TEXAS TRANSPORTATION INSTITUTE

ROLLOVER CAUSED BY CONCRETE SAFETY SHAPED BARRIER

VOLUME II - Appendixes

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16. Abstract

The objectives of this study are to: (2) identify the root causes of rollover of vehicles in impacts with concrete safety shaped barriers, (2) determine the extent and severity of overturn collisions with concrete safety shaped barriers, and (3) identify potential countermeasures to reduce shaped concrete barrier rollovers. The study approach consisted of critical review of literature, statistical and clinical analysis of four accident data files, and computer simulations. The extent of the rollover problem on concrete safety shaped barriers is found to be less than reported in previous literature. A number of impact conditions were identified from accident studies and confirmed by simulation as potential contributory factors to rollovers. Three alternate shapes were evaluated as potential countermeasures: (1) F-shape, (2) single constant sloped barrier, and (3) vertical wall. Results of the evaluation show that the F-shape barrier offers little performance improvement. The vertical wall barrier offers the greatest reduction in rollover potential, but also with the greatest increase in lateral accelerations. The single constant sloped barrier with an 80 degree slope may provide the best compromise solution. A benefit/cost analysis is needed and recommended to properly compare between the various barrier shapes.

This is volume II of a two-volume final report. The other volume is volume I, Technical Report FHWA-RD-88-219.

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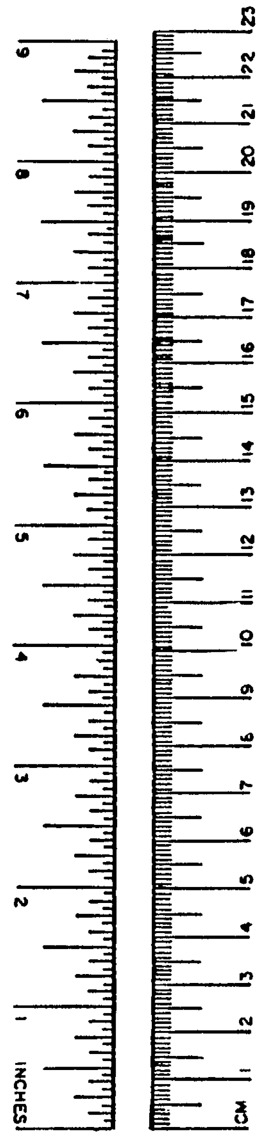
METRIC CONVERSION FACTORS

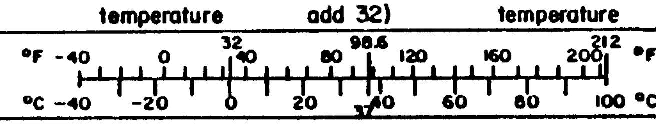
APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
	LENGTH			
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.6	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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ROLLOVER CAUSED BY CONCRETE SAFETY SHAPED BARRIER

TECHNICAL SUMMARY

Concrete safety shaped barriers have been one of the most popular barriers since its introduction in the early 1960's and there are hundreds of miles of such barriers currently in use on the nation's highways. The barrier has shown to be a low cost, low maintenance barrier capable of safely redirecting errant vehicles. However, the concrete safety barrier is not a panacea. One concern regarding the performance of concrete safety shaped barriers is the increased likelihood of vehicle rollover upon impact with this barrier, especially for small cars and vehicles with high center of gravity.

This study is a concerted effort to study this rollover problem in a comprehensive manner so as to obtain a clear understanding of the root causes and relative severity of rollover collisions with concrete safety shaped barriers, and to assess the effects of potential countermeasures. The objectives of this study are to: (1) identify the root causes of rollover of vehicles in impacts with concrete safety shaped barriers, (2) determine the extent and severity of overturn collisions with concrete safety shaped barriers, and (3) identify potential countermeasures to reduce shaped concrete barrier rollovers.

The study approach consisted of: a critical review of available literature, statistical and clinical analysis of four accident data files, and computer simulations. Some limited laboratory testing and one full-scale crash test were also conducted in the study. The major findings and conclusions from the study are as follows.

The extent of the rollover problem on concrete safety shaped barriers is found to be less than reported in previous literature. Rollover occurred in 8.5 percent of the accidents involving concrete safety shaped barriers on urban Interstates and freeways in Texas. The rollover rate of concrete safety shaped barriers was found to be actually lower than those of guardrails and bridge rails, but higher than other types of median barriers. It should be cautioned, however, that the rollover rates for the various barrier types are not directly comparable due to other influencing factors independent of the barrier properties. Also, a significant proportion of the rollovers was found to be unrelated to the barrier properties. This in effect reduces the extent of the rollover problem for concrete safety shaped barriers that can be treated by countermeasures.

Analysis of police level accident data identified a few factors that are correlated with rollover involvement. The rollover rate is found to be lower under adverse weather and surface condition and for vehicles that are skidding or rotating prior to impact with the barriers. Also, the rollover rate of smaller and lighter vehicles is much higher than their heavier and larger counterparts. Much of the problem can be attributed to the less stable nature inherent in the smaller vehicles, which is further aggravated by the shape of the concrete safety shaped barrier, particularly the lower sloped surface which gives the impacting vehicle a large upward force upon impact.

Clinical analysis of in-depth accident cases identified the following impact conditions as potential factors that are causative or contributory to rollovers on concrete safety shaped barriers: (1) high impact angle and moderate to high impact speed for tracking vehicles, (2) skidding sideways, i.e., high yaw angle and low yaw rate, (3) high impact speed and low impact angle, and (4) other factors, including glare screen on top of shaped concrete barrier, lateral displacement of barrier, and driver inputs after separation from the barrier. In contrast to the propensity for rollover for vehicles skidding sideways, vehicles that are rotating at impact, i.e., with a high yaw rate, are found to be less likely to result in rollovers.

Results from the simulation studies generally support findings from the accident studies. The concrete safety shaped barriers are found to perform relatively well for the majority of impact conditions, i.e., moderate angle, tracking impacts. As for impact conditions identified as potential contributory factors for rollovers, it was found that the simulation program is unable to accurately simulate high speed, low angle impacts or impacts involving glare screens. However, the simulation results confirmed that high angle impacts and high yaw angle, low yaw rate impacts are potential contributors to the rollover propensity of concrete safety shaped barriers.

The extent of the rollover problem on concrete safety shaped barriers is not considered serious enough to warrant retrofitting of existing concrete safety shaped barriers and only potential countermeasures that are applicable to new constructions or reconstruction were included in the evaluation. Three alternate shapes were selected for evaluation as potential countermeasures: (1) F shape, (2) single constant sloped barrier, and (3) vertical wall. Results of the evaluation show that the F shape barrier offers little performance improvement over concrete safety shaped barrier for these impact conditions. The single constant slope barrier with an 80 degree slope offers some rollover reductions while increasing lateral vehicle accelerations. The vertical wall barrier offers the greatest reduction in rollover potential, but also with the greatest increase in lateral accelerations.

While the vertical wall barrier shows the best potential for reducing the propensity for rollover, the single constant sloped surface barrier may provide the best compromise solution. It reduces the propensity for rollover when compared to the standard safety shaped barrier while showing less increase in the lateral accelerations than the vertical wall barrier. The initial construction cost should be the same or less than the standard safety shaped barrier, but substantially less in terms of maintenance costs. However, in order to properly compare the overall effectiveness between various barrier shapes, a benefit/cost analysis taking into account all the various factors as discussed above is needed and recommended.

Details of the study are presented in a two-volume final report. Volume I is the technical report detailing the study objectives, research approach and results. Volume II contains various appendices that are too bulky for inclusion in the technical report.

APPENDIX A
CRITICAL REVIEW OF LITERATURE

A number of references were critically reviewed as part of the study. A summary of pertinent information gathered from the literature review is presented as chapter III in volume I of the final report. Critical review of the individual references is provided in this appendix. A list of the references, arranged alphabetically, is provided first, followed by the review of the individual references.

Citation:

Briglia, P. M., Benac, J. D., Geno, D. E., and McDonald, K. A., "An Evaluation of Concrete Median Barrier in Michigan," Report No. TSD 531-83, Traffic and Safety Division, Michigan Department of Transportation, Lansing, Michigan, June 1983.[1]

Study Purpose:

The purpose of the study was to evaluate the relationship between CMB installation and accident severity, and between CMB accident severity and various roadway, roadside, traffic, and vehicle characteristics. A series of specific questions are posed to be addressed in the study, one of which is on the rollover performance of CMB.

Research Approach:

Accident experience for the years 1971-1981 was obtained for CMB installations, which were categorized into three groups:

Group I - 30 miles
Before condition - steel beam guardrail in the median
CMB installed in 1975 or later.

Group II - 18 miles
Before condition - grass median
CMB installed in 1975 or later.

Group III - 94 miles
Before condition - unknown
CMB installed in 1974 or earlier.

