes and embankments. Vehicles that strike guardrail terminals are often allowed to pass through the systems at a relatively high speed. There is a concern that even moderate embankments placed near the end of a guardrail could cause these vehicles to rollover. Safety performance evaluation criteria contained in NCHRP Report 350 recommend that guardrail terminals be tested on flat ground. Hence, there is a great deal of uncertainty regarding acceptable terrain configurations near a guardrail terminal.

One important finding from this study is that energy-absorbing terminals greatly reduce the velocity of small vehicles. Energy-absorbing terminals were found to reduce speeds by 75% during head-on impacts and approximately 50% when the terminal is struck at an angle of 15 degrees. These large reductions in vehicle velocity greatly reduce the risk of vehicle rollover as it moves onto roadside slopes and ditches. The HVOSM modeling effort predicted that energy absorbing terminals, when installed adjacent to roadside slopes of 4:1, would not be likely to cause rollovers. Further, the simulation effort did not predict rollover for nominal levels of friction, even when 3:1 slopes were placed behind the guardrail. The simulation study only predicted rollover when the tire ground friction was increased to artificially high levels to model wheel rutting in soft soil. Even under that circumstance, rollover was predicted for only one of the four crash tests included in the study.
DISCLAIMER STATEMENT

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State Highway Departments participating in the Midwest States’ Regional Pooled Fund Research Program nor the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.
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1 INTRODUCTION

1.1 Problem Statement

Roadways are elevated from the surrounding terrain in order to accommodate water drainage. As a result, almost all roadsides incorporate slopes of varying degrees. When possible, highway designers flatten slopes immediately adjacent to the roadway to provide a clear recovery area for errant motorists. Even though flat slopes have been proven to provide a safer environment, right of way limitations often require that steeper slopes be utilized at some locations along most highways.

Steep slopes are a significant problem when guardrails are utilized to protect motorists from roadside hazards. Full-scale crash testing has shown that W-beam guardrails do not perform well when installed on even modest roadside slopes of 6:1 or steeper (1). Further, in order to provide the maximum clear recovery area for errant motorists, guardrails are installed as far as possible from the traveled way. As a result, W-beam guardrails are almost always placed near the slope break point. This practice also causes guardrail terminals to be placed adjacent to roadside slopes and embankments.

Vehicles that strike guardrail terminals are often allowed to pass through the systems at a relatively high speed. There is a concern that the combination of impact with a guardrail terminal and even moderate roadside embankments can cause vehicles penetrating behind the terminal to rollover. Safety performance evaluation criteria contained in National Cooperative Highway Research Program (NCHRP) Report 350 (2) recommends that guardrail terminals be tested on flat ground, even though these systems are seldom used in such situations. As a result, the magnitude of the safety
problem associated with guardrail terminals installed adjacent to roadside slopes has never been investigated through full-scale crash testing.

The Federal Highway Administration (FHWA) has attempted to address the inconsistency between the terrain conditions under which guardrail terminals are tested and actual field installations. FHWA’s recommendations regarding terrain conditions adjacent to W-beam guardrail terminals are shown in Figures 1 and 2. These guidelines were based largely on engineering judgment and an evaluation of the potential for undercarriage contact with slope break points near the terminal. Large fill volumes are often required to meet these guidelines and as a result, implementation has been somewhat inconsistent. In an effort to better define appropriate grading recommendations for guardrail terminals, the Midwest States’ Pooled Fund Program sponsored the research study described herein.
**Figure 1.** FHWA Slope Recommendation, Tangent End Treatment

**Figure 2.** FHWA’s Slope Recommendation, Flared End Treatment
1.2 Objective

The objective of this project was to investigate the safety hazard associated with modest roadside slopes and embankments placed adjacent to guardrail terminals and to provide guidelines for guardrail terminal installations.

1.3 Scope

As previously mentioned, full-scale crash testing of guardrail terminals is conducted on flat ground. The risk of rollover associated with vehicles penetrating through guardrail terminals and encountering roadside slopes can be explored through computer simulation of post-impact vehicle trajectories. If a vehicle dynamics model can accurately replicate the actual post impact trajectories on flat ground, it should be capable of predicting vehicle behavior on other terrain configurations.

This procedure involves collecting post-impact vehicle conditions for a number of full-scale crash tests of various gating terminals. Post-impact vehicle conditions, including translational velocity and roll, pitch, and yaw rates as well as suspension deflections and velocities are then used to simulate the vehicle path after impacting the guardrail terminal to verify that the initial conditions are relatively accurate. The computer model is then used to predict vehicle stability for a variety of roadside terrain conditions.

Highway-Vehicle-Object Simulation Model (HVOSM) has been widely used for vehicle handling and stability analyses (3). This program has been extensively validated for modeling vehicles traversing roadside slopes and embankments (4-6). Therefore, HVOSM was selected for use in the current study.
2 GATING TERMINAL CRASH TESTS

2.1 Gating Terminal Test Definitions

Gating terminals normally allow impacting vehicles to pass through the end of the system and travel behind the guardrail. Although NCHRP Report 350 requires testing with both 820-kg (1800 lbs) passenger cars and 2000-kg (4400 lbs) pickup trucks, numerous research studies have shown that small passenger cars are more susceptible to rollover on roadside slopes than are ¾-ton pickup trucks. The two small car tests recommended by NCHRP Report 350 that involve the vehicle passing through the end of the terminal are Tests 3-30 and 3-32.

