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EMBANKMENT WIDENING AND SLOPES FOR ENERGY ABSORBING END TERMINALS

Submitted by

Tony J. Paulsen, B.S.M.E., E.I.T.
Graduate Research Assistant

Dean L. Sicking, Ph.D., P.E.
Professor and MwRSF Director

James C. Holloway, M.S.C.E., E.I.T.
Research Associate Engineer

MIDWEST ROADSIDE SAFETY FACILITY
University of Nebraska-Lincoln
1901 "Y" Street, Building "C"
Lincoln, Nebraska 68588-0601
(402) 472-6864

Submitted to

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16. 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.

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J.D. Reid, Ph.D., Associate Professor, Mechanical Engineering Department
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R.K. Faller, Ph.D., P.E., Research Assistant Professor
K.A. Polivka, M.S.M.E., Research Associate Engineer
R.W. Bielenberg, M.S.M.E., Research Associate Engineer
Undergraduate and Graduate Assistants

Connecticut Department of Transportation

Dionysia Oliveira, Transportation Engineer 3

Iowa Department of Transportation

David Little, P.E., Assistant District Engineer
Will Stein, P.E., Design Methods Engineer

Kansas Department of Transportation

Ron Seitz, P.E., Assistant Bureau Chief
Rod Lacy, P.E., Road Design Leader

Minnesota Department of Transportation

Jim Klessig, Implementation Liaison
Mohammad Dehdashti, P.E., Design Standards Engineer
Ron Cassellius, Research Program Coordinator (Retired)
Andrew Halverson, P.E., Assistant Design Standards Engineer (Retired)

Missouri Department of Transportation

Dan Smith, P.E., Research and Development Engineer

Montana Department of Transportation

Susan Sillick, Research Bureau Chief

Nebraska Department of Roads

Leona Kolbet, Former Research Coordinator
Mark Traynowicz, P.E., Assistant Engineer, Construction Division
Phil Tenhulzen, P.E., Design Standards Engineer
Amy Starr, Research Engineer

Ohio Department of Transportation

Monique Evans, P.E., Administrator
Dean Focke, Roadway Safety Engineer

South Dakota Department of Transportation

David Huft, Research Engineer
Bernie Clocksin, Lead Project Engineer

Texas Department of Transportation

Mark Bloschock, P.E., Supervising Design Engineer
Mark Marek, P.E., Design Engineer

Wisconsin Department of Transportation

Peter Amakobe, Standards Development Engineer
Beth Cannestra, P.E., Chief in Roadway Development

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John Perry, P.E., Nebraska Division Office

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1 INTRODUCTION

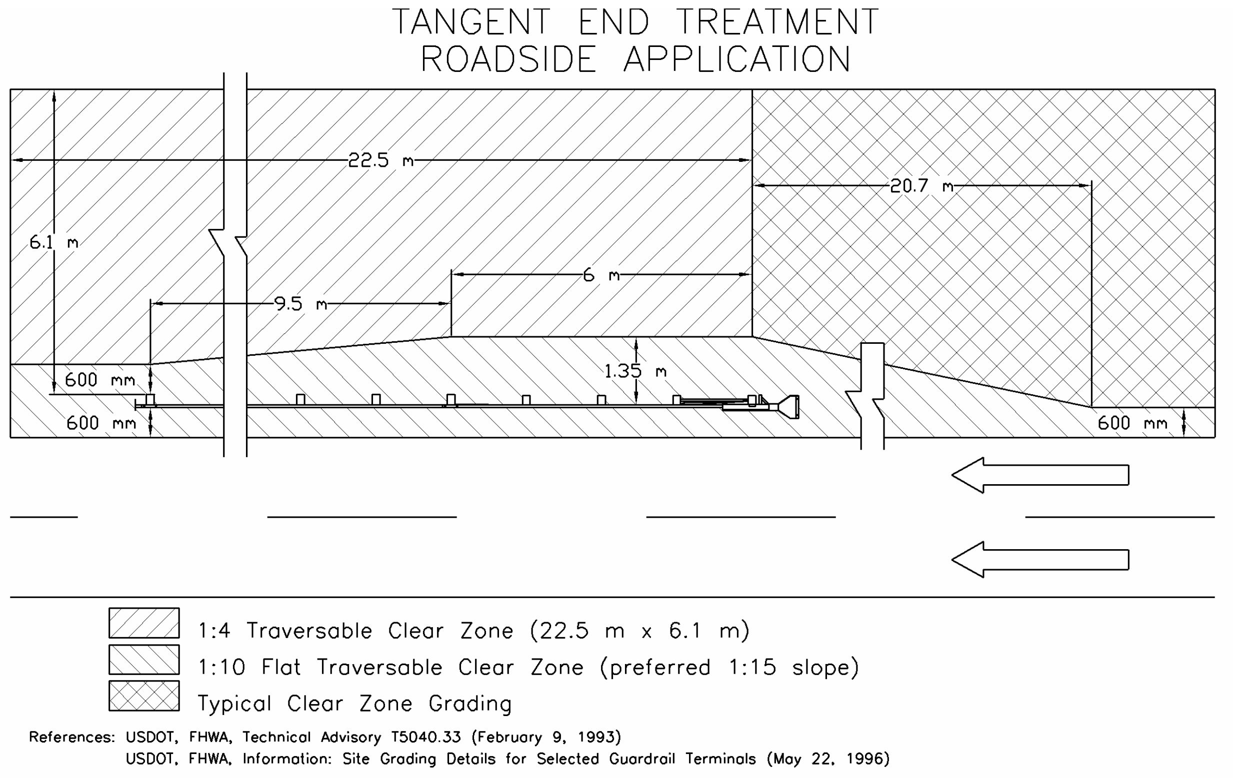
1.1 Problem Statement

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.

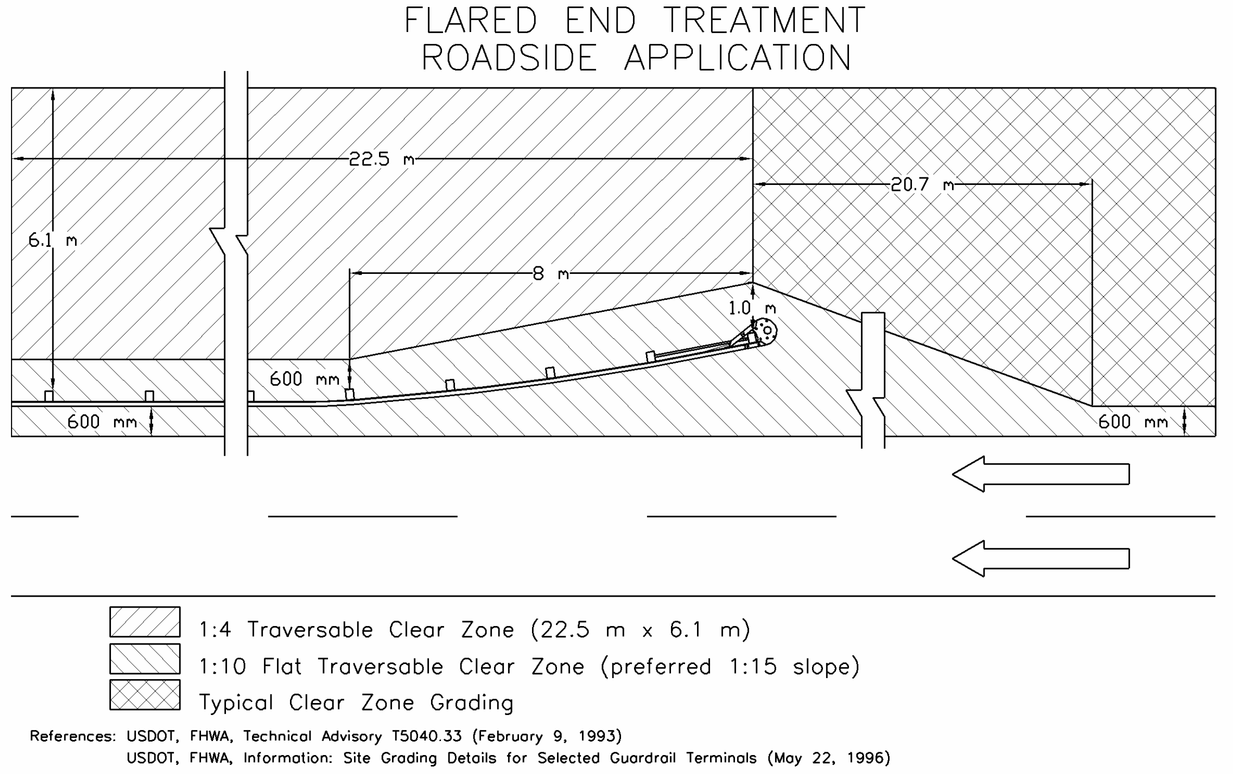
Vehicles that strike guardrail terminals are often allowed to pass through the systems at a relatively high speed. There is a concern that the combination of impact with a guardrail terminal and even moderate roadside embankments can cause vehicles penetrating behind the terminal to rollover. Safety 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.