CMB installation dates were obtained from construction records. Site characteristics were gathered using photolog. Since the first photolog inventory was completed in 1974/1975, no before condition was available for CMBs installed prior to 1975.

The dependent variables used were "accidents per mile" for accident frequency and "severity ratio" (ratio of injury and fatal accidents to total accidents) for accident severity. Accidents per mile per year was used instead of per 100 MVM since the study locations were short segments of urban freeways with variable ADTs and number of lanes. Also, the emphasis of the analysis was not on accident frequency, but accident severity.

The overall change in ADT for all study segments between 1971 and 1981 was an increase of 3 percent. Some segments increased and some decreased in ADT. Two segments doubled in ADT.

The data were subset in the analysis by group (I, II, and III), accident type, accident severity, and vehicle type and size, depending on the specific question being addressed.

Statistical techniques used included:

Simple linear regression - total accidents vs. time
Log-likelihood test - comparison of severity ratio
Paired t-test - percent secondary collision
Kolmogorov-Smirnov test - observed vs. expected number of fatal accidents
Multiple linear regression - number of injury and fatal CMB accidents vs. roadway, roadside, and traffic variables
Chi-square test - percent rollover vs. vehicle size.

Findings:

- CMB accidents per mile per year were higher than left-side guardrail accidents and than head-on and sideswipe-opposite direction accidents across grass median. However, the head-on and sideswipe-opposite direction accidents decreased by 70 percent after CMBs were installed in the grass medians. The same was true for injury and fatal accidents.

- Median barrier accidents were a relatively constant percentage of total freeway accidents, regardless of the type of barrier in place.

- The severity ratio of CMB accidents was greater than that for left-side guardrail accidents, but lower than that of head-on and sideswipe-opposite direction accidents. However, the differences were not statistically significant.

- Significant reduction in fatal barrier-related accidents was noted after CMB installation.

- The percentage of secondary, multivehicle accidents (i.e., those where a vehicle strikes the barrier and then strikes another vehicle) was not higher for CMBs.

- The regression model had an R^2 value of 0.21, most of which was contributed by ADT. The effect of cross section was very small, but the safest cross section is a 7 to 13-ft shoulder without curb and with a negative shoulder slope.

- Vehicle size had little effect on the severity ratio of CMB accidents.

- Rollovers accounted for 6 1/2 percent of CMB injury and fatal accidents. Small cars (under 2,500 lbs) appeared to be overrepresented in the injury and fatal rollover accidents.

Critique:

The study design was flawed in that no attempt was made to control for other factors that could affect the outcomes of the analyses, e.g.,

- No consideration is given to changes and improvements to the roadway and roadside other than CMB installations during the study period, such as addition of lanes and paved shoulders, resurfacing, and other safety improvements.

- No consideration is given to the changes in speed limit and driving patterns in 1973 as a result of the oil embargo and price increase. Accident data prior to 1974 should not be compared to those of later years due to the dramatic changes.

- No consideration is given to other significant changes that might affect the study outcome, such as vehicle downsizing, changes in accident reporting format and threshold.

It may be argued that the effects of these changes would have a greater effect on accident frequency than on accident severity. Even so, this lack of control in the study design raises doubts about the results.

There are also some flaws associated with the analyses, the more important of which are as follows:

- The dependent variable of accidents per mile per year does not take ADT into account. The other dependent variable, severity ratio or percent of injury and fatal accidents, is a very insensitive measure.

- The statistical techniques used are improper in many instances.

- No consideration is given to individual roadway segments by grouping the data together. The analysis results could be subject to the canceling of opposite effects and Simpson's paradox.

- The sample sizes in many of the analyses are too small for meaningful results.

- Some of the assumptions are questionable, such as ignoring the effect of different barrier types, the use of average barrier/nonbarrier accident ratio, effect of unreported accidents, etc.

- Some of the conclusions are not even supported by the analysis results.

In summary, the study methodology contains some severe flaws that would adversely affect the validity of the study findings and conclusions.

Citation:

Bronstad, M. E., Calcote, L. R., and Kimball, Jr., C. E., "Concrete Median Barrier Research," Report No. FHWA-RD-77-3 and 77-4, Federal Highway Administration, Washington, D.C., March 1976.[2]

Study Purpose:

The objective of the study was to conduct a comprehensive evaluation on the safety performance of permanent and temporary concrete safety shaped barriers and end treatments.

Research Methodology:

The study consists of the following major tasks:

- A state-of-the art survey on current practices regarding CMB.
- Analysis of accident data collected from participating highway agencies on inservice performance of CMB.
- Computer simulations with the HVOSM program to evaluate and compare the two currently used shapes, i.e., the GM and NJ shapes. A new shape (Configuration F) was identified during parametric evaluations.
- A total of 27 full-scale crash tests were conducted, including baseline tests on the three CMB shapes with standard (4,500-lb) and subcompact (2,250-lb) cars. Other full-scale crash tests were conducted to evaluate CMB end treatments, precast designs for use as temporary and permanent barriers, and heavy vehicle (40,000-lb intercity bus) impacts.

A limited amount of accident data was collected and analyzed in an effort to compare performance of various shaped concrete barriers and the performance of other types of barriers. Baseline crash tests were conducted to compare the performance of the New Jersey and General Motors shaped barriers over a wide range of impact conditions. A large simulation effort with HVOSM was then undertaken to develop a new shape which could give better impact performance. The simulation was first validated through simulation of several of the baseline crash tests. HVOSM was then used to evaluate the performance of several new barrier shapes and the most promising shape was selected for full scale crash testing.

Findings:

A total of 575 CMB accidents were provided by 15 State highway agencies, a summary of the data is shown in table 4 of the report and reproduced as follows. The numbers in parentheses are percentages of total accident cases with specified profile. The New Jersey (Mod) shape has an initial step of 4 to 5 in instead of the standard 3 in.

Barrier Type	No. of Accident Cases	Accident Severity PDO	Injury	Fatal	Vehicle Rollovers	Mounting
New Jersey	180 (33)	133 (79)	35 (21)	0 (0)	6 (3)	1 (1)
New Jersey (Mod)	73 (13)	58 (77)	15 (20)	1 (1)	9 (12)	0 (0)
General Motors	299 (54)	225 (75)	74 (25)	0 (0)	19 (6)	4 (1)
Total	552	416	124	1	34	5

The authors conclude that performance of the shapes is comparable except for the occurrence of vehicle rollover and that the New Jersey shape (MB5) shows a definite advantage over the other shapes in preventing this. Further, it was found that high reveals at the bottom of the concrete barrier tended to increase the number of rollover accidents.

The authors also report that the CMB has been effective in containing and redirecting large vehicles with only two of 49 heavy vehicle accidents resulting in penetration of the barrier, as shown in table 5 of the report and reproduced as follows.

Vehicle	Total	Vehicle Reaction Reported	Redirected	Over	Penetrated
Bus	3	3	2	0	0
Tractor/Trailer	41	28	25	1	2
3-Axle Truck	5	2	1	0	0

Also, significant barrier damage occurred in only 6 of 311 reported accidents involving unreinforced barriers.

The study also reports on a number of prior studies on the performance of CMBs, including:

- Schlosser, Patrick, "Report on Accident Experience - Concrete Median Barrier," FHWA Wisconsin Division, December 1973.
- Christianson, Paul, and Olinger, James, "Concrete Barrier Accident Study," State of Wisconsin Division of Highways Report, 1974.
- Tye, E. J., "California's Median Barrier Experience," presented at the Annual Meeting of Western Association of State Highway Officials, Helena, Montana, June 20, 1973.

- Olivarez, D. R., Traffic Engineer, Arizona Highway Department, "Safety Experiences with Concrete and Metal Beam Barriers," presented at the 2nd Western Summer Meeting of Highway Research Board, August 1969.

- Tye, E. J., Median Barriers in California," CALTRANS Traffic Bulletin No. 22, March 26, 1975.

- Letter and enclosed report dated 1-29-75 from H. R. J. Walsh, Indiana State Highway Commission, to M. E. Bronstad.

Schlosser reports that, of 170 reported accidents in Milwaukee County, Wisconsin, involving GM shape CMB during a 12-month period:

- 14% returned to traffic lane.
- 4% returned to traffic lane and had a secondary collision.
- 5% struck the barrier and rolled over.
- 7% mounted the barrier.
- 3% crossed the barrier and entered opposing lanes.
- 67% struck the barrier and remained in the shoulder adjacent to the barrier.(1)

Of the 13 vehicles that rolled over, 9 were small automobiles. There was only one vehicle crossing the median resulting in one fatality during this 1-year period. In comparison, there were 515 accidents in the prior 2 1/2 year period involving the medians, of which 101 were crossover accidents. Of the crossover vehicles, 51 struck opposing traffic resulting in 9 fatalities.

The virtual elimination of crossover accidents is reported in the various studies. Also, the CMB compares favorably with the yielding barriers in accident severity.