1. 3-30 Test Designation – 820C, 100 km/h (62.4 mph), 0 degrees, quarter-point offset
2. 3-32 Test Designation – 820C, 100 km/h (62.4 mph), 15 degrees, centerline impact

The offset associated with the head-on crash test, 3-30, assures that the small car will experience high yaw rotations as it exits from the terminal. However, this impact condition also causes the vehicle to slow dramatically, and the exit velocities are often very low. Test 3-32 involves a vehicle striking the terminal at an angle and, as a result, the vehicle passes through the terminal quickly without a great velocity reduction. However, because the center of the vehicle strikes the center of the terminal, this test seldom generates high vehicle roll or yaw rates.

2.2 Full-Scale Crash Tests

Originally, data was to be collected on all widely used guardrail terminals. However, there was limited cooperation from the developers of ET-2000 and SRT. Although the developers of the Regent provided available info, this system has not gained wide acceptance. As a result, only the BEST, BEAT-MT, and SKT end terminals were utilized in the study. The 3-30 tests chosen for evaluation included: SP-1, a test
of the SKT-350 with steel breakaway posts; and BEST-8, a test of the BEST 350 guardrail terminal. The 3-32 tests chosen for evaluation included: BMT-2, a test of the BEAT-MT; and BEST-4, a test of the BEST 350 terminal. Test summaries are included in Figures 3 through 6. Summaries of the exit conditions are included in Table 1. All crash tests selected were performed at Midwest Roadside Safety Facility (MwRSF).

<table>
<thead>
<tr>
<th>Test Designation</th>
<th>Roll (deg)</th>
<th>Pitch (deg)</th>
<th>Yaw (deg)</th>
<th>Roll Rate (deg/s)</th>
<th>Pitch Rate (deg/s)</th>
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<th>Long. Velocity (ft/s)</th>
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<tr>
<td>BMT-2</td>
<td>3-32</td>
<td>4.5</td>
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<td>-34.0</td>
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<tr>
<td>BEST-4</td>
<td>3-32</td>
<td>0.0</td>
<td>-5.0</td>
<td>4.0</td>
<td>0.0</td>
<td>20.8</td>
<td>-56.0</td>
<td>38.4</td>
</tr>
</tbody>
</table>
Test Number ................................................................. SP-1
Date .............................................................................. 2/2/98
Installation .................................. Sequential Kinking Terminal
Total Length ............................................................... 41.91 m
Vehicle Model ............................................ 1993 Ford Festiva
  Curb ................................................................. 795 kg
  Test Inertial ........................................................ 819 kg
  Gross Static ...................................................... 894 kg
Vehicle Speed
  Impact ............................................................... 98.6 km/hr
  Exit ................................................................. 16.0 km/hr
Vehicle Angle
  Impact ............................................................... 1.08 degrees
  Exit ................................................................. 139.4 degrees
Vehicle Impact Location ............. Head-on, offset quarterpoint
Occupant Ridedown Deceleration
  Longitudinal ...................................................... 12.12 g's
  Lateral ............................................................ 10.81 g's
Occupant Impact Velocity
  Longitudinal ...................................................... 8.40 m/s
  Lateral ............................................................ 3.51 m/s
Vehicle Damage
  TAD ................................................................. 12-FR-3
  VDI ................................................................. 12FREN2
Vehicle Stopping Distance ............ 10.38 m downstream
  (Center of Gravity) ................................. 4.65 m behind the system

Figure 3. Summary of SP-1
Test Number...............................................................BEST-8
Date............................................................................10/3/96
Installation ........................................................BEST System
Total Length...................................................................46 m
Vehicle Model ............................................1990 Ford Festiva
    Curb ........................................................................781 kg
    Test Inertial .........................................................817 kg
    Gross Static........................................................892 kg
Vehicle Speed
    Impact ..........................................................100.4 km/hr
    Exit ..............................................................23.8 km/hr
Vehicle Angle
    Impact ...................................................................0.6 degrees
    Exit ...................................................................-121.4 degrees
Vehicle Impact Location ......................Center of Impact Head
Occupant Ridedown Deceleration
    Longitudinal ......................................................12.0 g's
    Lateral ....................................................................4.7 g's
Occupant Impact Velocity
    Longitudinal ....................................................10.0 m/s
    Lateral ....................................................................1.2 m/s
Vehicle Damage
    TAD ........................................................................1-FC-4
    VDI ........................................................................12FCEN2
Vehicle Stopping Distance ....................25.58 m downstream
    (Center of Gravity) ...................................................11.98 m behind the system
Amount of rail fed through cutter ......................1.28 m

Figure 4. Summary of BEST-8
Test Number............................................... BMT-2
Date............................................................. 5/25/01
Installation ..................................Box-Beam Median Terminal
Total Length............................................................... 62.03 m
Vehicle Model ............................................... 1995 Geo Metro
  Curb .............................................................. 803 kg
  Test Inertial .................................................. 819 kg
  Gross Static................................................... 894 kg
Vehicle Speed
  Impact .......................................................... 101.6 km/hr
  Exit ................................................................ 45.0 km/hr
Vehicle Angle
  Impact .......................................................... 15.5 degrees
  Exit ................................................................ 21.5 degrees