References: USDOT, FHWA, Technical Advisory T5040.33 (February 9, 1993)
USDOT, FHWA, Information: Site Grading Details for Selected Guardrail Terminals (May 22, 1996)

Figure 1. FHWA Slope Recommendation, Tangent End Treatment



References: USDOT, FHWA, Technical Advisory T5040.33 (February 9, 1993)
USDOT, FHWA, Information: Site Grading Details for Selected Guardrail Terminals (May 22, 1996)

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

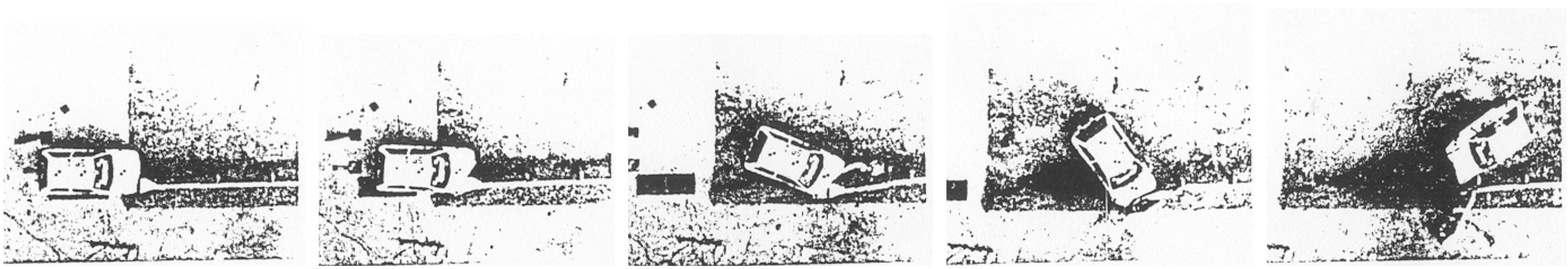
The offset associated with the head-on crash test, 3-30, assures that the small car will experience high yaw rotations as it exits from the terminal. However, this impact condition also causes the vehicle to slow dramatically, and the exit velocities are often very low. Test 3-32 involves a vehicle striking 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 1. Exit Conditions for Selected Crash Tests

Test	Designation	Roll (deg)	Pitch (deg)	Yaw (deg)	Roll Rate (deg/s)	Pitch Rate (deg/s)	Yaw Rate (deg/s)	Long. Velocity (ft/s)	Lat. Velocity (ft/s)
BMT-2	3-32	4.5	-4.3	21.5	4.1	9.72	-29.5	40.9	2.9
BEST-8	3-30	28.4	0.0	-121.4	-47.0	0.0	-400.0	-19.4	9.7
SP-1	3-30	-17.2	0.0	139.4	-11.4	-34.0	231.8	-14.5	-1.8
BEST-4	3-32	0.0	-5.0	4.0	0.0	20.8	-56.0	38.4	17.1



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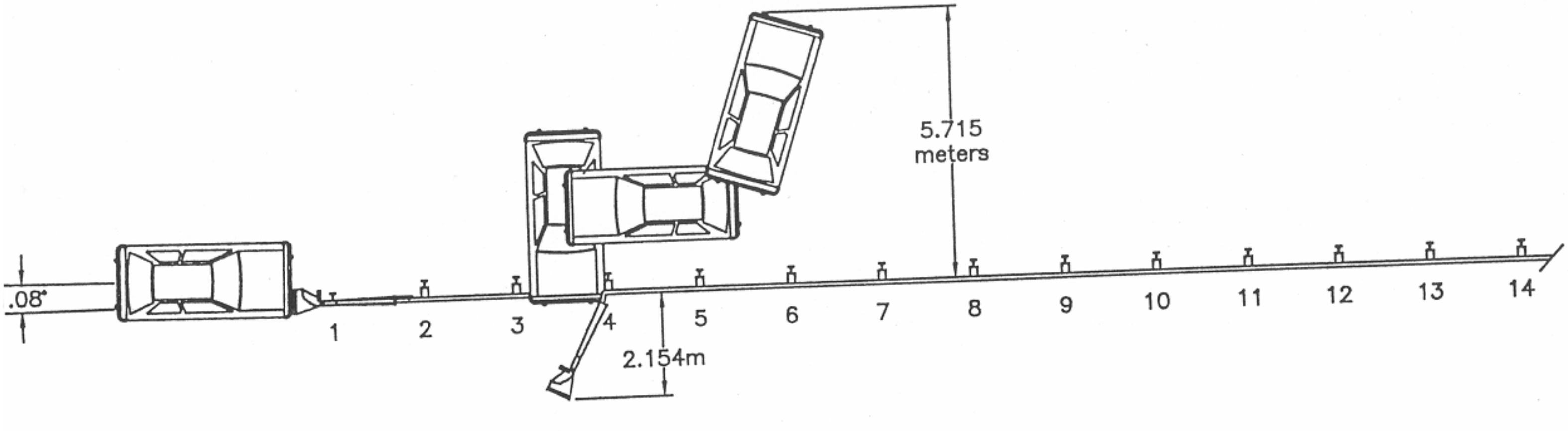
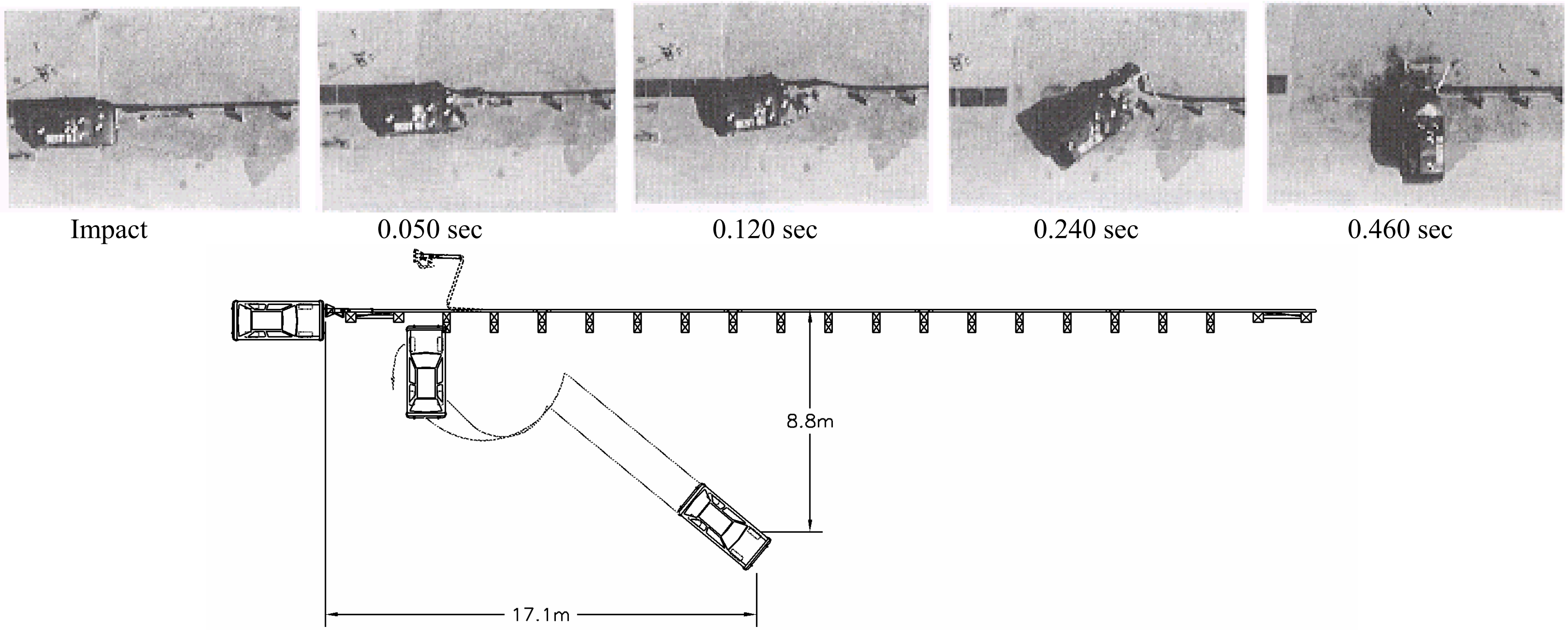


Test Number	SP-1
Date	2/2/98
Installation	Sequential Kinking Terminal
Total Length	41.91 m
Vehicle Model	1993 Ford Festiva
Curb	795 kg
Test Inertial	819 kg
Gross Static	894 kg
Vehicle Speed	
Impact	98.6 km/hr
Exit	16.0 km/hr
Vehicle Angle	
Impact	1.08 degrees
Exit	139.4 degrees
Vehicle Impact Location	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