Memoranda from two States in FHWA region 5 indicate a problem with vehicles mounting GM shaped barriers and knocking down light pole installations on the barriers. This was not found to be a problem with the New Jersey shape as reported by a toll authority in another State.

The Indiana study provides an indication of frequency of unreported to reported accidents on CMBs. On one section, 12 accidents were reported with an estimated 47 involvements based on marks on the barrier. On another section, 53 marks resulted in 20 reported accidents. The authors conclude that less than half of the involvements result in reported accidents.

Baseline crash testing revealed that the New Jersey shaped concrete barrier tends to impart higher accelerations on an impacting vehicle than the General Motors shape. However, it was observed that maximum roll angles for tests of the GM shape were significantly higher than for tests of NJ shaped barrier.

HVOSM was found to give adequate simulation rigid barrier impacts involving full size vehicles. However, initial efforts to simulate subcompact vehicle tests were unsatisfactory. A parameter study revealed that the simulation was very sensitive to the yaw moment of inertia of the test vehicle. The simulation was found to be only moderately sensitive to roll moments of inertia and suspension stiffness parameters were found to be unimportant. After accurately determining vehicle properties, HVOSM was found to give reasonably good predictions of rollover, maximum roll angle, height of climb and vehicle accelerations. Simulations of alternate barrier shapes indicated that slope of the upper barrier face is critical for preventing vehicle climb and rollover. A change in the slope of the upper face of only 4 degrees could change predicted maximum vehicle roll angle by as much as 10 degrees. Further, it was found that the height of the lower curb face affected the height of vehicle climb and the propensity for rollover.

Based on simulation findings, a new configuration, known as the "F"-shaped barrier, was constructed and crash tested. As predicted by HVOSM, testing indicated that the barrier reduced the propensity for vehicle rollover while increasing maximum vehicle accelerations.

Critique:

The accident data portion of the study was cursory and descriptive in nature and the sample size is fairly small. However, the data do suggest that the standard New Jersey shape has lower incidence of rollover than the GM or modified New Jersey shapes.

Of the reports cited in the literature review, the report by Schlosser is of some interest since it points to the potential rollover problem for small cars. Also of interest is the Indiana study which provides some indication on the extent of unreported accidents on CMBs.

Overall, the accident data reported and cited in this study were collected before the advent of small cars and are not indicative of the current vehicle population.

Limitations of HVOSM precluded simulation of more complex barrier shapes and therefore the study includes only minor variations in the basic safety shape.

Citation:

Cobb, L. C., "A New, Expanded Performance Range Highway Safety Barrier System," Proceedings of the 25th Annual Conference of the American Association For Automotive Medicine, Arlington Heights, Illinois, October 1981, pp. 335-346.[(3)]

Study Purpose:

This paper describes a new barrier system developed by the International Barrier Corporation (IBC).

Research Methodology:

This paper describes the history of development, design, and testing results of the IBC barrier.

Findings:

The IBC MK-7 barrier consists of a series of light gauge steel boxes, open at the bottom and with light, nonstructural lids, joined end to end to make a continuous chain, and filled with sand. It is not anchored to the ground so that no heavy equipment is required for the installation. The weight of the barrier when filled - up to 1,200 lb per linear foot - prevents translation of the barrier even when struck by large passenger vehicles. However, the barrier is free to be translated if the energy of impact exceeds a certain threshold value.

For a low energy impact (e.g., 2,000-lb car at 60 mi/h and 15 degrees), deflection of the barrier face will be almost entirely elastic because the supporting fill spreads the loads over a wide area. For a heavier impact (e.g., 4,500 lb car at 60 mi/h and 25 degrees), considerable plastic deformation of the front face of the barrier will occur and a considerable mass of sand will be compressed and displaced, but no lateral translation. For still heavier impacts, the extensive compression of the fill will begin to push the back face of the barrier across the ground, at least near the point of impact. For impacts with the largest vehicles, the entire barrier can act like a chain with a number of bins being translated as much as several feet. Full-scale crash tests with the new barrier successfully met the performance testing criteria.

The author outline the problems associated with small cars and CMBs, citing studies by Bronstad and Jehu:

- Smaller vehicles show extreme sensitivity to the exact profile of the CMB in their impact behavior.

- Against a rigid barrier, any deflection required to keep accelerations within acceptable levels must come entirely from the structure of the impacting vehicle. Small vehicles have less structure to be deformed before compromising the integrity of the passenger compartment.

- The CMB always elevates the barrier side of an impacting vehicle and, in some successful small car tests, lifted the car completely off the ground for distances of over 30 ft. A high roll angle is produced which could roll the vehicle over upon exit from the barrier.

The author concludes that this new barrier can accommodate the full range of vehicles and is very forgiving over a wide range of impact conditions. The barrier is designed to bend but not break, by utilizing the energy absorbing qualities of sand within a deformable steel container which is not anchored to the ground.

Critique:

This barrier design is very appealing conceptually and results of full-scale crash tests are very good. However, the system needs to be evaluated under real-world accident conditions to establish its effectiveness.

It is very difficult to compare this barrier design with the CMB since they are based on totally different concepts. However, the impacting vehicles do appear to be more stable during impact. The stable vehicle behavior can probably be attributed to the unique pot-belly shape of the barrier and the low coefficient of friction of the metal surface.

Citation:

Galati, J. V., "Box Beam Median Barrier Accident Study, Interstate 83, Harrisburg, Pennsylvania," Research and Studies Division, Bureau of Traffic Engineering, Pennsylvania Department of Highways, March 1969.[4]

Study Purpose:

The objective of the study was to determine the field performance of a newly installed Box Beam Median Barrier on Interstate 83 in Harrisburg, Pennsylvania.

Research Methodology:

The box beam median barrier was installed on a 4-ft wide inclined concrete median for a length of 9.4 miles. Impacts with the median barrier were recorded monthly over a 12-month period. Each damage was logged as to location and direction, and the severity of damage was classified into 16 categories, ranging from minor scratch to break-through.

Accident data over the same period were collected, as part of a before-after accident study.

Findings:

A total of 204 damages were recorded in the study period. Of these, 153 (75%) were classified as minor, 41 (20%) medium, and 10 (5%) major. There was one break-through type damage recorded.

During the same period, only 33 accidents involving the median barrier were reported compared to 204 damages recorded. In other words, 84% of impacts involving the box beam barrier were not reported.

Critique:

None.

Note that this study is included in the literature review only because of information pertaining to unreported accidents.

Citation:

Griffin, L. I., "Probability of Overturn in Single Vehicle Accidents as a Function of Road Type and Passenger Car Curb Weight," Texas Transportation Institute, Texas A&M University System, College Station, Texas, November 1981.[5]

Study Purpose:

The purpose of this paper was to consider the effect of passenger car curb weight and road type on the probability of vehicle overturn in single vehicle accidents.

Research Methodology:

Accident data in 1980 from the State of Texas were used in the analyses. The data were subset to include only single vehicle accidents involving passenger cars of known curb weight and manufactured after 1969. Overturn was defined by the first harmful event.

The data were categorized by highway type: Interstate, U.S. and State highway, Farm to Market road, county road, and city street. For each highway type, logistic regression equation was developed relating the probability of overturn to the vehicle curb weight.

Findings:

A summary of the data is shown as follows:

Highway Type	Number of Single Vehicle Accidents	Overturning Accidents	
		Number	Percent
Interstate	4,841	536	10.1
US & State Highway	10,119	1,052	10.4
Farm to Market Road	4,144	732	17.7
County Road	3,138	617	19.7
City Street	17,177	679	4.0

The author concludes that the probability of passenger car overturn in a single vehicle accident is highly dependent upon vehicle weight, with lighter weight vehicles displaying a much greater propensity to overturn. The likelihood of vehicle overturn is also influenced by road class. Passenger cars are most apt to overturn in single vehicle accidents on county roads (19.7%), and least apt to overturn in single vehicle accidents on city streets (4.0%).

For illustration purposes, the probabilities of overturn for vehicles weighing 5,200 lb and 1,600 lb are shown in the following table.

Highway Type	Vehicle Curb Weight (lbs.) 5200	1600	Ratio
Interstate	0.0238	0.2930	12.31
US & State Highway	0.0251	0.3010	11.99
Farm to Market Road	0.0437	0.4395	10.06
County Road	0.0559	0.4454	7.97
City Street	0.0050	0.1873	37.46

Critique:

The author appropriately categorizes the data by road class which has a great influence on the probability of overturn in a single vehicle accident. However, no consideration is given to the area type, i.e., urban versus rural, except for county road and city street. It was found in another study that the area type also has significant effect on the probability of overturn and should have been included in the analyses.

Citation:

Hall, J. W., and Zador, P., "Survey of Single-Vehicle Fatal Rollover Crash Sites in New Mexico," Transportation Research Record 819, Transportation Research Board., Washington, D. C., 1981, pp. 1-8.(6)

Study Purpose:

The purpose of the study was to examine the hypothesis that the roadway and roadside characteristics at the sites where rollover crashes occurred are more adverse than for the road system in general. A separate but similar study was also conducted in Georgia by Wright and Zador.