Vehicle Impact Location ......................Center of Impact Head
Occupant Ridedown Deceleration (10 msec avg.)
  Longitudinal .................................................. 10.07 g’s
  Lateral............................................................ 6.18 g’s
Occupant Impact Velocity
  Longitudinal .................................................. 10.34 m/s
  Lateral............................................................ 2.34 m/s
Vehicle Damage................................................. Moderate
  TAD ................................................................. 1-FD-5
  SAE ................................................................. 1-FDEW5
Vehicle Stopping Distance .................... 19.52 m downstream
(Center of Gravity) ................... 4.38 m behind the system
Barrier Damage................................................. Moderate

Figure 5. Summary of BMT-2
Test Number ............................................................... BEST-4
Date ................................................................. 8/2/96
Installation .............................................................. BEST System
Total Length ........................................................... 30.5 m
Vehicle Model ............................................ 1991 Ford Festiva
  Curb ................................................................. 819 kg
  Test Inertial ....................................................... 820 kg
  Gross Static ....................................................... 896 kg
Vehicle Speed
  Impact ............................................................. 101.7 km/hr
  Exit ................................................................. 46.1 km/hr
Vehicle Angle
  Impact ............................................................. 13.6 degrees
  Exit ................................................................. 4.0 degrees
Vehicle Impact Location ............. Head-on, offset quarterpoint
Occupant Ridedown Deceleration
  Longitudinal ...................................................... 16.7 g’s
  Lateral .......................................................... 4.9 g’s
Occupant Impact Velocity
  Longitudinal ...................................................... 10.1 m/s
  Lateral .......................................................... 2.8 m/s
Vehicle Damage
  TAD ................................................................. 12-FL-3
  VDI ................................................................. 12FYEN2
Vehicle Stopping Distance .......... 16.04 m downstream
  (Center of Gravity) ................................... 9.10 m behind the system
Amount of rail fed through cutter .................................. 1.83 m

Figure 6. Summary of BEST-4
3 HVOSM

The HVOSM computer program has been used extensively to simulate vehicles traversing roadside embankments. HVOSM is a three-dimensional program developed to study a range of vehicle-roadway problems including the handling response of a vehicle on and off the travel way and impacts with rigid longitudinal barriers (5). There are several versions of HVOSM currently available, HVOSM-VD2, HVOSM-RD2, and HVOSM-TTI. The VD2 version has a more complex vehicle model including driver response simulation and additional degrees of freedom for tire spin. The RD2 version is intended for safety appurtenance design and more heavily emphasizes barrier impacts. HVOSM-TTI is a version of the code developed at Texas Transportation Institute (TTI). The TTI program cannot simulate vehicles with four-wheel independent suspension. All three versions of HVOSM appear to be capable of modeling vehicles traversing roadside slopes (6). Since HVOSM-RD2 was readily available, that version was selected for use in this study.
4 VALIDATION OF TESTS

4.1 Vehicle Model

A 1995 Geo Metro was used for BMT-2. Vehicles used for BEST-8, BEST-4, and SP-1 are 1990, 1991, and 1993 Ford Festivas, respectively. Because vehicle mass, wheel base, and basic construction are very similar for all of the vehicles, the 1995 Geo Metro was used to model all crash tests. The model for the 1995 Geo Metro was developed under NCHRP Project 17-11 (7). That study attempted to model vehicles traversing roadside slopes similar to those encountered in this study. Therefore, the model should be adequate for the purposes defined in this study. The vehicle model is described in Appendix A with the HVOSM output of the vehicle model.

4.2 Model Validation

In order to use HVOSM to predict vehicle behavior on roadside slopes after impacting a guardrail terminal, the vehicle and initial conditions need to correlate with the observed data from the crash tests. When the simulation results accurately correlate with crash test results, the simulation input parameters can be used in a model with a sloped terrain. More specifically, HVOSM can be used to predict vehicle behavior on slopes and embankments placed adjacent to guardrail terminals.

The following basic procedure was used in each validation effort. Vehicle motion data was obtained from high-speed film and a rate gyro mounted on the vehicle. Vehicle center of gravity (CG) position and velocities were obtained from the overhead high-speed film. Angular data was obtained from using the rate gyro when it was available. For tests without rate gyro data, angular rates and positions were obtained using the high-speed film. Yaw data could be easily obtained from the overhead views.
of the test. However, roll and pitch data had to be estimated using various downstream and side views of the crash test.

The initial conditions obtained from test data were placed into the HVOSM input deck. The first component to correct was the initial z-position of the CG. Initial tire to ground forces of the HVOSM simulation were compared to the initial conditions observed in the high-speed film. The z-position was adjusted to create initial forces on the tires that were in contact with the ground and to remove forces from the tires that were not in contact with the ground. The next component to match was the vehicle trajectory. This included correcting the lateral and longitudinal velocities to create the proper trajectory angle and also adjusting the initial magnitude of the velocity. Yaw angle was the next component correlated with the crash data. In certain cases, the initial yaw rate had to be adjusted to create proper results. In other cases, the friction coefficient between the tires and the ground was adjusted to create proper simulation results.

Roll and pitch positions were the last components to be validated. In some cases, the angular rates were adjusted. In other cases, the initial z-position was adjusted to change the initial forces on the car in order for the roll and pitch behavior of the simulation to correlate with the crash test.