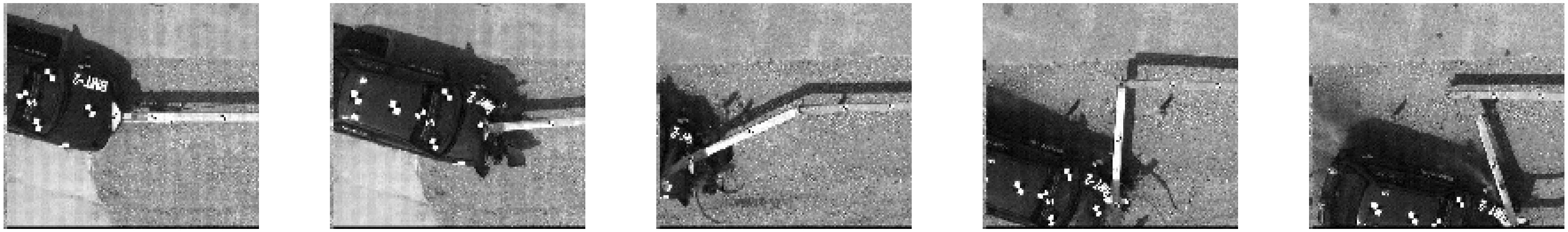
Figure 3. Summary of SP-1



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



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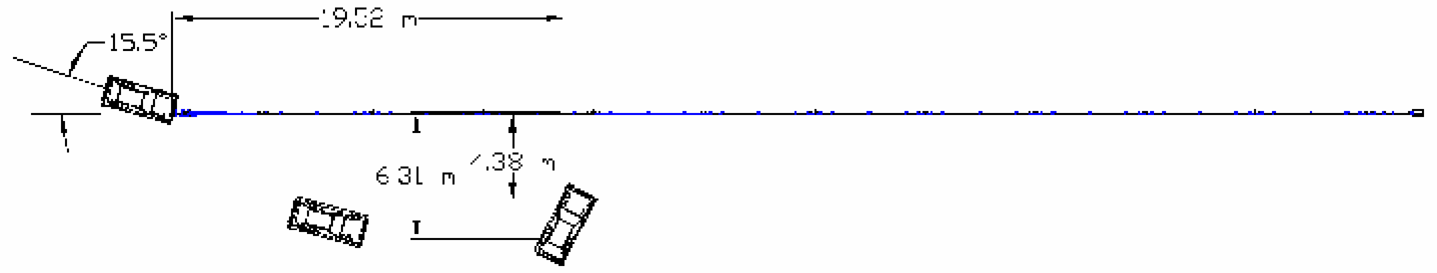
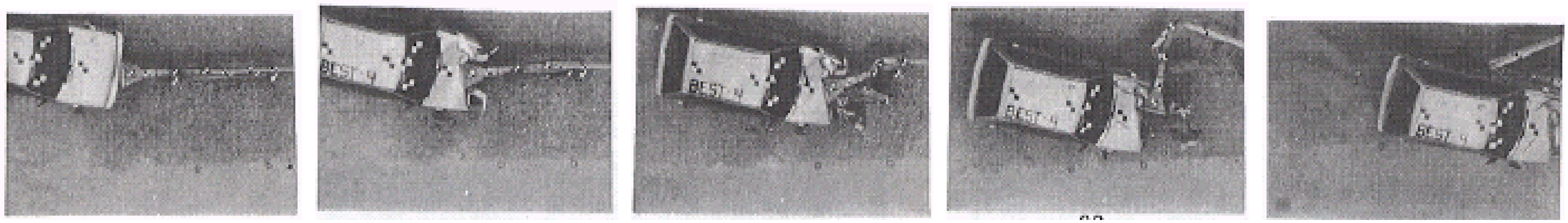


Test Number	BMT-2
Date	5/25/01
Installation	Box-Beam Median Terminal
Total Length	62.03 m
Vehicle Model	1995 Geo Metro
Curb	803 kg
Test Inertial	819 kg
Gross Static	894 kg
Vehicle Speed	
Impact	101.6 km/hr
Exit	45.0 km/hr
Vehicle Angle	
Impact	15.5 degrees
Exit	21.5 degrees

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



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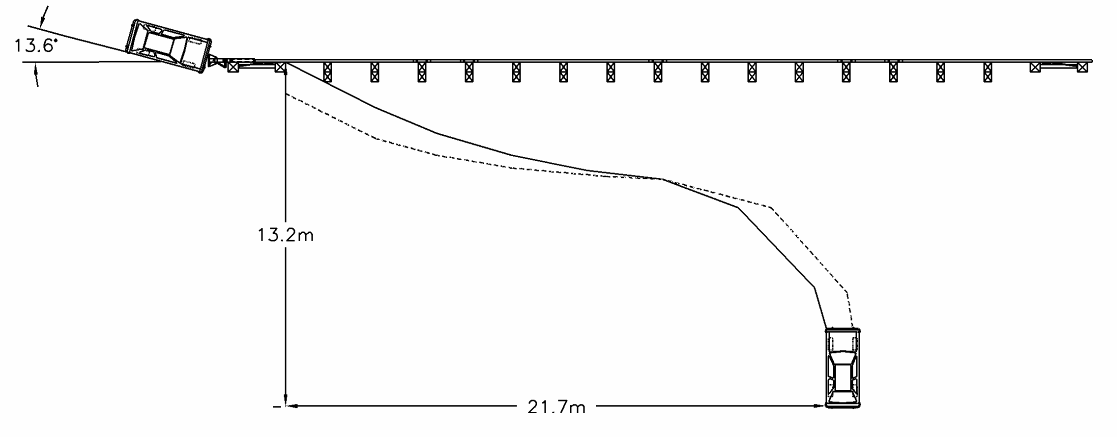

Test Number	BEST-4
Date	8/2/96
Installation	BEST System
Total Length	30.5 m
Vehicle Model	1991 Ford Festiva
Curb	819 kg
Test Inertial	820 kg
Gross Static	896 kg
Vehicle Speed	
Impact	101.7 km/hr
Exit	46.1 km/hr
Vehicle Angle	
Impact	13.6 degrees
Exit	4.0 degrees

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).

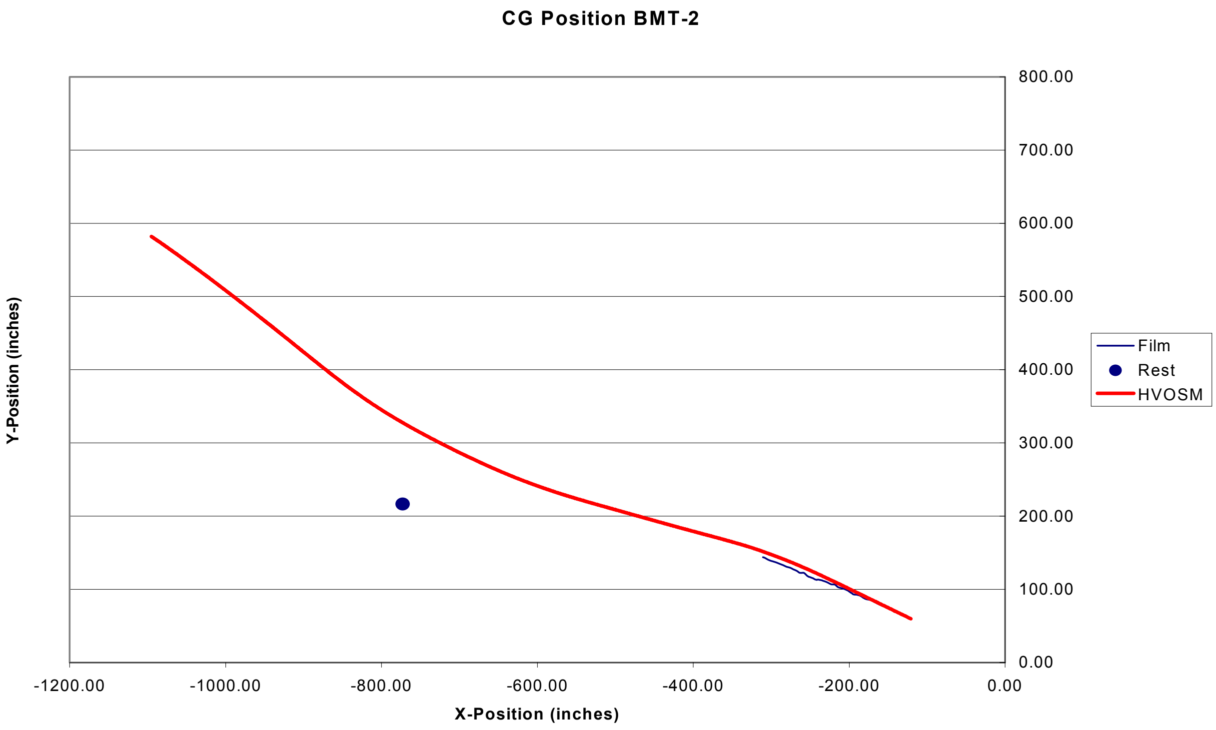

Figure 7. BMT-2 CG Position Plot of Initial HVOSM Simulation

Table 2. Comparison of Steer Properties

	1984 Dodge Colt	**1986 Ford LTD Sedan**
Moment of Inertia	200.0 lb-sec^2-in	4920.0 lb-sec^2-in
Coulomb Friction Torque	240 lb-in	600 lb-in
Pneumatic Trail	1.1 in.	1.5 in.

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.