Research Methodology:

The methodology used was designed to compare the roadway and roadside characteristics at the sites of fatal rollover crashes with similar characteristics for a matched set of comparison sites, located one mile in advance of the crash sites. Field surveys were conducted at the crash and comparison sites to take such measurements as curvature, superelevation, and gradient. Other characteristics of the sites, including road and shoulder widths, roadside slopes, pavement friction, speed limit, and number of intersections and driveways, were also recorded. Roadside spot objects were enumerated and elongated objects were measured. At the crash sites, measurements were also made of the lateral and longitudinal distances traveled off the roadway by the overturning vehicle.

The analyses were mostly descriptive in nature. Statistical comparisons were made on average values using t-tests.

Findings:

- The roadway and roadside characteristics at the sites of fatal overturning crashes in New Mexico were more adverse than the comparison sites, especially for horizontal curvature. Maximum curvature in excess of 5 degrees occurred at crash sites at twice the expected rate. Curves to the left were more frequent and sharper at crash sites. Roadway gradients at crash sites were significantly steeper than at comparison sites, especially for downgrades of more than 2 percent which were 40 percent more common at crash sites. Left curves on steep downgrades were twice as frequent at the crash sites.

- Vehicles that departed the traveled way had serious difficulty in traversing a 4:1 slope. More than half of the fatal overturning crashes occurred where embankment heights were less than 1.2 m in height. Current guardrail warrants do not specify the use of guardrail for such embankment height. The data indicate that less than 15 percent of the crash sites would warrant the installation of guardrails. The authors recommend that the current standards on sideslopes and guardrail warrants be reexamined.

- A number of differences were noted in comparing the results between the New Mexico and Georgia studies:

  - Fatal overturning crashes accounted for a lower percentage of all crashes in Georgia than in New Mexico. On the other hand, fatal accidents involving fixed objects in Georgia were higher than in New Mexico (29% vs. 11%). One explanation suggested was the more extensive use of guardrail, more spot fixed objects, and the extent and height of embankments in Georgia.

  - The Georgia data show significantly more adverse horizontal alignment condition than those found in New Mexico. On the other hand, downgrades were significantly more common at New Mexico sites.

Critique:

While the research methodology used in the study is generally appropriate, there are some questions on specific analyses and conclusions.

- An implicit assumption is made that there is a cause and effect relationship between fatal overturning accidents and roadway and roadside characteristics. There are many factors that could affect the severity outcome of accidents that are not considered, such as vehicle type and size, restraint usage, impact conditions, etc.

- The use of average value in analyzing the effects of curvature and gradient is bothersome, especially when there are a substantial number of zeros (i.e., tangent or level) and with signed (i.e., + and -) values. A categorical type of analysis may be more appropriate than the t-test used.

- The small sample size limits the level of detail in the analyses and precludes the examination of interaction terms.

- No consideration was given to other factors that might affect the study results, such as highway type and differences in design standards.

- The study concludes that left curves are overrepresented at crash sites, yet no explanation is given to the results that the percentages of sites with left curves of greater than 5 degree sites were equal or higher at comparison sites than at crash sites for gradients of greater than -0.55 percent.

Citation:

International Barrier Corp., "Review of Maintenance of IBC MK-VII Barrier," Toronto, Ontario, 1984.[7]

Study Purpose:

The objective of this report is to document the repairs required on the I.B.C. barrier installed on I-95 in Broward County, Florida, after the barrier was in service from September, 1983 to May, 1984.

Research Methodology:

The report first describes the damages sustained by the I.B.C. barrier, followed by details of the repair procedures for different levels of damage.

Findings:

There have been over 60 impacts against the I.B.C. barrier during the first 7 to 8 months of service.

A total of five repairs were conducted -- three cosmetic overlays and two component replacements for a total estimated cost of less than $4,000.

Critique:

None.

Citation:

Jehu, V. J., and Pearson, L. C., "Impacts of European Cars and Passenger Coach Against Shaped Concrete Barriers", Transport and Road Research Laboratory, Report No. 801, Crowthorne, Berkshire, 1977.[8]

Study Purpose:

The objective of this effort was to investigate the safety performance of several shaped concrete barriers through full-scale crash testing.

Research Approach:

A variety of shaped concrete barriers similar to the standard NJ shape were tested with mini-size vehicles. Two of the shapes were tested with a mid-sized sedan and one shape, similar to the "tall wall" NJ barrier, was tested with a bus. Shape 1 was the same as a standard NJ barrier with a 3 in reveal except that the lower sloped face was a total of 13 in high compared to a height of 10 in for the standard NJ shape. The next tests involved shape 2, which was a standard NJ design with a 6 in reveal at the base. Shape 3 involved a NJ type barrier with a 2.5 in flat knee between the two sloped surfaces. The fourth series of tests involved a NJ shaped barrier with a 3 in reveal and the upper surface extended to a total height of 59 in for redirection of trucks and busses. Finally, shape 5 was the same as shape 4 without the 3 in reveal at the base.

Findings:

Mini-size vehicle impacts with the first two shapes at speeds from 60 to 70 mi/h resulted in the vehicle climbing to the top of the barrier and rolling over away from the barrier before returning to the ground. Both barriers had a lower curb height of 16 in, suggesting that the higher curb face may promote vehicle climb and enhance probability of rollover. Testing of the third shape with a shorter curb face showed that recessing the upper sloped surface back from the curb did not improve barrier performance with the mini-size vehicle.

Tests involving shapes 4 and 5 show that elimination of the 3-in reveal at the base of the NJ shape can reduce vehicle climb and improve mini-vehicle exit conditions slightly. The overall improved performance of shape 5 may be attributed to a reduction in suspension damage afforded by the reduction in the overall height of the lower curb face. Several of the tests in this series involved mini-size vehicles leaving the barriers at relatively low roll angle and subsequently rolling over due to spin out on sod or damage to tires and suspension. These results further emphasize the importance of approach terrain to performance of shaped concrete barriers.

Critique:

None.

Citation:

Lisle, F. N., and Hargroves, B. T., "The Performance of Portable Precast Concrete Traffic Barriers," Report No. VHTRC 79-R29, Virginia Highway and Transportation Research Council, Charlottesville, Virginia, November 1978.(9)

Study Purpose:

The purpose of the study was to evaluate the performance of the portable precast concrete traffic barrier during the widening of the Virginia-Norfolk Expressway (Rte. 44).

Research Methodology:

The study involved an examination of accident data and tire marks involving the concrete barriers as well as the effect of construction on traffic characteristics.

Findings:

Of interest from this study is the comparison between unreported and reported accidents involving the concrete barrier. The barrier is of the New Jersey shape and placed immediately adjacent to the passing lane, which was narrowed to only 9.5 feet.

During the period of September 22, 1976 to November 23, 1976, over a length of 2.37 miles (section A), there was evidence of 154 vehicle involvements above the 3 in vertical curb, but only 3 reported accidents involving the barrier (a ratio of 51:1). During the period of June 27, 1977 to July 21, 1977 over a length of 2.28 miles (section B), there was evidence of 89 vehicle involvements above the 3-in vertical curb, but only 2 reported barrier accidents (a ratio of 45:1).

Comparing to the Indiana study, cited in the report by Bronstad, on two roadway sections which had 99 vehicle involvements and 32 reported accidents (a ratio of 3:1), there is a big difference in the ratio of unreported vehicle involvements to reported accidents. The barriers used in the Indiana study are also of the New Jersey shape, but are permanent installation and are located in medians which vary in width from 4 to 11 ft. The authors suggest that the distance between the travelway and the barrier could significantly affect this ratio of unreported vehicle involvements to reported accidents.

The end of the barrier flare was the most frequently struck point location (13% of all vehicle involvements in Section A and 8% in Section B). Roadway alignment seemed to have some effect on the frequency of vehicle involvements with the barrier. The number of vehicle involvements per million vehicle miles of exposure was 12.4 for left curves, 8.7 for tangents, and 32.3 for right curves. However, the high rate for right curves was attributed to one particular curve which was preceded by a 1.7

mile tangent section. Time-lapse photography showed that drivers tended to start turning after the vehicles were already in the curve, thus moving closer to the barrier than when in tangent section. The authors suggested that additional lane width or the shifting of the lane away from the barrier is required under these circumstances to compensate for the delayed driver maneuvers.

Critique:

None. The analyses are all descriptive in nature. However, the point made by the authors that the lateral offset of barriers has a significant effect on the ratio of unreported vehicle involvements to reported accidents is well taken.

Citation:

McLean, S., "A Survey of Highway Accidents Involving Median Barrier on an 8 3/4-Mile Stretch of Highway I-95, in Broward County, Florida," A report prepared for the International Barrier Corporation, Toronto, Ontario, 1984.[(10)]

Study Purpose:

The purpose of this study was to evaluate the field performance and accident experience of the new IBC barrier installed on a 1-mile stretch of I-95 in Broward County, Florida, during the first 6 months of operation.