4.2.1 BMT-2

4.2.1.1 Test Description (820C, 100 km/hr, 15 degrees)

This test involved a 1995 Geo Metro impacting the terminal at 101.6 km/h (92.6 ft/s) and at an angle of 15.5 degrees at the center of the end terminal head. The vehicle was considered to be in contact with the system until the transition between post nos. 2
and 3 failed at 290 ms. Following this, the end terminal head and a section of guardrail stayed with the test vehicle. The position of the CG at loss of contact was 3.07 m (120.9 in.) downstream from the end terminal and 1.52 m (59.8 in.) perpendicular to the centerline of the end terminal. The yaw angle of the vehicle was 21.5 degrees with a yaw rate of -29.5 deg/sec. The longitudinal velocity of the vehicle was 44.9 km/h (40.9 ft/s) with a lateral velocity of 3.2 km/h (2.9 ft/s). Pitch and roll angles were small, measuring -4.3 degrees and 4.5 degrees, respectively. Pitch and roll rates were 9.72 and 4.1 deg/s, respectively. The final CG position was 19.63 m (772.8 in.) downstream and 5.50 m (216.5 in.) behind the end terminal with a vehicle yaw angle of -47 degrees.

The vehicle’s post-impact trajectory is shown in Figure 5 (8).

4.2.1.2 Initial HVOSM Results

The initial objective in the validation of the HVOSM simulations was to match the vehicle trajectory as close as possible. Data available to track the CG of the vehicle includes the overhead high-speed film for 426 ms after loss of contact with the guardrail and the final resting position of the vehicle. Initial simulations showed the vehicle steering straight rather than continuing to yaw around to the rest position. Figure 7 shows a comparison of the position plots from the film and the initial HVOSM simulation. Two problems were believed to contribute to this behavior: 1) the friction coefficient between the tires and the ground was too high and 2) the initial steer properties were too loose on the car allowing the car to be steered too easily. The friction coefficient was changed to 0.5. The initial steer properties were obtained from Holloway’s 1994 curb study; with initial values pertaining to the 1984 Dodge Colt model in the study (9). The steer properties were modified to be the same as the 1986 Ford LTD sedan model.
included in the same curb study. These values allowed for proper behavior of the simulation model. Table 2 compares the different values for each vehicle model. Steer moment of inertia was much lower for the Colt than for the sedan. This caused the steering system to be too loose. The changes in the friction coefficient and the steering properties allowed HVOSM to accurately replicate overall vehicle trajectory (Figure 8).

![CG Position BMT-2](image)

**Figure 7.** BMT-2 CG Position Plot of Initial HVOSM Simulation

**Table 2.** Comparison of Steer Properties

<table>
<thead>
<tr>
<th></th>
<th>1984 Dodge Colt</th>
<th>1986 Ford LTD Sedan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment of Inertia</td>
<td>200.0 lb-sec²-in</td>
<td>4920.0 lb-sec²-in</td>
</tr>
<tr>
<td>Coulomb Friction Torque</td>
<td>240 lb-in</td>
<td>600 lb-in</td>
</tr>
<tr>
<td>Pneumatic Trail</td>
<td>1.1 in.</td>
<td>1.5 in.</td>
</tr>
</tbody>
</table>

Roll and pitch behavior of the simulation was out of sync with the rate gyro data obtained from the crash test. There were low points (valleys) in the roll and pitch angle plots when there should have been high points (peaks). Initial simulations placed all of
the tires off the ground at the time the vehicle lost contact with the terminal. In reality, the front two tires were in contact with the ground. The initial z-position of the CG was then lowered to obtain more realistic tire forces. Initial velocities and vehicle trajectories were also adjusted until the vehicle’s simulated trajectory closely matched test results. One indicator, used to determine if the initial velocity was correct, was the position comparison with the film. The vehicle path during the test was measured from overhead high-speed film for 426 ms after the vehicle lost contact with the terminal. The trajectory of the vehicle had to be adjusted as well in order for the simulation vehicle to pass through the final rest position of the test vehicle. Notice in Figure 8 that the simulation did not stop at the final rest position of the test. This occurrence was attributed to the fact that HVOSM doesn’t account for partial braking due to unknown factors such as fenders rubbing on tires and undercarriage contact with the ground. The simulation vehicle was going slow enough at that point, 39.5 km/h (36 ft/s), that it was concluded that the vehicle trajectory was correct.

Comparison plots of yaw (Figure 9), roll (Figure 10), and pitch (Figure 11) also showed good correlation between the rate gyro data for the crash test and the HVOSM simulation. Therefore, it was concluded that the HVOSM simulations accurately predicted the post-impact trajectory for BMT-2.
Figure 8. BMT-2 CG Position Comparison

Figure 9. BMT-2 Yaw Angle Comparison
Figure 10. BMT-2 Roll Angle Comparison

Figure 11. BMT-2 Pitch Angle Comparison
4.2.2 SP-1

4.2.2.1 Test Description (820C, 100 km/hr, 0 degrees)

This test involved a 1993 Ford Festiva impacting the terminal at 98.6 km/hr (89.9 ft/s), head-on and offset one-fourth the width of the vehicle toward the back of the rail. The impact angle was 1.08 degrees towards the back of the guardrail system. The vehicle was observed to be in contact with the system until the vehicle lost contact with post no. 4 at 656 ms after impact. A yaw rate of 232 deg/s was observed at this time. The yaw angle of the vehicle was 139.4 degrees. The position of the CG was 6.85 m (269.7 in.) downstream from the end terminal and 1.08 m (42.7 in.) perpendicular to the centerline of the end terminal. The longitudinal velocity of the vehicle was -15.9 km/h (-14.5 ft/s) with a lateral velocity of -2.0 km/h (-1.8 ft/s). The pitch angle was approximately 0 degrees, and the roll angle was estimated to be -17.2 degrees at loss of contact. Pitch and roll rates were -34.0 and -11.4 deg/s, respectively. The final CG position was 10.38 m (408.5 in.) downstream and 4.65 m (183.0 in.) behind the end terminal with a total vehicle yaw angle of 288 degrees. The vehicle’s post-impact trajectory is shown in Figure 3 (10).