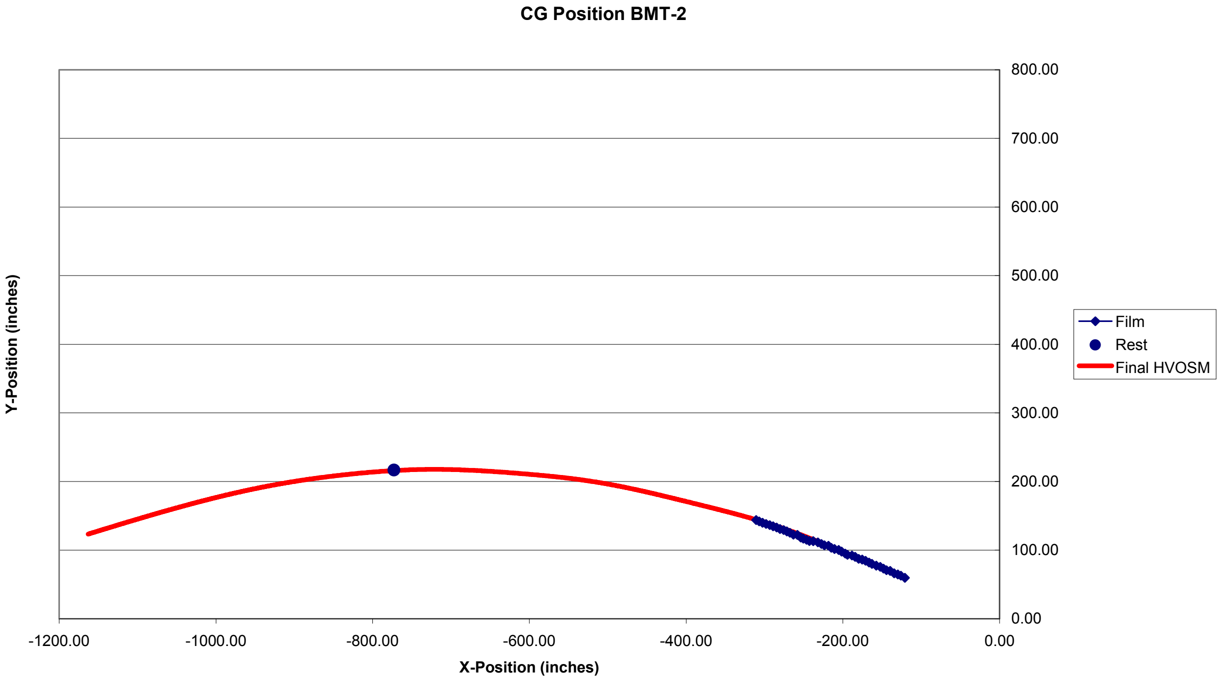

Figure 8. BMT-2 CG Position Comparison

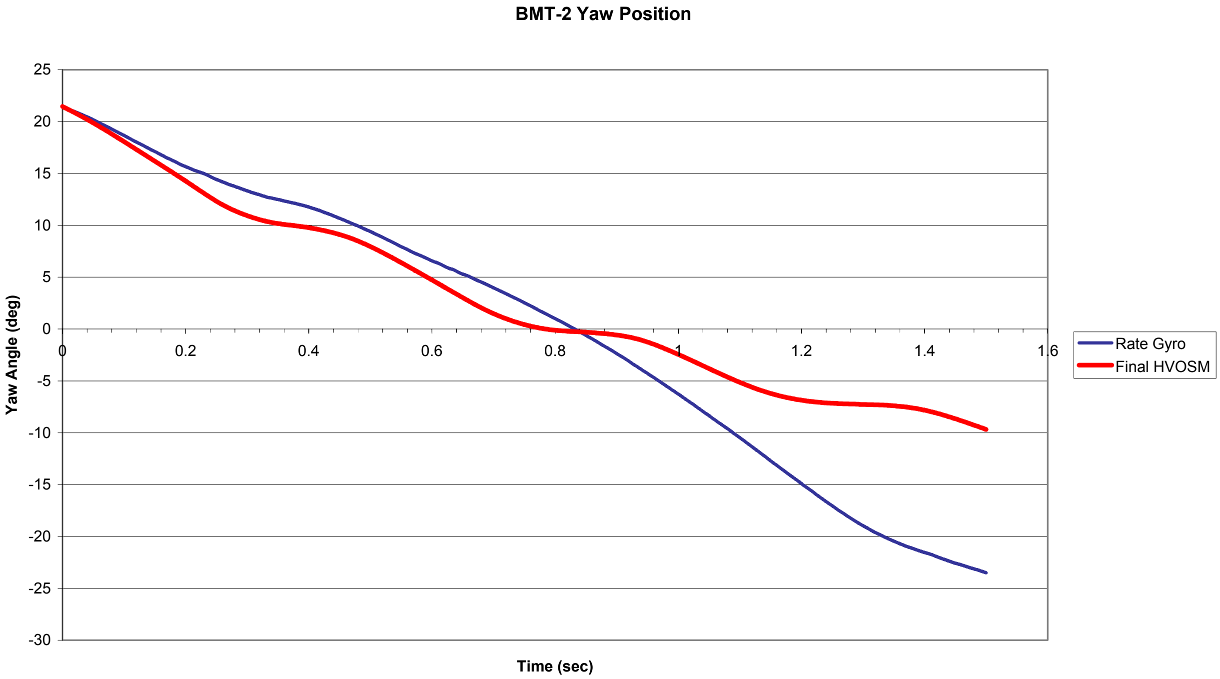

Figure 9. BMT-2 Yaw Angle Comparison

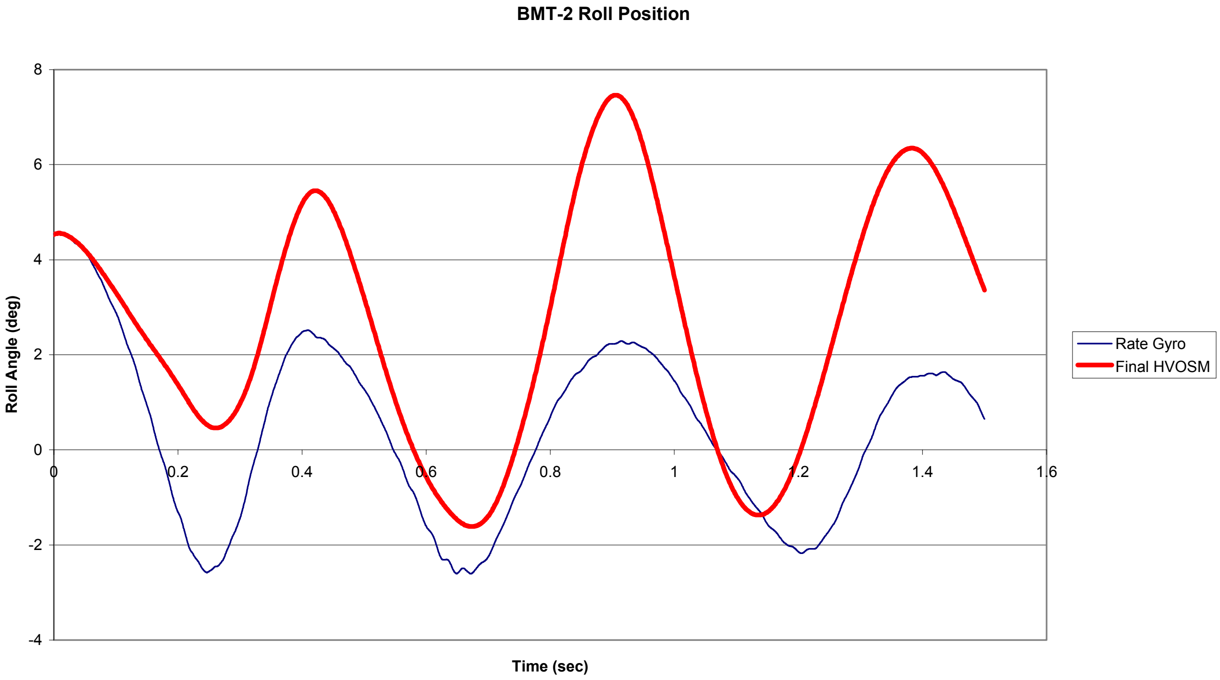

Figure 10. BMT-2 Roll Angle Comparison

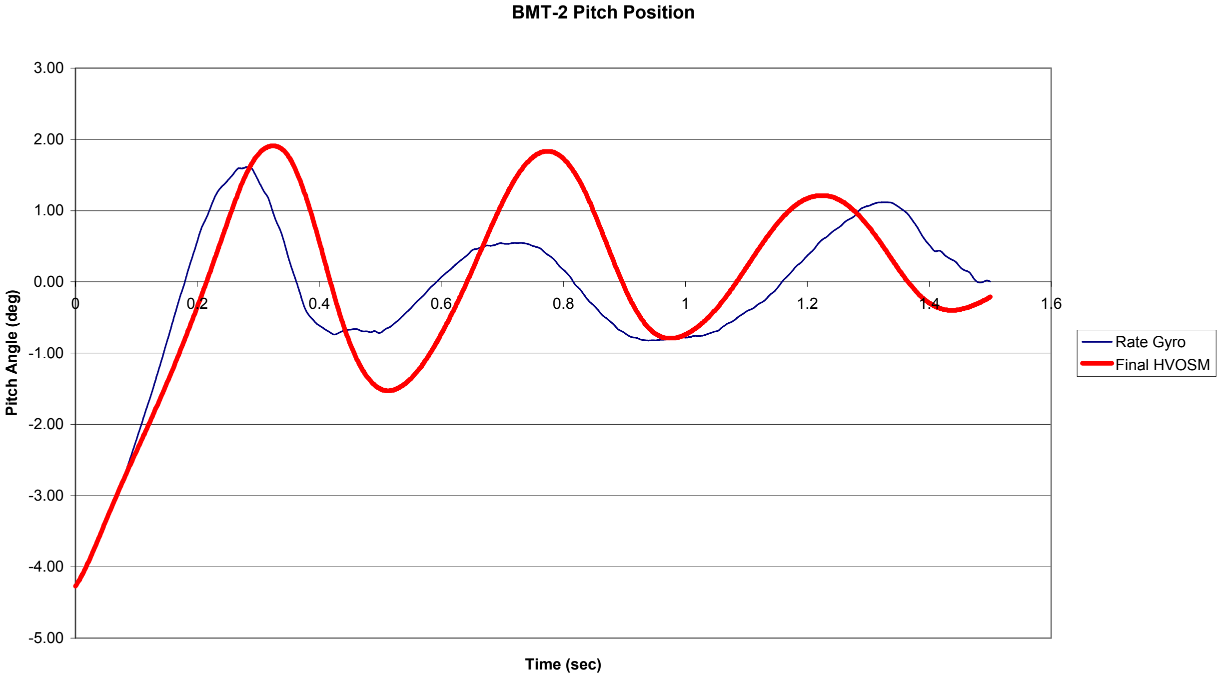

Figure 11. BMT-2 Pitch Angle Comparison

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.