Research Methodology:

The study was limited to an 8 3/4-mile stretch of I-95 on which median barriers were installed during the summer of 1983. The installation included 1 mile of the new IBC barrier and the remaining 7 3/4 miles are CMBs of the New Jersey design. Hard copies of accident reports during the 6-month period from September 15, 1983 to March 15, 1984 were reviewed. Only accidents involving either the IBC barrier or CMB were considered.

The accident experience of the IBC barrier was compared to that of the CMB in terms of accident frequency, severity and average cost of damage per vehicle per accident. The comparisons were strictly descriptive.

Findings:

58 eligible accidents were identified during the study period, 48 of which involved the CMB and the remaining 10 accidents involved the new I.B.C. barrier. The data are summarized as follows:

	IBC Barrier	CMB
Number of Police Reports	10	48
Number of Vehicles	11	53
Damage to Vehicles		
Disabled	7 (63.6%)	41 (77.4%)
Functional	2 (18.2%)	9 (17.0%)
Other	2 (18.2%)	3 (5.7%)
Cost per Vehicle ($)	1,441	2,816
Vehicles Overturned	0 (0)	5 (9.4%)
Number of Occupants	19	66
Severity of Injuries		
Fatality	0 (0)	0 (0)
Incapacitating	1 (5.3%)	11 (16.7%)
Non-Incapacitating	4 (21.1%)	9 (13.6%)
Possible	3 (15.8%)	8 (12.1%)
No Injury	11 (57.9%)	38 (57.6%)

Of the five vehicles that overturned, there were nine occupants, six of whom received incapacitating injuries. All of the vehicles had inpacted a CMB.

Inspections by Florida DOT show that the IBC barrier was struck a total of 41 times during the first 6 months of installation, but only 14 accident reports were filed (10 of which fell into the time frame of the study).

The author conclude that:

- One out of every 10 vehicles that struck the CMB overturned. No vehicle that struck the IBC barrier overturned.

- There was over three times the likelihood of an occupant suffering an incapacitating injury when a vehicle struck the CMB than the IBC system.

- The average amount of damage to a vehicle that struck a CMB was almost double that of the IBC system.

Critique:

The sample size for accidents involving the IBC system is relatively small so that a change in the outcomes of one or two accidents could totally reverse the conclusions.

The fact that both barrier types are on the same stretch of highway provides for good comparisons. It is reasonable to assume that the exposure is the same for both barrier types and any observed differences should be attributable to the barrier types.

There are also some unanswered questions from examining the data:

- The IBC barrier has a higher accident frequency than the CMB on a per mile basis (10 vs. 6.8). Also, it is reported that there are nearly 3 incidents for every reported accident (41 vs. 14) involving the IBC barrier.

  Assuming equal exposure, it may be argued that the barriers would have similar frequencies of incidents. Since the CMBs have fewer number of reported accidents per mile, it may suggest that the CMBs have a higher percentage of unreported accidents (4.3 incidents per reported accident). This would then change the conclusions regarding the severity of accidents.

  On the other hand, a California study found that 40 percent of incidents involving CMBs on freeways were not reported, (1.7 incidents for every reported accident). There is too much discrepancy in the data to be more definitive on the extent of unreported accidents. It would be ideal if comparable data were collected for the CMB within the study area. This would have provided an excellent opportunity to better determine the extent of unreported accidents.

- It appears that 4 accidents involving the IBC barrier narrowly missed the study period. (No explanation is given as to why the study period was not adjusted to include these 4 accidents in light of the small sample size.) It is possible that the results and conclusions would change drastically if these four accidents were included.

- No consideration is given to the vehicle type involved in the accidents.

In summary, the study results points to the potential advantages of the IBC barrier system over the CMB, but the sample size is too small for much significance to be attached to the results.

Citation:

Perchonok, K., Ranney, T., Baum, S., Morris, D., and Eppich, J., "Hazardous Effects of Highway Features and Roadside Objects," Report No. FHWA-RD-78-201 and 78-202, Federal Highway Administration, Washington, D. C., September 1978.[11]

Study Purpose:

The major objectives of the study were to:

- Determine the relationship between the frequency and severity of single vehicle accidents and roadway geometric features.
- Determine the specific relationships between the frequency and severity of single vehicle accidents and roadside features.
- Identify appropriate countermeasures.

Research Methodology:

Accident data were collected by State police or highway patrol agencies from six participating States: California, Wyoming, South Dakota, Georgia, Maine, and Tennessee. In addition to the data contained in the police accident report, the investigating officers were asked to complete a supplemental data form, a detailed diagram of the accident sequence, and to provide photographic coverage of the accident scene and involved vehicles. Roadway and roadside characteristics were recorded from records maintained by the State highway departments, including photologs. The data were then coded and computerized for analysis in the study.

Overall, the data file contained a total of 7,972 single vehicle accidents in which the first injury or damage producing event occurred after at least one wheel exited the roadway or occurred as a result of contact with an obstacle immediately adjacent to the roadway. The roadway was defined as that portion of the road designed or ordinarily used for vehicular travel, exclusive of the shoulder.

The analyses conducted on the data mostly descriptive in nature. Statistical evaluations are limited to contingency coefficients and chi-square tests. Extensive one- and two-way tables were compiled on the data elements, but higher order interactions are not examined.

Findings:

Due to the voluminous amount of data presented in the report, only findings pertinent to rollovers and barrier impacts are included in the review.

Sample Descriptors. General characteristics of the sample are as follows:

- Approximately 85 percent of the accidents occurred on undivided roads, almost all of which were two-lane roads.

- Low volume roads with less than 400 ADT accounted for 30 percent of the sampled accidents.

- Distribution of the accidents by alignment are: 57 percent occurred on straight roads and 39 percent on curves; 35 percent occurred on level roads, and 43 percent on tangent grades.

- The distribution of the vehicles are: 69 percent automobiles, 29 percent trucks, and 2 percent utility vehicles.

- Half the accidents occurred in daylight, 44 percent at night. 79 percent of the accidents occurred on dry roads, 12 percent on wet roads, and 8 percent on roads with winter covering. 15 percetn of the accidents occurred during inclement weather.

<u>Rollover</u>. Nearly one-half (48%) of the accidents involved rollovers. The percentage of rollover is higher for non-tracking vehicles than for tracking vehicles (36.3% vs. 15.8%). The percentage of rollover by vehicle type is shown as below:

Vehicle Type	Percent Rollover
Cars:	
Sports car, or Subcompact	28.3
Compact	18.6
Intermediate	12.6
Full Size	10.3
Utility Vehicle	49.7
Trucks:	
Light Truck	32.4
Van, or Motor Home	40.4
Heavy Truck	
With Trailer	40.1
No Trailer	50.0

Nearly half of the accidents involving utility vehicles and heavy trucks with no trailers resulted in rollovers. Other truck types are also more prone to rollover than passenger cars. The increased propensity for rollovers with smaller vehicle size is clearly evident with the data.

The percentage of rollover is higher for fill than ditch sections (28.0% vs. 20.1%). The likelihood of rollover decreases with flatter slope, but increases with greater height, as shown in the following tables.

Slope	% Rollover	Slope	% Rollover
Fill		Ditch	
6:1, or flatter	28.4	6:1, or flatter	26.3
4:1	28.2	4:1	24.0
3:1	30.2	3:1	13.4
2:1	22.7	2:1	12.0
1:1	26.7	1:1	11.9

Height (Feet)	% Rollover	Height (Feet)	% Rollover
Fill		Ditch	
1	18.9	1	13.8
2	18.2	2	15.0
3	24.7	3	15.5
4-5	33.7	4-5	30.8
6-10	28.3	6+	17.6
11-20	30.2		
20+	28.0		

Barrier Impacts. There were 316 accidents in which striking a longitudinal barrier was the primary impact and a total of 570 barrier impacts. Almost all of the struck barriers are guardrails (294 out of 316 accidents and 519 out of 570 impacts). Only 7 of the 519 guardrail impacts resulted in rollovers. However, almost one-third (31.4%) of the vehicles went through or over the guardrails are another 3 percent vaulted (became airborne) as a result of hitting guardrails.

Critique:

The results from this study provide some general information on rollovers, but are of little utility for the study on shaped concrete barrier rollovers since there are so few applicable accidents.

Citation:

Phillips, R. G., and Bryden, J. E., "Roadside Barriers for Bridge Pier Protection," Research Report 117, New York State Department of Transportation, Albany, New York, December 1984.(12)

Study Purpose:

The purpose of the study was to determine the impact severity, strength, and redirectional characteristics of a concrete-pier-protection barrier design used in New York State. The design consists of a concrete safety shaped barrier half-section directly in front of the piers, flaring back from the pavement at a 1:8 rate just upstream of the piers. A 6-by 6-by 3/16-in box-beam guiderail protects the exposed upstream end of the concrete barrier. The guiderail end is bolted flush to the face of the concrete barrier.