4.2.2.2 Initial HVOSM Results

The yaw rates were so high during the SP-1 crash test that the rate gyro reached its maximum of 250 deg/s. When this occurs, the rate gyro data becomes unusable because a significant amount of yaw data is incorrect over the period of time that the vehicle yaw rate is greater than 250 deg/s. The roll and pitch data are also affected by this problem. Rate gyro data has to be uncoupled in order to produce proper roll, pitch, and yaw angles. If there is a problem with just one of the data outputs, then the other
two are affected as well. Therefore, all comparisons had to be made using data gathered from the high-speed film. Film analysis showed that the pitch angle remained approximately 0 degrees for the duration of the crash test. After an initial roll angle of 17.8 degrees at loss of contact, the vehicle corrected and the roll angle was never greater than 5 degrees thereafter. Validation of the HVOSM model involved matching the CG position for 844 ms after loss of contact (until the vehicle leaves the field of view on the overhead high-speed film). In order to do this, slight changes had to be made to the initial velocities and trajectories in order for the simulation to match the test through 844 ms after loss of contact. Tire forces were also examined to make sure that the initial CG height was correct. A comparison of the CG position plot is shown in Figure 12. It was noted that the vehicle motion does not pass through the final rest position of the crash test. However, the validation through 844 ms was relatively good as the vehicle was moving very slowly at the end of this period.

For further validation, a plot of the vehicle yaw angle is shown in Figure 13. Very good correlation between the yaw data gathered from film analysis and the HVOSM simulation was observed. It was concluded that the HVOSM simulation program accurately predicted the vehicle trajectory of the SP-1 crash test.
Figure 12. SP-1 CG Position Comparison

Figure 13. SP-1 Yaw Angle Comparison
4.2.3 BEST-8

4.2.3.1 Test Description (820C, 100 km/hr, 0 degrees)

This test involved a 1990 Ford Festiva impacting the terminal at 100.4 km/hr (91.5 ft/s), head-on and offset one-fourth the width of the vehicle toward the back of the rail. The impact angle was 0.6 degrees towards the back of the guardrail system. The vehicle was observed to be in contact with the system until the vehicle lost contact with post no. 3 at 553 ms after impact. The vehicle snagged on post no. 3 creating a very large yaw rate of -400.0 deg/s in the test vehicle. The yaw angle of the vehicle was -121.4 degrees. The position of the center of gravity (CG) was 5.23 m (206.0 in.) downstream from the end terminal and 1.54 m (60.8 in.) perpendicular to the centerline of the end terminal. The longitudinal velocity of the vehicle was -21.3 km/h (-19.4 ft/s) with a lateral velocity of 10.6 km/h (9.7 ft/s). The pitch angle was approximately 0 degrees at loss of contact although a maximum pitch angle of approximately 10 degrees was observed during the test. The roll angle at loss of contact was estimated to be 28.4 degrees. Pitch and roll rates were 0.0 and -47.0 deg/s, respectively. The final CG position was 16.04 m (631.4 in.) downstream and 9.10 m (358.3 in.) behind the end terminal with a total vehicle yaw angle of -336 degrees. The vehicle's post-impact trajectory is shown in Figure 4 (11).

4.2.3.2 Initial HVOSM Results

Rate gyro data was not available for BEST-8. Therefore, all crash data was obtained from high-speed film. Data for CG position and vehicle yaw could be obtained for 889 ms after loss of contact with the guardrail. Maximum pitch and roll angles were estimated from perpendicular and downstream high-speed camera views. Initial
simulations showed that the vehicle trajectory and speed were similar, but the yaw angle of the vehicle was not as high in the simulation as it was in the crash test. Slight adjustments were made to the initial velocity, yaw rate, pitch rate, and z-position of the CG. An adjustment to the friction coefficient between the tire and the ground had to be made because the vehicle spun out on the concrete apron rather than on the soil as in BMT-2 and SP-1. A friction coefficient of 0.65 produced the desired results.