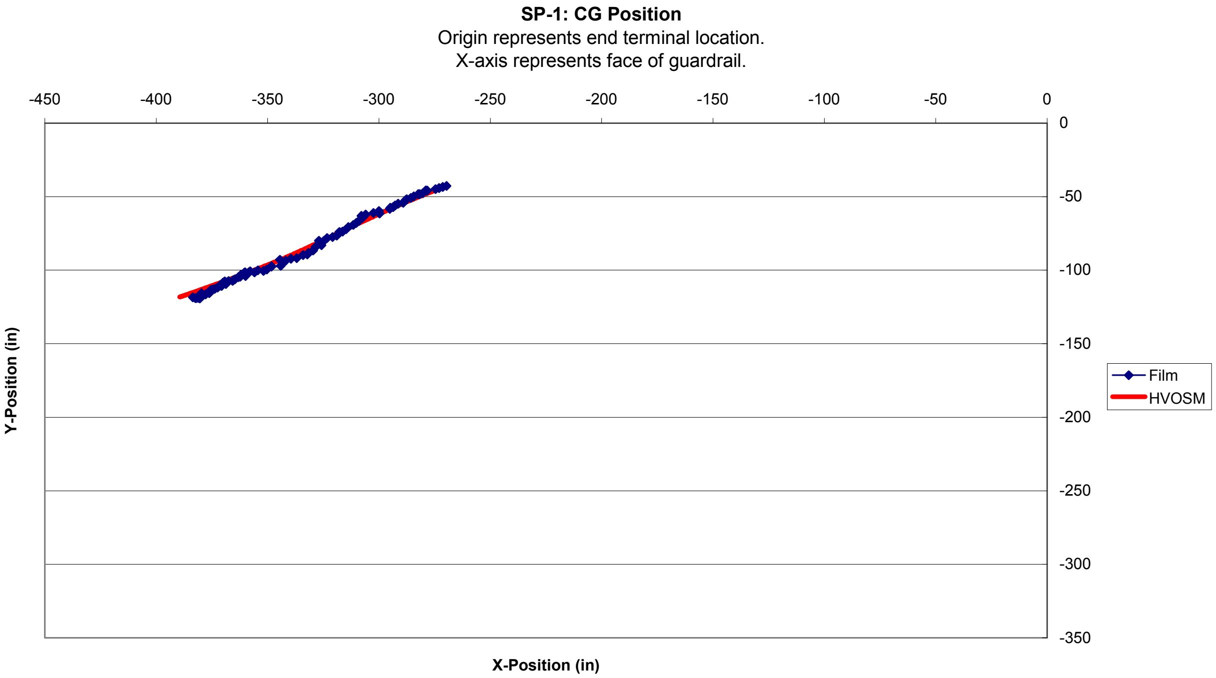

Figure 12. SP-1 CG Position Comparison

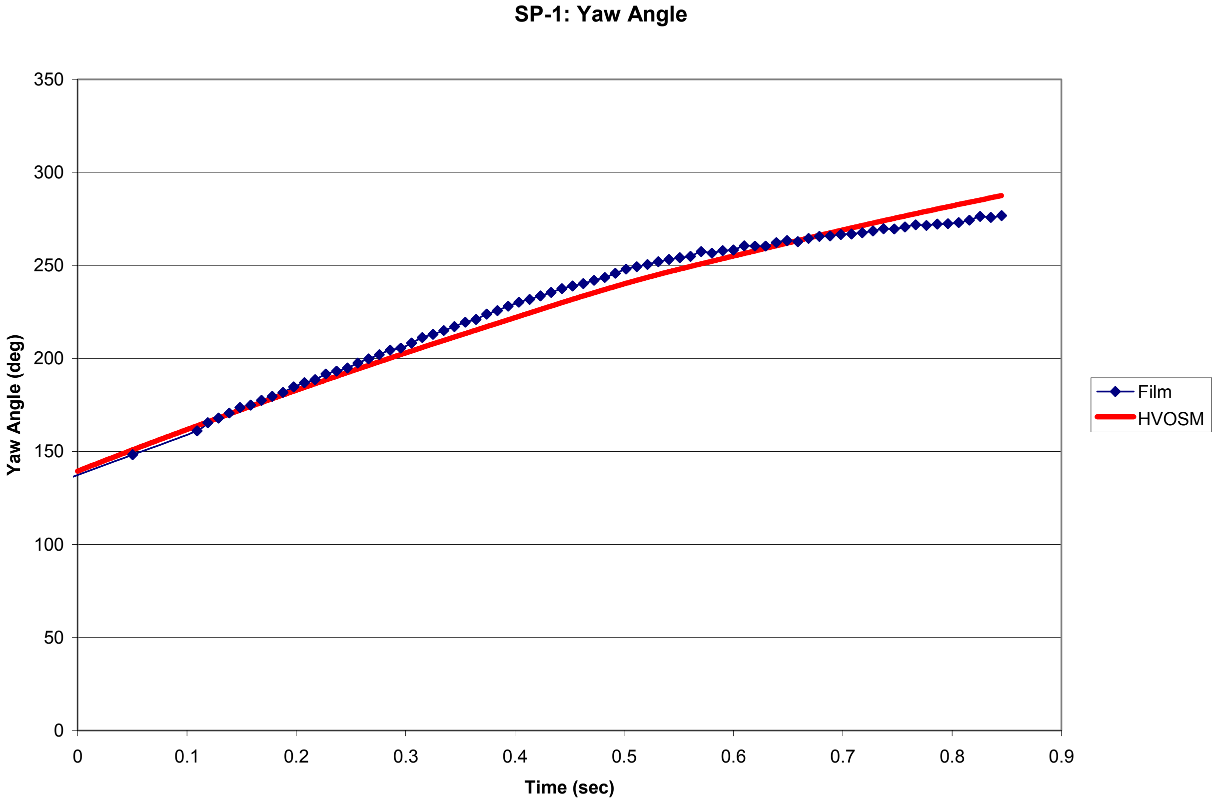

Figure 13. SP-1 Yaw Angle Comparison

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.