Research Approach:

Seven crash tests were conducted, following NCHRP 230 guidelines. Five were strength tests and the other two occupant risk tests.

Findings:

In two similar strength tests (63 and 78) with the point of impact a short distance upstream from the first bridge column, the vehicles climbed to the top of the concrete barrier; impacted the bridge columns, and rolled over. The vehicles sustained severe damages with high impact severity.

The design was modified by extending the box-beam past the columns and bolting it to the face of the concrete barrier using carriage bolts. Two tests, one severity (76) and one strength (77), were conducted with the modified design with impact locations similar to those of tests 63 and 78. The test results were favorable with only moderate damages to the vehicles, light barrier damages, and acceptable occupant impact severity. The vehicles were smoothly redirected without them climbing on top of the concrete barrier or rolled over (the maximum roll angles were +3 and +5 degrees for test 76 and 77, respectively).

The authors conclude that the concrete barrier does not provide safe performance for high-angle impacts. The vehicles climbed to the top of the concrete barrier, developed a very high roll angle, contacted the columns, and rolled over on exiting. The modified design eliminates this unsuitable behavior and meets the NCHRP 230 performance criteria.

Critique:

These tests demonstrated the undesirable behavior of concrete barrier impacts at high angles. A potential countermeasure is to place a box-beam (or maybe W-beam) on the top portion of the concrete barrier to reduce vehicle climb and the roll angle.

Citation:

Post, E. R., McCoy, P. T., Wipf, T. J., Bolton, R. W., "Feasibility Study of Retrofitting Concrete Median Barriers", Report No. DOT/RSPA/DMA-50/83-33, Office of University Research, Washington, D. C., May 1983.[13]

Study Purpose:

This publication describes an effort to develop a procedure for evaluating the need for retrofitting concrete safety shaped barrier to reduce the number of rollover accidents.

Research Approach:

A benefit/cost analysis procedure was developed for determining when retrofitting concrete barriers might be cost-beneficial. The procedure was based on published accident analysis information and the estimated effectiveness for eliminating rollover accidents. HVOSM simulations were used to predict rigid barrier impact conditions that cause various classes of vehicles to rollover. Finally, two full scale crash tests of retrofit barriers were conducted in an effort to compare performance of modified design with previous test results.

Findings:

Benefit/cost analyses suggested that retrofitting a New Jersey shaped concrete barrier may become cost-beneficial at traffic volumes as low as 60,000 ADT.

HVOSM simulations of rigid barrier impacts were found to correlate reasonably well with crash test results. Simulation input data were obtained from studies conducted at SwRI and TTI. Simulations of the subcompact and full-size sedans predicted potential vehicle rollover at 60 mi/h for 25 degree impacts, and at 70 mi/h at impact angles of 15 degrees.

Crash testing revealed that the retrofit could effectively reduce maximum roll angle and height of climb with only a minor increase in vehicle accelerations for small car impacts at 60 mi/h and 15 degrees.

Critique:

Predictions of retrofit effectiveness and barrier impact severities used in the benefit/cost analysis were based largely on subjective evaluations by the authors. No attempt was made to account for the improved performance of the retrofit design for heavy vehicle impacts.

Simulation results predicting full-size vehicle rollover for impacts at 60 mi/h and 25 degrees conflict with published crash test results. Limitations of HVOSM precluded simulation of the retrofit design. Retrofit design was crash tested under impact conditions where conventional concrete barriers have been shown to perform acceptably.

Citation:

Reinfurt, D. W., Li, L. K., Popkin, C. L., O'Neill, B., Burchman, P.F., and Wells, J.K., "Rollover and Serious Driver Injury Differences among Various Utility Vehicles, Pickup Trucks and Passenger Car Groups," Proceedings of the 26th Annual Conference of the American Association for Automotive Medicine, Arlington Heights, Illinois, October 1982, pp. 297-312.[14]

Study Purpose:

The purpose of this study was to examine the crash experience of various types of vehicles, including utility vehicles and various passenger car size groups.

Research Methodology:

Statewide police-reported accident data for North Carolina and Maryland during 1973-1978 were used along with Fatal Accident Reporting System (FARS) data for the United States during 1978-1979. Registration frequencies provided by R.L. Polk and Co. starting in calendar year 1975 were used as the measure of exposure since vehicle-specific mileage was not available. Only findings from North Carolina and FARS are reported in the paper. However, the authors point out that the findings obtained from North Carolina data are consistent with those from the Maryland data.

The makes and models of vehicles were extracted primarily by using Vehicle Identification Number (VIN) pattern specifications. Passenger car size groups were defined by wheelbase length (subcompact < 102 in.; compact 102-111 in., intermediate 112-120 in.; full size > 120 in.).

Findings:

Rollovers occur more than 10 times as often in single vehicle accidents as in multivehicle accidents. This report focuses on single vehicle accidents. Table 1 summarizes the single vehicle crash involvement rate (per 10,000 registered vehicles), rollover rate, and percentages with rollovers by vehicle type from the North Carolina data.

Utility vehicles, as a group, had the highest single vehicle crash rates, rollover rates, and percentages of rollover, among the three vehicle groups, especially for the Jeep CJ-5. Pickup trucks had the lowest single vehicle crash involvement rates and rollover rates, but a higher percentage of rollover than passenger cars.

In all three groups, smaller vehicles had higher rates of rollover involvement than larger vehicles. Among the passenger cars, there were very pronounced relationships with car size, i.e., smaller cars had four to five times higher involvement rates in rollover crashes than larger cars. Similarly, among pickup trucks, smaller imported models were involved in rollover crashes at least twice as often as larger domestic models. Among utility vehicles, size was also a factor.

Table 1. Crash involvement rates (per 10,000 registered vehicles), rollover rates, and percentages of rollover for single vehicle accidents by type of vehicle.

Type of Vehicle	Crash Involvement Rate	Rollover Rate	Percentages with Rollovers
Utility Vehicles	145	55.5	36.6%
Jeep CJ-5	228	95.8	40.2%
Ford Bronco	162	68.6	37.4%
Chev. Blazer	95	21.7	22.5%
Pickup Trucks	62	11.8	18.7%
Ford F-100, F-150	72	12.8	17.5%
Chevrolet C-10, K-10	65	12.3	18.1%
Toyota	138	38.0	27.3%
Datsun	85	25.4	30.2%
Passenger Cars	119	15.1	12.6%
Subcompact	160	33.8	20.0%
Compact	150	20.2	13.5%
Intermediate	111	8.9	8.1%
Full Size	73	3.6	5.0%

Utility vehicles had serious and fatal (A+K) driver injury rates that were approximately three times higher than the rates for either passenger cars or pickup trucks (19.6 vs 7.8 and 4.6, respectively). Among the utility vehicles, the Jeep CJ-5 had the highest (A+K) driver injury rate (37.4) while the Chevrolet Blazer had the lowest (9.8). The Toyota and Datsun pickup truck rates (10.5 and 7.2, respectively) were between those of the utility vehicle group (19.6) and the Ford and Chevrolet pickups (5.4 and 5.5, respectively). The (A+K) rates for passenger cars decreased as wheelbase increased (12.6 for subcompacts down to 4.1 for full-size cars).

Similarly, (A+K) driver injury rates in single vehicle rollover crashes were much higher for utility vehicles than passenger cars and pickups (10.0 vs. 2.0 and 1.5, respectively).

Seat belt usage rates were quite low in all vehicle classes with highest use reported in passenger cars followed rather closely by utility vehicles; usage was considerably lower in pickup trucks (14.9% vs 12.2% vs 6.6%). There was a substantially lower incidence of (A+K) injuries among the belted drivers of the various vehicle groups than among the unbelted drivers.

As for driver age, crash-involved drivers of utility vehicles were somewhat younger than their pickup truck or passenger car counterparts. The Jeep CJ-5 had on average the youngest of all drivers with over 60 percent of their drivers being under age 25. However, by comparing rollover percentages with driver age groups among the various utility vehicle types, the authors conclude that age has only a marginal effect, if any, on single vehicle rollover rates.

Table 2 summarizes the crash rates and rollover percentages for fatal single vehicle accidents in the U. S. using the 1978-1979 FARS data files. Again, utility vehicles had the highest fatal crash rate -- almost three times higher than pickup trucks and passenger cars -- with the Jeep CJ-5 rate (8.6) being over twice that of the utility group average (3.1). Among all vehicle types, a high percentage of fatal single vehicle crashes involved rollover ranging from a low of 35 percent for full-size passenger cars to a high of 87 percent for the Jeep CJ-5's.

Critique:

The authors appropriately point out the fact that other nonvehicular facts that might have influenced the study results, such as differential use patterns or environmental conditions, were not examined. Also, the exposure measure of registration data is less preferable than mileage data.