Figure 14 shows the vehicle trajectory comparison for 889 ms after loss of contact. A comparison of the vehicle yaw angle is shown in Figure 15. Pitch and roll angle data was estimated from the high speed film, but the amount of real data was not significant enough to create comparison plots with the HVOSM simulation. Trajectory and yaw angle plots showed good correlation between the simulation and the data gathered from the high-speed film. Therefore, it was concluded that HVOSM accurately predicted the vehicle trajectory of the BEST-8 crash test.
4.2.4 BEST-4

4.2.4.1 Test Description (820C, 100 km/hr, 15 degrees)

This test involved a 1991 Ford Festiva impacting the terminal at 101.7 km/hr (92.7 ft/s) with an impact angle of 13.6 degrees at the center of the impact head. The vehicle was observed to be in contact with the system until the driver’s side lost contact with the buckled piece of guardrail at 458 ms after impact. The result of the interaction with the guardrail system reduced the yaw angle at exit to 4.0 deg and created a yaw rate of –56.0 deg/s. The position of the CG was 6.05 m (238.3 in.) downstream from the end terminal and 2.45 m (96.4 in.) perpendicular to the centerline of the end terminal. The longitudinal velocity of the vehicle was 42.1 km/h (38.4 ft/s) with a lateral
velocity of 18.8 km/h (17.1 ft/s). The pitch and roll angles at loss of contact were approximately -5.0 and 0.0 degrees, respectively. Pitch and roll rates were estimated to be 20.8 and 0.0 deg/s, respectively. The final CG position was 25.58 m (1007 in.) downstream and 11.98 m (471.8 in.) behind the end terminal with a total vehicle yaw angle of -90 degrees. The vehicle's post-impact trajectory is shown in Figure 6 (11).

4.2.4.2 Initial HVOSM Results

Although it was very limited, the only data available for BEST-4 was high-speed film. Insufficient data was available to track roll and pitch behavior of the vehicle. However, adequate overhead high-speed film existed to track the vehicle trajectory and yaw angle for 597 ms after loss of contact. Initial simulation results produced the correct vehicle trajectory, but the initial velocity was too high. Therefore, the initial velocity was reduced in order to obtain improved results. Since the vehicle ran off onto the concrete apron in BEST-4, an initial friction value of 0.65 was used (same as BEST-8). However, initial simulations indicated a drop off in the yaw rate. This was attributed to an excessive friction coefficient. The friction coefficient was reduced to 0.5, which is a reasonable value considering the fact that a significant amount of loose soil traveled with the vehicle and onto the concrete apron.

Figure 16 provides a comparison of the vehicle trajectories for the BEST-4 crash test and the simulation for 597 ms after loss of contact. Figure 17 provides a comparison of the yaw angle of the vehicle. The results shown in both plots indicate that good correlation between the crash test and the HVOSM simulation was observed. Therefore, it was concluded that HVOSM accurately predicted post impact trajectory for BEST-4.
Figure 16. BEST-4 CG Position Comparison

Figure 17. BEST-4 Yaw Angle Comparison
5 SLOPE VARIATIONS

5.1 Initial Simulations

In the preceding section, the HVOSM simulation program was shown to be capable of accurately predicting post-impact trajectories. However, the original tests were conducted on flat, well-consolidated soil. Since roadside slopes are often less compacted, vehicles can be expected to be less stable. As a result, rutting in the soil can increase tripping forces and can accentuate rollover. This increased tripping force can be approximated by increasing the tire side friction ($\tau$). This tripping behavior can sometimes be accentuated even further if the driver steers back. Therefore, the side friction was increased in certain simulations involving roadside slopes to account for this potential and both free wheeling and steer back were used in the estimation for the risk of rollover.

FHWA’s recommended terrain configurations (Figure 1) were explored for all crash tests. Table 3 is a summary of predicted stability values from the HVOSM simulations for each described crash test. Flat terrain and slopes of 4:1 and 3:1 with a friction coefficient of 0.5 were simulated for each described crash test. Additional simulations were performed with higher friction values of 1.25 and 1.5 and steer back. The maximum predicted roll angles for each simulation was summarized in Table 4. It is noted that steer back was not included in the 3-30 tests because the behavior of such tests makes the addition of steer back impractical.
### Table 3. Maximum Roll Angles From HVOSM With Different Slopes

<table>
<thead>
<tr>
<th>Test</th>
<th>Designation</th>
<th>Slope</th>
<th>Time</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
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<tbody>
<tr>
<td>BMT-2</td>
<td>3-32</td>
<td>Flat</td>
<td>0.906</td>
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<tr>
<td></td>
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<td>1.184</td>
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<td>-3</td>
<td>8</td>
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<tr>
<td></td>
<td></td>
<td>1:3</td>
<td>1.120</td>
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<td>-5</td>
<td>6</td>
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<tr>
<td>BEST-8</td>
<td>3-30</td>
<td>Flat</td>
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<td>-5</td>
<td>-253</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1:4</td>
<td>0.369</td>
<td>-26</td>
<td>6</td>
<td>-236</td>
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<tr>
<td></td>
<td></td>
<td>1:3</td>
<td>0.377</td>
<td>-31</td>
<td>7</td>
<td>-237</td>
</tr>
<tr>
<td>SP-1</td>
<td>3-30</td>
<td>Flat</td>
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<td>5</td>
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<td>-16</td>
<td>-4</td>
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<tr>
<td></td>
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<td>0.490</td>
<td>28</td>
<td>4</td>
<td>-18</td>
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</tbody>
</table>

*Pitch and yaw angles are from time of maximum roll

### Table 4. Summary of Maximum Roll Angles for Various HVOSM Simulations

<table>
<thead>
<tr>
<th>Test</th>
<th>Designation</th>
<th>Slope</th>
<th>Friction</th>
<th>Steer Back</th>
<th>Max Roll</th>
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<tr>
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<td>23</td>
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<td>1.50</td>
<td>YES</td>
<td>26</td>
</tr>
<tr>
<td>BEST-8</td>
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6 SUMMARY AND CONCLUSIONS

The stability of mini-size vehicles striking energy-absorbing terminals was evaluated using a lumped-parameter computer simulation model. Vehicle velocities at loss of contact with the terminals were identified from full-scale crash test results. These exit velocities were used as starting conditions to predict vehicle stability for various terrain conditions behind the terminal. The HVOSM program was first calibrated to predict the post-impact trajectory of the test vehicle on flat terrain. After the model was adjusted to adequately replicate the test results, it was used to predict vehicle stability when a roadside slope is placed near the end of the terminal.