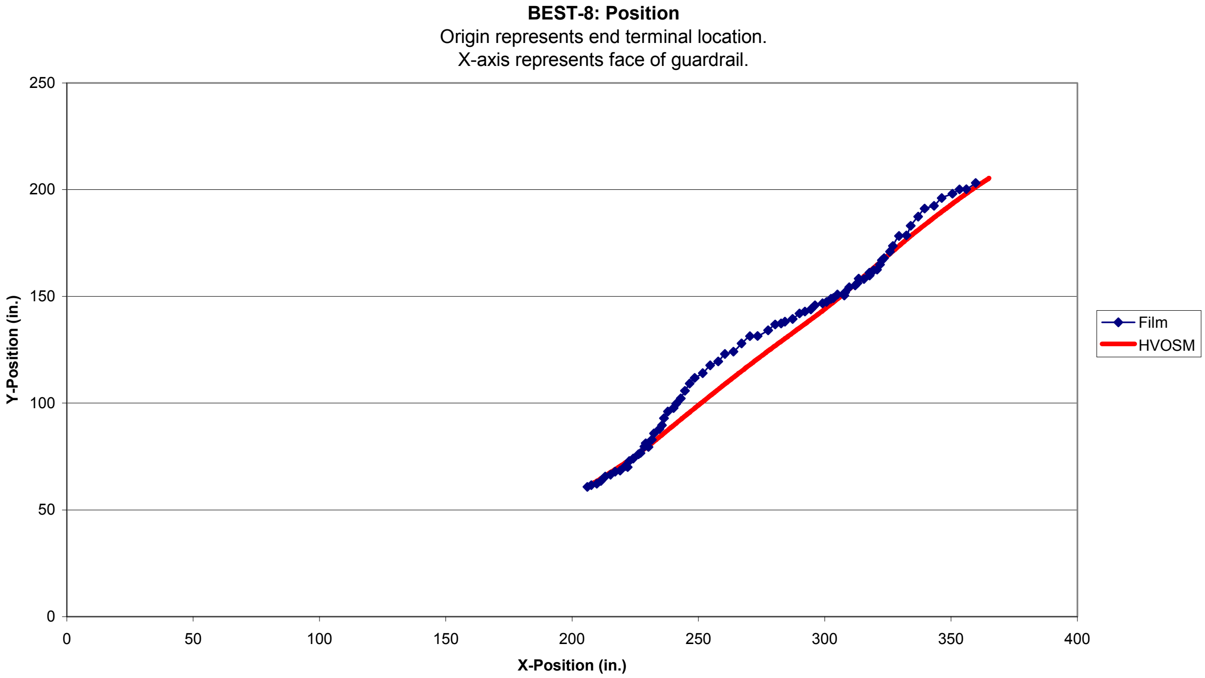

Figure 14. BEST-8 CG Position Comparison

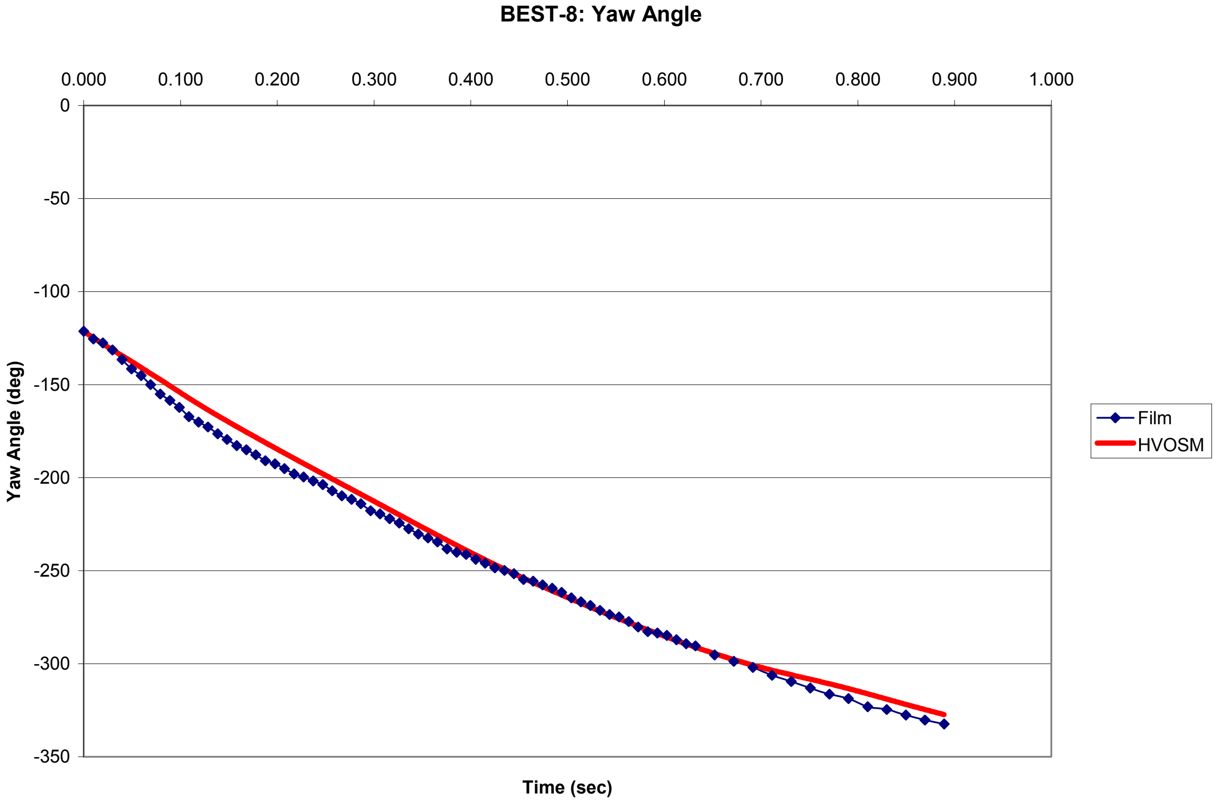

Figure 15. BEST-8 Yaw Angle Comparison

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.

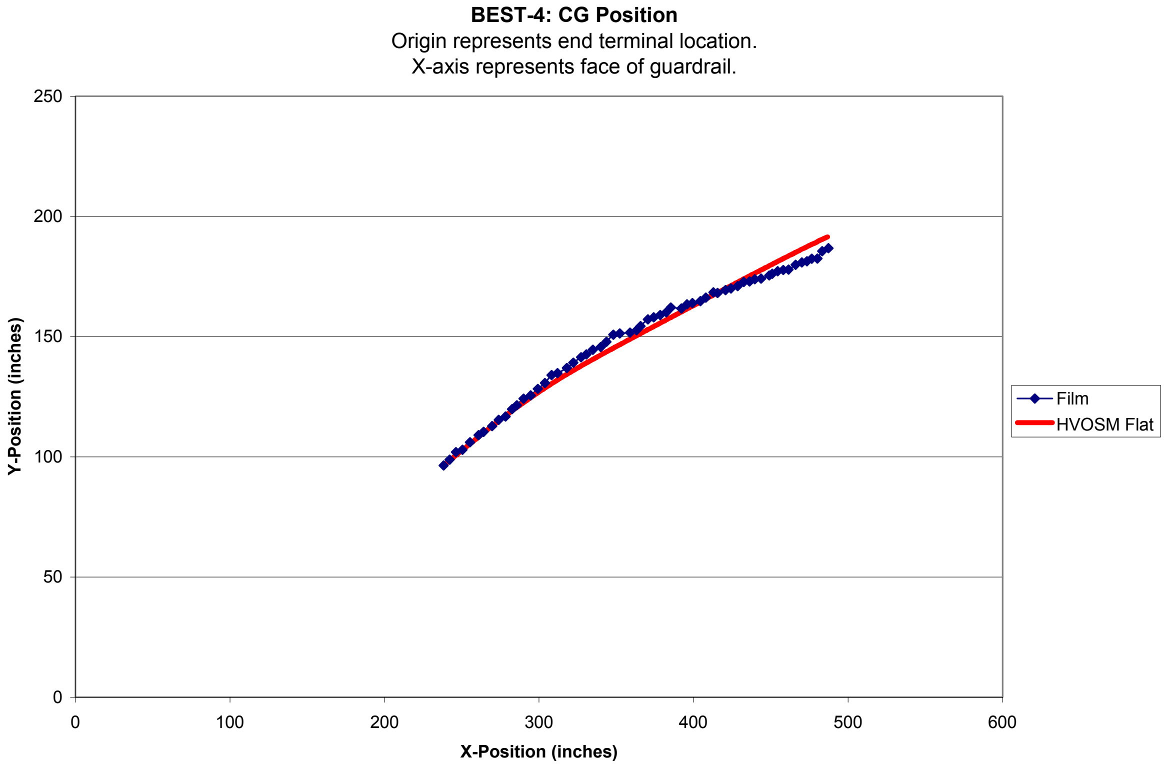

Figure 16. BEST-4 CG Position Comparison

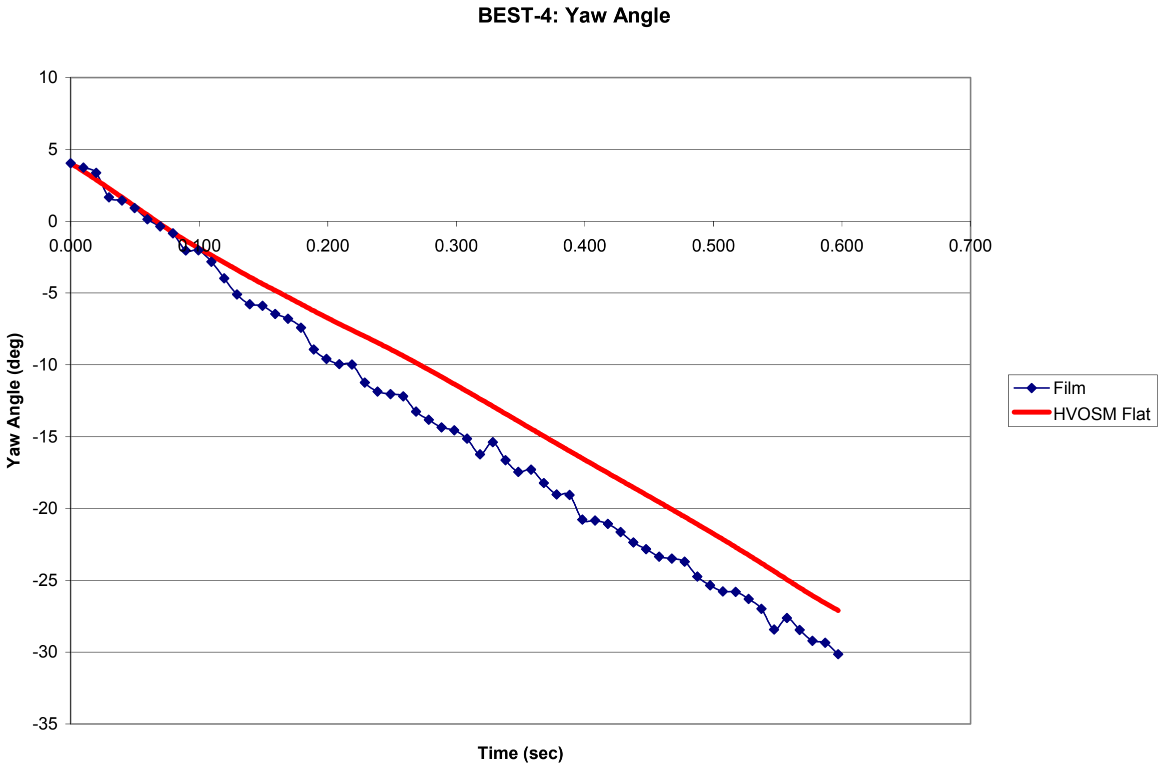

Figure 17. BEST-4 Yaw Angle Comparison

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 (7). 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