Intuitively, the use pattern of utility vehicles may vary significantly from the other vehicle groups which could affect the study results. It would be desirable to account for the differential vehicle use pattern is by categorizing the data into various area and highway types and analyzing the data separately for each combination.

Table 2. Crash rates (per 10,000 registered vehicles) and rollover percentages for fatal single vehicle accidents - U. S. 1978-1979

Type of Vehicle	No. Registered	No. in Fatal Crashes	Fatal Crash Rate	% With Rollover
Utility Vehicles	2,127,170	633	3.1	83
Jeep CJ-5	347,490	297	8.6	87
Ford Bronco	176,848	48	2.7	83
Chev. Blazer	757,098	121	1.6	79
Pickup Trucks	19,500,685	2,556	1.3	64
Ford F-100, F-150	5,347,531	610	1.2	61
Chevrolet C-10, K-10	5,284,591	770	1.5	60
Toyota	570,228	91	1.6	62
Datsun	924,616	138	1.5	64
Passenger Cars	129,449,005	10,145	0.8	47
Subcompact	32,432,320	3,596	1.1	56
Compact	28,785,463	2,458	0.9	45
Intermediate	40,213,833	2,668	0.7	41
Full Size	28,017,389	1,423	0.5	35

Citation:

"Rollover Potential of Vehicles on Embankments, Sideslopes and Other Roadside Features," Task A Report - Review of Literature and Accident Data Analyses, Contract No. DTFH61-83-C-00060, Arvin/Calspan Advanced Technology Center, Buffalo, New York, March 1984.[15]

Study Purpose:

The objective of this task was to determine the general state of knowledge of rollover accidents, particularly with regard to the frequency of occurrence for various classes of vehicles, the severity of such accidents, and the identification of possible causative factors.

Research Methodology:

The information presented in this interim report was gathered from a review of 13 references, supplemented by limited analysis of 1979-1981 NASS data. The data cited are mostly descriptive in nature with little statistical testing for significance.

Most of the data pertain to rollovers as the first harmful event, although rollovers subsequent to prior impacts are also addressed. There is no specific reference to rollover involvement of accidents with longitudinal barriers.

Findings:

The key points made in this literature review are as follows:

- Rollover is relatively frequent for single vehicle accidents.
- Rollover rates vary greatly by vehicle type and size. Utility vehicles have the highest rollover rate (40 to 60 percent), and are about 3 to 5 times more likely to overturn than passenger cars as a whole. The results are consistent among the various studies with regard to the rank ordering of the different vehicle classes by rollover rate.

  For passenger cars, the rollover rate increases with decreasing car size and weight. The relationships tend to be curvilinear, flattening out at weights above 3,500 lb.

  Tables 3 through 5 are based on 1979-1981 NASS data compiled for this study, showing the rollover rates for single vehicle accidents.
- In most of the rollover accidents (50 to 80 percent), the vehicles were skidding out of control at a large sideslip angle prior to overturning. Table 6 is excerpted from a study by Malliaris on the NCSS data.
- The likelihood of rollover increases with increasing speed prior to impact. Data from several sources are cited in the literature review

Table 3. Incidence of rollover as first harmful event (1979-1981 NASS data).

Vehicle Type	No. of Single Vehicle Accidents		Percent Rollover	
Utility Vehicles	86		38.4	
Pickup Truck	503		19.3	
Van	119		13.5	
Station Wagon	811		7.9	
Passenger Cars	1637		7.1	
<= 3500 lb.		1015		10.0
> 3500 lb.		622		2.3
	----		----	
All Vehicle Types	3156		10.3	

Table 4. Incidence of any rollover, regardless of first harmful event (1979-1981 NASS data)[1].

Vehicle Type	On Roadway No. SVA	On Roadway % R.O.	Off Roadway No. SVA	Off Roadway % R.O.	Combined % R.O.
Utility Vehicle	24	79.2	65	60.0	65.2
Pickup Truck	76	34.2	430	40.7	39.7
Van	33	18.2	86	34.9	30.3
Station Wagon	143	6.3	668	23.2	20.2
Passenger Cars	302	7.6	1346	24.6	21.5
<= 2000 lb	33	24.2	105	49.5	43.5
2100-2500 lb	31	22.6	204	35.3	33.6
2600-3000 lb	30	13.3	227	30.8	28.8
3100-3500 lb	69	2.9	323	21.1	17.9
3600-4000 lb	67	3.0	264	15.2	12.7
4100-4500 lb	51	0.0	167	12.6	9.6
>= 4600 lb	21	0.0	56	14.3	10.4
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All Vehicle Types	578	14.4	2595	28.1	25.6

[1] 59% of the rollovers were not first harmful event.

Table 5. Comparison of passenger car relative rollover involvement rates (single vehicle accidents, 1979-1981 NASS data).

Car Weight (Lb.)	Proportion of All Accidents No.	%	Proportion of All Rollovers No.	%	Relative Rollover Involvement Rate
<= 2000	138	8.4	60	16.9	2.01
2100-2500	235	14.2	79	22.3	1.57
2600-3000	257	15.6	74	20.9	1.34
3100-3500	392	23.8	70	19.8	0.83
3600-4000	331	20.1	42	11.9	0.59
4100-4500	218	13.2	21	5.9	0.45
>= 4600	77	4.7	8	2.3	0.49
Total	1648	100.0	354	100.0	1.00

Table 6. Pre-crash conditions and rollover involvement in single vehicle accidents (NCSS data).

Pre-Crash Condition	Percent Rollover: Passenger Car	Percent Rollover: Light Truck and Van	Relative Rate of Involvement: <= 3500 lb.	Relative Rate of Involvement: > 3500 lb.
Straight	4.5	7.8	1.24	0.81
Skid Sideways	9.1	17.4	1.43	0.65
Skid Front	1.1	2.3	1.15	0.88
Spin	0.7	3.1	1.33	0.73
Other	0.9	2.7	1.28	0.77
All	16.3	33.3	1.29	0.76

and summarized in Tables 7 through 9.

- Rollover accidents tend to be more severe than other accident types, citing the following references.

  FARS Data. Viner reported that overturn was the leading cause of roadside fatalities in 1981, accounting for 33.8 percent of the fatalities on all roads and 44.7 percent of those on the Interstate system.[18] McGuigan and Bondy observed that 53 percent of all occupants in fatal rollover accidents were killed as opposed to 41.6 percent of the vehicle occupants in nonrollover fatal accidents.

  NCSS Post-March 1978 Data File. McGuigan and Bondy report a severe injury rate (AIS >= 3) of 11.5 percent for occupants of rollover vehicles compared to 4.1 percent for occupants of nonrollover accidents.[19] 40 percent of occupants of passenger cars that overturned were ejected and 53 percent of those who were killed were ejected.

  Texas Accident Data. For single vehicle accident in Texas in 1981, 2.32 percent of overturn accidents resulted in driver fatality as compared to 1.21 percent for nonrollover accidents, a ratio of nearly 2 to 1.

  North Carolina Accident Data. Reinfurt, et al. reported that the rates for serious and fatal (A+K) driver injuries in single vehicle rollover crashes per 10,000 registered vehicles was much higher for drivers of utility vehicles (10.0) compared to passenger cars (2.0).[14] Among passenger cars, the serious injury rates decreased with increasing car size with an approximately five-fold difference (4.1 vs. 0.8) between subcompact and full-size cars.

  CPIR Data File. Huelke, et al. cited a 2 out 3 (67%) fatal ejection rate.[16] The distributions of injury severity for passenger car rollovers and for all accidents are shown as follows.

Injury Severity (AIS)	Rollover	All Accidents
0 - No Injury	15.3	23.9
1 - Minor	44.6	46.6
2 - Moderate	12.8	11.9
3 - Severe	7.8	6.0
4 - Serious	1.4	2.0
5 - Critical	2.5	1.7
6-9 - Fatal	15.6	7.9
Total	100.0	100.0

Table 7. Impact speed and rollover involvement (CPIR data file)[16]

Speed (mi/h)	All Accidents No.	All Accidents %	Rollovers No.	Rollovers %	% of Rollovers %	% of Rollovers Cum.	Relative Rollover Involvement
1-10	178	9.5	4	2.2	1.9	1.9	0.20
11-20	157	8.4	2	1.1	1.0	2.9	0.11
21-30	341	18.3	9	2.6	4.4	7.3	0.24
31-40	405	21.7	37	9.1	18.0	25.3	0.83
41-50	361	19.3	55	15.2	26.7	52.0	1.38
51-60	195	10.4	41	21.0	19.9	71.9	1.91
61-70	157	8.4	33	21.0	16.0	87.9	1.90
71-80	38	2.0	9	23.7	4.4	92.3	2.20
81-90	25	1.3	10	40.0	4.9	97.2	3.77
91-100	10	0.5	6	60.0	2.9	100.0	5.80
Total	1867	100.0	206	11.0	100.0		

Table 8. Estimated speeds of rollover.[17]

Speed (mi/h)	Rollover No.	Rollover %	Cumulative %
0-10	2	2.3	2.3
10-20	13	14.9	17.2
20-30	18	20.7	37.9
30-40	22	25.3	63.2
40-50	17	19.5	82.7
50-60	8	9.2	91.9
60-70	6	6.9	98.8
70-80	1	1.2	100.0
Total	87	100.0	

Table 9. Distribution of primary impact speed(11)[1]

Speed (mi/h)	Primary Impact No.	Primary Impact %	Cumulative %
0-10	683	8.9	8.9
11-20	1861	24.2	33.1
21-30	2731	35.6	68.7
31-40	1429	18.6	87.3
41-50	679	8.8	96.1
51-60	219	2.9	99.0
>60	79	1.0	100.0
Total	7681	100.0	

[1] 46% of primary impacts were rollovers.