One important finding from this study is that energy-absorbing terminals greatly reduce the velocity of small vehicles, even for impacts at angles up to 15 degrees. Energy-absorbing terminals were found to reduce speeds by 75% during head-on impacts and approximately 50% when the terminal is struck at an angle of 15 degrees. These large reductions in vehicle velocity greatly reduce the risk of vehicle rollover as it moves onto roadside slopes and ditches.

The HVOSM modeling effort predicted that energy-absorbing terminals, when installed adjacent to roadside slopes of 4:1, would not be likely to cause rollovers. This finding indicates that FHWA recommended grading around energy-absorbing terminals should be at least adequate, if not a little conservative (12). Further, the simulation effort did not predict rollover for nominal levels of friction, even when 3:1 slopes were placed behind the guardrail. The simulation study only predicted rollover when the tire ground friction was increased to artificially high levels to model wheel rutting in soft soil.
Even under that circumstance, rollover was predicted for only one of the four crash tests included in the study.

This research clearly indicates that energy-absorbing terminals are not likely to produce vehicle rollovers when utilizing FHWA recommended grading guidelines. Further, the study showed that mini-size vehicles could be expected to remain stable when roadside slopes as steep as 3:1 are installed adjacent to most energy-absorbing terminals. In order to further evaluate the safety of using 3:1 slopes behind energy absorbing guardrail terminals, it is recommended that two full-scale crash tests, Tests 3-30 and 3-32, be conducted. This testing would determine whether FHWA grading recommendations are overly conservative. If both tests were successful and the test vehicle came to a safe stop without producing a rollover, then the FHWA recommendations could be relaxed to allow 3:1 slopes behind energy-absorbing guardrail terminals.
7 REFERENCES


Appendix A

Sample Input Deck for BMT-2

VEHICLE DATA

TIRE DATA

GENERATED CURB SURFACE

Initial conditions

PRGAM CONTROL DATA

START TIME T0 = 0.0000 SEC
END TIME T1 = 2.4000 SEC
INTEGRATION INCREMENT DT = 0.0010 SEC
INTEGRATION MODE
MODE = 1
-3= RUNGA-KUTTA
-2= FIXED STEP ADAMS-MOULTON

PRINT INTERVAL
DTPRTN = .0010 SEC

SUSPENSION OPTION
ISUS = 0
-3= INDEPENDENT FRONT SUSPENSION, SOLID REAR AXLE
-2= INDEPENDENT FRONT AND REAR SUSPENSION
-1= SOLID FRONT AND REAR AXLES
0= NO CURB, NO STEER DEGREE OF FREEDOM

CURB/STEER OPTION
INCRB = -1
-3= CURB
-2= STEER DEGREE OF FREEDOM, NO CURB
0= NO BARRIER

CURB INTEGRATION INCR.
DELT = .00000 SEC

BARRIER OPTION
INDB = 0
|1= RIGID BARRIER , FINITE VERT. DIM.
|2= ' ' ', INFINITE ' ' '
|3= DEFORM. ' ' ', FINITE ' ' '
|4= ' ' ', INFINITE ' ' '