Test	Designation	Slope	Time	Roll	Pitch	Yaw
BMT-2	3-32	Flat	0.906	7	0	-1
		1:4	1.184	23	-3	8
		1:3	1.120	28	-5	6
BEST-8	3-30	Flat	0.450	-25	-5	-253
		1:4	0.369	-26	6	-236
		1:3	0.377	-31	7	-237
SP-1	3-30	Flat	0.511	5	-2	242
		1:4	1.5	-16	-4	340
		1:3	1.973	-22	0	367
BEST-4	3-32	Flat	1.205	8	0	-56
		1:4	0.396	23	3	-14
		1:3	0.490	28	4	-18

*Pitch and yaw angles are from time of maximum roll

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

Test	Designation	Slope	Friction	Steer Back	Max Roll
BMT-2	3-32	1:4	1.25	NO	23
		1:4	1.50	NO	23
		1:4	1.25	YES	24
		1:4	1.50	YES	24
		1:3	1.25	NO	32
		1:3	1.50	NO	33
		1:3	1.25	YES	25
		1:3	1.50	YES	26
BEST-8	3-30	1:4	1.25	NO	27
		1:4	1.50	NO	28
		1:3	1.25	NO	-90
		1:3	1.50	NO	-90
SP-1	3-30	1:4	1.25	NO	-22
		1:4	1.50	NO	-22
		1:3	1.25	NO	-22
		1:3	1.50	NO	-22
BEST-4	3-32	1:4	1.25	NO	27
		1:4	1.50	NO	28
		1:4	1.25	YES	27
		1:4	1.50	YES	27
		1:3	1.25	NO	32
		1:3	1.50	NO	41
		1:3	1.25	YES	32
		1:3	1.50	YES	33

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.

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12. *Site Grading Details for Selected Guardrail Terminals,* Federal Highway Administration, U.S. Department of Transportation, May 22, 1996