BARRIER INTEGRATION INCR.
DELTB = .00000 SEC

SIGN IMPACT OPTION
COLL = 0
0 = NO : 1 = YES

INITIAL CONDITIONS

SPRUNG MASS C.G. POSITION
XCOP = 120.90 INCHES
YCOP = 59.80 INCHES
ZCOP = -27.25 INCHES
PHI0 = 4.53 DEGREES

SPRUNG MASS ORIENTATION
THETA0 = -4.27 DEGREES
PSI0 = 21.45 DEGREES

UNSPRUNG MASS POSITIONS
DEL0 = 1.25 INCHES
DEL10 = 2.88 INCHES
DEL20 = 3.50 INCHES

PHIR0 = -1.89 DEGREES

STEER ANGLE
PSIFD0 = .00 DEG/SEC

VEHICLE DATA
GENERATED CURB SURFACE
initial conditions

TIRE DATA

SPRUNG MASS
XMS = 3.890 LB-SEC**2/IN

FRONT UNSPRUNG MASS
XMUR = .341 LB-SEC**2/IN

REAR UNSPRUNG MASS
XUR = 288.500 LB-SEC**2/IN

X MOMENT OF INERTIA
XIX = 1622.250 LB-SEC**2/IN

Y MOMENT OF INERTIA
XYI = 6731.870 LB-SEC**2/IN

Z MOMENT OF INERTIA
XIZ = 6779.120 LB-SEC**2/IN

XZ PRODUCT OF INERTIA
XIXZ = 1500.000 LB-SEC**2/IN

FRONT AXLE MOMENT OF INERTIA
XIF = .000 NOT USED

REAR AXLE MOMENT OF INERTIA
XIR = 288.500 LB-SEC**2/IN

GRAVITY
G = 386.400 IN/SEC**2

ACCELEROMETER 1 POSITION
X1 = .00 INCHES
### Steering System

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<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
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<td>Z1 - Roll-Steer Coef.</td>
<td>0.00 INCHES</td>
</tr>
<tr>
<td>X2 - Roll-Steer Coef.</td>
<td>0.00 INCHES</td>
</tr>
<tr>
<td>Y2 - Roll-Steer Coef.</td>
<td>0.00 INCHES</td>
</tr>
<tr>
<td>Z2 - Roll-Steer Coef.</td>
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<td>ACCELEROMETER 2 POSITION</td>
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<td>AKDS - Roll-Steer Coef.</td>
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<tr>
<td>AKDS2 - Roll-Steer Coef.</td>
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<tr>
<td>AKDS3 - Roll-Steer Coef.</td>
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### Suspension System

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<td>CPSP - Coulomb Friction Torque</td>
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<td>EPSP - Friction Lag</td>
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<td>AKPS - Angular Stop Rate</td>
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<td>CMPS - Angular Stop Position</td>
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<td>EPS2 - Accelerometer 2 Position</td>
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<td>AKDS2 - Accelerometer 2 Position</td>
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<tr>
<td>AKDS3 - Accelerometer 2 Position</td>
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<td>AKDS4 - Accelerometer 2 Position</td>
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### Front Suspension

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<td>AKR2 - Suspension Rate</td>
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<tr>
<td>AKR3 - Suspension Rate</td>
<td>167.000 LB/IN</td>
</tr>
<tr>
<td>XLMF - Steer Inertia</td>
<td>750 INCHES</td>
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<tr>
<td>XLMR - Steer Inertia</td>
<td>710 INCHES</td>
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<tr>
<td>CMFS - Steer Inertia</td>
<td>3.470 LB-SEC/IN</td>
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<tr>
<td>CMFR - Steer Inertia</td>
<td>3.470 LB-SEC/IN</td>
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<tr>
<td>CMFT - Steer Inertia</td>
<td>3.470 LB-SEC/IN</td>
</tr>
<tr>
<td>CRR - Steer Inertia</td>
<td>2.680 LB-SEC/IN</td>
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</table>

### Front Wheel Camber

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Z1 - Deltaf PHIC</td>
<td>-3.00</td>
</tr>
<tr>
<td>X2 - Deltaf PHIC</td>
<td>-3.00</td>
</tr>
<tr>
<td>Y2 - Deltaf PHIC</td>
<td>-3.00</td>
</tr>
<tr>
<td>Z2 - Deltaf PHIC</td>
<td>-3.00</td>
</tr>
<tr>
<td>DELTAR PHIC</td>
<td>-1.50</td>
</tr>
<tr>
<td>DELTAR PHIC</td>
<td>-1.50</td>
</tr>
<tr>
<td>DELTAR PHIC</td>
<td>-1.50</td>
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<td>DELTAR PHIC</td>
<td>-1.50</td>
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### Vehicle Data

<table>
<thead>
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<tr>
<td>VEHICLE DATA</td>
<td>Initial conditions</td>
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<tr>
<td>GENERATED Curb Surface</td>
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<tr>
<td>TIRE DATA</td>
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<tr>
<td>OCTOBER</td>
<td></td>
</tr>
<tr>
<td>bmt 2 RD2SMN model</td>
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</tr>
<tr>
<td>Node</td>
<td>X'(Inches)</td>
</tr>
<tr>
<td>------</td>
<td>------------</td>
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<tr>
<td>-1.00</td>
<td>-1.00</td>
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<tr>
<td>-.50</td>
<td>-.63</td>
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<tr>
<td>0.00</td>
<td>-.38</td>
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<tr>
<td>.50</td>
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</table>
1       .00       .00       .00       2
2       .00       600.00      .00       2
3       1200.00    .00       .00       2
4       1200.00    600.00    .00       2

ELEMENT SLOPES, ORIENTATIONS AND NO. OF SIDES

ELEM. NO.  SLOPE,PHIS  ORIEN.TN.,PSIS  NO. OF SIDES
           (DEG.)      (DEG.)
                1       .00       .00       4

ELEMENT NODE NUMBERS

ELEMENT NO.  NODES IN COUNTERCLOCKWISE SEQUENCE
                1       1       2       4       3

NODAL CONNECTIVITY

NODE NO.  NODES CONNECTED IN COUNTERCLOCKWISE SEQUENCE
                1       2       3
                2       4       1
                3       1       4
                4       3       2

ELEMENT CONNECTIVITY (0 = OUTSIDE EDGE)

ELEMENT NO.  ELEMENTS CONNECTED TO EACH SIDE IN COUNTERCLOCKWISE SEQUENCE (SIDE 1 STARTS FROM NODE 1)
                1       0       0       0       0

OUTSIDE CURB NODE NUMBERS IN COUNTERCLOCKWISE SEQUENCE
                1       2       4       3

OUTSIDE CURB ELEMENTS IN COUNTERCLOCKWISE ,SEQUENCE STARTING FROM OUTSIDE CURB NODE NO. 1
                1       1       1       1

OUTSIDE BARRIER NODE NUMBERS IN COUNTERCLOCKWISE SEQUENCE