APPENDIX A

Sample Input Deck for BMT-2

```
1
0bmt 2 RD2SMN model                                                         0 100
00.0     2.4     .001    .001    70.0    0.0     0.0                        0 101
00.0     -1.     0.      0.0     0.0     0.0                     0.0        0 102
01.0                                                                        0 103
01.0     1.0     1.0     1.0     1.0     1.0     1.0                        0 104
0VEHICLE DATA                                                               0 200
03.890   0.350   0.341   1622.25 6731.87 6779.12 1500.   288.50             0 201
035.76   53.74   53.0    53.0    0.0     36.0                               0 202
00.0     0.0     0.0     0.0     0.0     0.0     13.38   12.86              0 203
0152.0   278.9   238.08  278.9   10.0    0.75    -2.05   2.85               0 204
0167.0   70.0    203.57  70.0    10.0    0.71    -2.25   2.55               0 205
03.47    12.0    3.47    20.0    3.47    31.0    0.1     1.8                0 206
03.47    5.0     3.47    12.5    3.47    30.0    3.47    1.6                0 207
02.68    5.0     2.68    12.25   2.68    32.5    0.1     1.8                0 208
02.68    12.5    2.68    20.0    2.68    30.0    2.68    1.6                0 209
00.      0.                                                                 0 210
04920.   600.    0.40    5000.   0.075   1.50                               0 211
0-3.00   3.00    0.50    0.0     0.0                                        0 212
0-1.5    -1.375  -1.25   -1.125  -1.0    -0.625  -0.375  0.0     0.625      1 212
01.00    1.45    1.75    2.125                                              2 212
0TIRE DATA                                                                  0 300
01.0     1.0     1.0     1.0                                                0 301
0800.    3.0     3.0     1256.8  13.24   1829.1  0.533   -31246. 1.0        1 301
010.875  0.5     0.0     2000.   0.05    0.8     4.88                       2 301
0GENERATED CURB SURFACE                                                     0 500
04.      0.      4.      1.      1.0                                        0 507
00.      0.      0.      0.      600.    0.      1200.   0.      0.         1 507
01200.   600.    0.                                                         2 507
04.                                                                         1 508
01.  0.  2.  0.  4.  0.  3.  0.                                             1 509
01.  1.  2.  1.  4.  1.  3.  1.                                             1 510
0initial conditions                                                         0 600
04.53    -4.27   21.45   4.12    9.72    -29.50  -10.0   0.0                0 601
0120.9   59.8    -27.25  490.93  34.33   -70.                               0 602
0-1.25   2.875   3.5     -1.89   11.     11.     -6.     -38.92             0 603
0                                                                           09999
1         bmt 2 RD2SMN model                                                                                    OCTOBER
     VEHICLE DATA                            TIRE DATA
     GENERATED CURB SURFACE                  initial conditions

0                        P R O G R A M   C O N T R O L   D A T A
          START TIME                    T0     =     .0000  SEC
          END TIME                      T1     =    2.4000  SEC
          INTEGRATION INCREMENT         DTCOMP =     .0010  SEC
```

```
                                                              (0=VARIABLE STEP ADAMS-MOULTON
          INTEGRATION MODE              MODE   =    1        -)1= RUNGA-KUTTA
                                                              (2= FIXED STEP ADAMS-MOULTON
          PRINT INTERVAL                DTPRNT =     .0010  SEC
0                                                             (0= INDEPENDENT FRONT SUSPENSION, SOLID REAR AXLE
          SUSPENSION OPTION             ISUS   =    0        -)1= INDEPENDENT FRONT AND REAR SUSPENSION
                                                              (2= SOLID FRONT AND REAR AXLES
                                                              (0= NO CURB, NO STEER DEGREE OF FREEDOM
          CURB/STEER OPTION             INDCRB =   -1        -)1= CURB
                                                              (-1=STEER DEGREE OF FREEDOM, NO CURB
          CURB INTEGRATION INCR.        DELTC  =    .00000  SEC
0                                                             (0= NO BARRIER
                                                              |1= RIGID BARRIER , FINITE VERT. DIM.
          BARRIER OPTION                INDB   =    0        -)2=  ''     ''   ,INFINITE  ''    ''
                                                              |3= DEFORM. ''    , FINITE  ''    ''
                                                              (4=   ''    ''   ,INFINITE  ''    ''
          BARRIER INTEGRATION INCR.     DELTB  =    .00000  SEC
0
          SIGN IMPACT OPTION            COLL   =   0.          ( 0 = NO : 1 = YES

0

                                                    I N I T I A L   C O N D I T I O N S

                                        XC0P   =  120.90   INCHES                                          U0   =  490.93   IN/SEC
          SPRUNG MASS C.G. POSITION     YC0P   =   59.80   INCHES         SPRUNG MASS LINEAR VELOCITY      V0   =   34.33   IN/SEC
                                        ZCOP   =  -27.25   INCHES                                          W0   =  -70.00   IN/SEC
0                                       PHI0   =    4.53   DEGREES                                         P0   =    4.12   DEG/SEC
          SPRUNG MASS ORIENTATION       THETA0 =   -4.27   DEGREES        SPRUNG MASS ANGULAR VELOCITY     Q0   =    9.72   DEG/SEC
                                        PSI0   =   21.45   DEGREES                                         R0   =  -29.50   DEG/SEC
0                                       DEL10  =   -1.25   INCHES                                        DEL10D =   11.00   IN/SEC
          UNSPRUNG MASS POSITIONS       DEL20  =    2.88   INCHES         UNSPRUNG MASS VELOCITIES       DEL20D =   11.00   IN/SEC
0                                       DEL30  =    3.50   INCHES                                        DEL30D =   -6.00   IN/SEC
                                        PHIR0  =   -1.89   DEGREES                                       PHIR0D =  -38.92   DEG/SEC
          STEER ANGLE                   PSIFI0 =  -10.00   DEGREES        STEER VELOCITY                 PSIFD0 =     .00   DEG/SEC
1         bmt 2 RD2SMN model                                                                                     OCTOBER
     VEHICLE DATA                            TIRE DATA
     GENERATED CURB SURFACE                  initial conditions

0         SPRUNG MASS                   XMS   =     3.890 LB-SEC**2/IN     FRONT WHEEL X LOCATION    A    =    35.760 INCHES
          FRONT UNSPRUNG MASS           XMUF  =      .350 LB-SEC**2/IN     REAR WHEEL X LOCATION     B    =    53.740 INCHES
          REAR UNSPRUNG MASS            XMUR  =      .341 LB-SEC**2/IN     FRONT WHEEL Z LOCATION    ZF   =    13.380 INCHES
0         X MOMENT OF INERTIA           XIX   =  1622.250 LB-SEC**2-IN     REAR WHEEL Z LOCATION     ZR   =    12.860 INCHES
          Y MOMENT OF INERTIA           XIY   =  6731.870 LB-SEC**2-IN     FRONT WHEEL TRACK         TF   =    53.000 INCHES
          Z MOMENT OF INERTIA           XIZ   =  6779.120 LB-SEC**2-IN     REAR WHEEL TRACK          TR   =    53.000 INCHES
          XZ PRODUCT OF INERTIA         XIXZ  =  1500.000 LB-SEC**2-IN     FRONT ROLL AXIS           RHOF =      .000 NOT USED
0         FRONT AXLE MOMENT OF INERTIA  XIF   =      .000 NOT USED         REAR ROLL AXIS            RHO  =      .000 INCHES
          REAR AXLE MOMENT OF INERTIA   XIR   =   288.500 LB-SEC**2-IN     FRONT SPRING TRACK        TSF  =      .000 NOT USED
          GRAVITY                       G     =   386.400 IN/SEC**2        REAR SPRING TRACK         TS   =    36.000 INCHES
0                                       X1    =       .00 INCHES           FRONT AUX ROLL STIFFNESS  RF   =       .00 LB-IN/RAD
          ACCELEROMETER 1 POSITION      Y1    =       .00 INCHES           REAR AUX ROLL STIFFNESS   RR   =       .00 LB-IN/RAD
```

```
                              Z1    =       .00 INCHES           REAR ROLL-STEER COEF.     AKRS =     .0000 RAD/RAD
                              X2    =       .00 INCHES                                     AKDS =      .000 NOT USED
        ACCELEROMETER 2 POSITION      Y2    =       .00 INCHES           REAR DEFL-STEER COEFS.    AKDS1=      .000 NOT USED
                              Z2    =       .00 INCHES                                     AKDS2=      .000 NOT USED
                                                                                           AKDS3=      .000 NOT USED
0             S T E E R I N G   S Y S T E M
        MOMENT OF INERTIA       XIPS  =  4920.000 LB-SEC**2-IN
        COULOMB FRICTION TORQUE CPSP  =   600.000 LB-IN
        FRICTION LAG            EPSP  =      .075 RAD/SEC
        ANGULAR STOP RATE       AKPS  =  5000.000 LB-IN/RAD
        ANGULAR STOP POSITION   OMGPS =      .400 RADIANS
        PNEUMATIC TRAIL         XPS   =     1.500 INCHES
0                                 FRONT SUSPENSION                    REAR SUSPENSION

        SUSPENSION RATE                  AKF    =   152.000 LB/IN            AKR    =   167.000 LB/IN
        COMPRESSION STOP COEFS.          AKFC   =   278.900 LB/IN            AKRC   =    70.000 LB/IN
                                         AKFCP  =   238.080 LB/IN**3         AKRCP  =   203.570 LB/IN**3
0       EXTENSION STOP COEFS.            AKFE   =   278.900 LB/IN            AKRE   =    70.000 LB/IN
                                         AKFEP  =    10.000 LB/IN**3         AKREP  =    10.000 LB/IN**3
        COMPRESSION STOP LOCATION        OMEGFC =    -2.050 INCHES           OMEGRC =    -2.250 INCHES
        EXTENSION STOP LOCATION          OMEGFE =     2.850 INCHES           OMEGRE =     2.550 INCHES
0       STOP ENERGY DISSIPATION FACTOR   XLAMF  =      .750                  XLAMR  =      .710
        COMP. VISC. DAMP. COEF. NO. 1    CFJ(1) =     3.470 LB-SEC/IN        CRJ(1) =     2.680 LB-SEC/IN
        VEL. AT THE CHANGE OF COEF. 1    DLFJ(1)=    12.000 IN/SEC           DLRJ(1)=     5.000 IN/SEC
        COMP. VISC. DAMP. COEF. NO. 2    CFJ(2) =     3.470 LB-SEC/IN        CRJ(2) =     2.680 LB-SEC/IN
        VEL. AT THE CHANGE OF COEF. 2    DLFJ(2)=    20.000 IN/SEC           DLRJ(2)=    12.250 IN/SEC
        COMP. VISC. DAMP. COEF. NO. 3    CFJ(3) =     3.470 LB-SEC/IN        CRJ(3) =     2.680 LB-SEC/IN
0        EXTN. VISC. DAMP. COEF. NO. 1    CFR(1) =     3.470 LB-SEC/IN        CRR(1) =     2.680 LB-SEC/IN
        VEL. AT THE CHANGE OF COEF. 1    DLFR(1)=     5.000 IN/SEC           DLRR(1)=    12.500 IN/SEC
        EXTN. VISC. DAMP. COEF. NO. 2    CFR(2) =     3.470 LB-SEC/IN        CRR(2) =     2.680 LB-SEC/IN
        VEL. AT THE CHANGE OF COEF. 2    DLFR(2)=    12.500 IN/SEC           DLRR(2)=    20.000 IN/SEC
        EXTN. VISC. DAMP. COEF. NO. 3    CFR(3) =     3.470 LB-SEC/IN        CRR(3) =     2.680 LB-SEC/IN
        VEL. AT THE CHANGE OF COEF. 3    DLFR(3)=    30.000 IN/SEC           DLRR(3)=    30.000 IN/SEC
0        EXTN. VISC. DAMP. COEF. NO. 4    CFR(4) =     3.470 LB-SEC/IN        CRR(4) =     2.680 LB-SEC/IN
        COULOMB FRICTION                 CFP    =    31.000 LB               CRP    =    32.500 LB
        FRICTION LAG                     EPSF   =      .100 IN/SEC           EPSR   =      .100 IN/SEC
        POWER IN POWER LAW DAMPING       POWF   =     1.600                  POWR   =     1.600
1       bmt 2 RD2SMN model                                                                                       OCTOBER
   VEHICLE DATA                            TIRE DATA
   GENERATED CURB SURFACE                  initial conditions

0        FRONT WHEEL CAMBER        REAR WHEEL CAMBER      FRONT HALF-TRACK CHANGE    REAR HALF-TRACK CHANGE
                VS                         VS                         VS                         VS
       SUSPENSION DEFLECTION     SUSPENSION DEFLECTION     SUSPENSION DEFLECTION     SUSPENSION DEFLECTION

          DELTAF     PHIC          DELTAR     PHIRC          DELTAF     DTHF           DELTAR     DTHR
          INCHES    DEGREES        NOT USED  NOT USED        INCHES    INCHES          NOT USED  NOT USED
0         -3.00     -1.50          -3.00       .00           -3.00       .00           -3.00       .00
          -2.50     -1.38          -2.50       .00           -2.50       .00           -2.50       .00
          -2.00     -1.25          -2.00       .00           -2.00       .00           -2.00       .00
          -1.50     -1.13          -1.50       .00           -1.50       .00           -1.50       .00
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            -1.00     -1.00           -1.00       .00           -1.00       .00           -1.00       .00
             -.50      -.63            -.50       .00            -.50       .00            -.50       .00
              .00      -.38             .00       .00             .00       .00             .00       .00
              .50       .00             .50       .00             .50       .00             .50       .00
             1.00       .63            1.00       .00            1.00       .00            1.00       .00
             1.50      1.00            1.50       .00            1.50       .00            1.50       .00
             2.00      1.45            2.00       .00            2.00       .00            2.00       .00
             2.50      1.75            2.50       .00            2.50       .00            2.50       .00
             3.00      2.13            3.00       .00            3.00       .00            3.00       .00
1         bmt 2 RD2SMN model                                                                                    OCTOBER
     VEHICLE DATA                            TIRE DATA
     GENERATED CURB SURFACE                  initial conditions

0                                                            T I R E   D A T A
                                                      RF          LF          RR          LR
0         TIRE LINEAR SPRING RATE        AKT    =   800.000     800.000     800.000     800.000  LB/IN
          DEFL. FOR INCREASED RATE       SIGT   =     3.000       3.000       3.000       3.000  INCHES
          SPRING RATE INCREASING FACTOR  XLAMT  =     3.000       3.000       3.000       3.000
                                         A0     =  1256.800    1256.800    1256.800    1256.800
                                         A1     =    13.240      13.240      13.240      13.240
          SIDE FORCE COEFFICIENTS        A2     =  1829.100    1829.100    1829.100    1829.100
                                         A3     =      .533        .533        .533        .533
                                         A4     =-31246.000  -31246.000  -31246.000  -31246.000
          TIRE OVERLOAD FACTOR           OMEGT  =     1.000       1.000       1.000       1.000
          TIRE UNDEFLECTED RADIUS        RW     =    10.875      10.875      10.875      10.875  INCHES
          TIRE / GROUND FRICTION COEF.   AMU    =      .500        .500        .500        .500
          TIRE DAMPING PARAMETER         ANUT   =      .000        .000        .000        .000  SEC
          TIRE RIM STIFFNESS TERM        AKTR   =  2000.000    2000.000    2000.000    2000.000  LB/IN
          RIM FORCE VELOCITY COEF.       CTR    =      .050        .050        .050        .050
          RIM FORCE POWER TERM           PTR    =      .800        .800        .800        .800
          TIRE DEFLECTION TO THE RIM     RDR    =     4.880       4.880       4.880       4.880  INCHES
          RIM / CURB FRICTION COEFF.     AMURC  =      .000        .000        .000        .000
          FRICTION LAG FOR RIM FRICION   EPSVR  =      .000

0NO ANTI-PITCH TABLES
1         bmt 2 RD2SMN model                                                                                    OCTOBER
     VEHICLE DATA                            TIRE DATA
     GENERATED CURB SURFACE                  initial conditions

0                 C U R B / B A R R I E R   D A T A


          CURB FRICTION COEFFICIENT FACTOR    AMUC  =   1.000


          NODE LOCATIONS & NO. OF NODES CONNECTED


          NODE                    LOCATION                 NO. OF NODES
           NO.      X'(INCHES)    Y'(INCHES)    Z'(INCHES)   CONNECTED
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```
  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   ORIENTN.,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
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 WHEEL RADIUS-RADIAL SPRING FOR TABLE
 RWHJB(BEGIN)   =    .000 INCHES
 RWHJE(END)     =    .000   ''
 DRWHJ(INCRE.)  =    .000   ''
1
1
 UNEXPECTED END OF FILE ENCOUNTERED IN STMT NO. 1 OF SUBROUTINE INPUT.  LAST CARD READ WAS9999
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