Mackay and Tampen.(17) The injury severity of 89 rollover accidents of British passenger cars and light vans (147 occupants) is as follows.

Injury Severity	No. of Accidents	Percent
None	26	29.2
Minor	33	37.1
Moderate	14	15.7
Severe	10	11.2
Fatal	6	6.8
Total	89	100.0

Perchonok, et al.(11) The distribution of the most severe injury level in rollover and nonrollover accidents is shown as follows.

	Injury Severity						
	PDO		Injury		Fatal		
Impact Type	No.	%	No.	%	No.	%	Total
Rollover	1189	33.4	2134	60.0	235	6.6	3558
Non-Rollover	2160	51.2	1914	45.4	146	3.5	4220
Overall	3349	43.1	4048	52.0	381	4.9	7778

- The effect of roadside features on rollover occurrences was also examined in the literature review, but the emphasis was on embankments, ditches, culverts, and curbs. Longitudinal barrier was not one of the roadside objects considered.

Critique:

The findings are based mostly on available literature with very little original research. Refer to the individual references for critique.

Of the limited analyses conducted on the 1979-1981 NASS data, it is important to note that the authors do not weight the cases according to the sampling scheme nor mention the potential biases introduced in the results. Since the NASS sampling scheme is biased toward more severe injury accidents and certain vehicle types, e.g., trucks, the results should be viewed accordingly.

Citation:

Schlosser, P., "Report on Accident Experience - Concrete Median Barrier," Federal Highway Administration, Wisconsin Division, December 1973.[20]

Zavoral, J. R., Area Engineer, Federal Highway Administration, Wisconsin Division, "Report on Accident Experience - Concrete Median Barrier," June 1973.[21]

Wisconsin Department of Transportation, Division of Highways, "Concrete Barrier Accident Study," 1974.[22]

Memorandum from John O. Hibbs, Division Administrator, Wisconsin, to Donald E. Trull, Regional Federal Highway Administrator, dated January 30, 1976, on Concrete Median Barrier - Accident Experience on I-94 and I-894 in Milwaukee County for 1973 and 1974.[23]

Study Purpose:

All the above reports pertained to an inservice evaluation on concrete median barriers installed on the Interstate system in Milwaukee County, Wisconsin. The reports covered slightly different time periods and are thus grouped under the same citation. Results from the Schlosser report are used since it is the most comprehensive of the three reports.

Research Methodology:

Police accident data were collected for the period November 1972 to November 1973, though the reporting periods varied for the three studies. Descriptive statistics were compiled from the accident data with no statistical tests.

Findings:

For the 12-month period from December 1972 to November 1973, there were 170 reported accidents with the GM shaped CMB, involving 205 vehicles. In comparison, for the 2 1/2-year period from January 1, 1969 to July 1, 1971, there were 515 accidents involving the medians, of which 101 were crossover accidents. Of the crossover vehicles, 51 struck opposing traffic resulting in 9 fatalities.

There were 11 automobiles that mounted the barrier, 4 of which were on right curves. There were 13 automobiles that rolled over after hitting the barrier, 9 of which were small cars. Two of the rollover accidents resulted in fatalities, one of which also mounted and crossed the barrier. Nearly half (49%) of the accident occurred when it was raining, snowing, or when the road surface was wet and 52 percent of the accidents occurred during periods of darkness.

Vehicle reactions after colliding with the barrier were compiled for the period of November 1972 to April 1973, as follows:

- 14% returned to traffic lane.
- 4% returned to traffic land and had a secondary collision.
- 5% struck the barrier and rolled over.
- 7% mounted the barrier.
- 3% crossed the barrier and entered opposing lanes.
- 67% struck the barrier and remained in the shoulder adjacent to the barrier.

The accident data for 1973 and 1974 for the GM concrete CMB are as follows:

	1973				1974			
Description	PDO	Injury	Fatal	Total	PDO	Injury	Fatal	Total
Crossed Barrier	0	2	1	3	0	0	0	0
Mounted Barrier	3	4	0	7	3	2	0	5
Rolled Over	4	8	1	13	3	3	0	6
Redirected into Traffic	18	13	0	31	13	14	0	27
Remained in Roadside	91	34	0	125	67	22	0	89
Totals	116	61	2	179	86	41	0	127

Critique:

None. The analyses were all descriptive in nature. The vehicle population for the study period was very different from the current population for much significance be attached to the study results. However, the data did suggest the potential problem of small car rollovers on GM shaped concrete median barriers.

Citation:

Sides, K., "Passenger Vehicle Rollovers with Median Barriers in California in 1979," Presentation to Committee A2A04 at the Transportation Research Board Annual Meeting, Washington, D. C., January 1982.[24]

Study Purpose:

The purpose of this paper was to investigate whether small cars were overrepresented in rollover accidents that involved three different types of median barriers: concrete median barrier, cable median barrier, and metal beam median barrier.

Research Methodology:

Median barrier accidents were identified from the 1979 California accident data file. The accidents were hand sorted to separate the passenger cars from trucks, motorcycles, and specialty vehicles. Each passenger car involved in a rollover accident with a median barrier was classified as imported (surrogate for small cars) or domestic and the curb weight was recorded either from MVMA Passenger Car Specifications or estimated.

For comparison purposes, the 1976 California registration data of passenger vehicles by curb weight compiled by R. L. Polk was used. The author cautioned that there were fewer small cars in 1976 than in 1979 (e.g., the percentage of imported passenger car was 26% in 1976 and 30.5% in 1979) and the results should be viewed accordingly.

Chi-square tests were used to determine if imported passenger cars are significantly overrepresented in median barrier accidents that result in overturn. Comparisons were also made between the three barrier types on rollover involvement. It is assumed that the exposure is the same for imported and domestic passenger cars. The distributions of curb weights for the overturned vehicles were compared to the registration data without statistical testing.

Findings:

A summary of the 1979 California freeway reported median barrier accident data is shown in table 10. Table 11 shows the breakdown of the passenger car median barrier rollover accidents by imported and domestic makes with the mean curb weights shown in table 12.

Using the 1979 registration data that 30.5 percent of the passenger cars were imported as the basis of comparison, the Chi-square test results indicate that the imported passenger cars are significantly overrepresented in rollover accidents for all three barrier types. However, there is no significant difference in the proportions of imported passenger cars between the three barrier types.

Table 10. 1979 California freeway reported median barrier accidents

Barrier Type	Total Accidents	Median Barrier Rollover Accidents: Passenger Cars Only No.	%	Other Vehicles No.	%	Total No.	%
Concrete	1,796	123	6.8	54	3.0	177	9.9
Cable	2,305	83	3.6	60	2.6	143	6.2
Metal Beam	2,005	37	1.8	41	2.0	78	3.9

Table 11. Percentage of imported and domestic passenger vehicles median barrier rollover accidents.

Barrier Type	Median Barrier Rollover Accidents: Imported Cars No.	%	Domestic Cars No.	%	Total
Concrete	73	59	50	41	123
Cable	46	55	37	45	83
Metal Beam	17	46	20	54	37

Table 12. Mean curb weight of imported and domestic passenger vehicles median barrier rollover accidents

Barrier Type	Mean Curb Weight (Lbs.): Imported Cars	Domestic Cars	Combined
Concrete	2,150	3,100	2,550
Cable	2,000	3,250	2,550
Metal Beam	2,600	3,575	3,125

For each barrier type, the curb weight distribution of the vehicles involved in median barrier rollover accidents is compared to that of the 1976 vehicle registration data in California, as shown in figures 1 to 4 of the paper. The author concludes that a higher percentage of the smaller vehicles (less than 2,500 lb) are involved in overturns with concrete median barriers and cable rail median barriers than are registered. The metal beam median barriers, however, do not appear to be as sensitive to curb weight.

The author also notes that the Volkswagon Beetle comprised 62 percent of all the overturns for vehicles less than 1,950 lb. (CMB - 62%, cable - 63%, and metal beam - 57%) and suggested that geometry probably plays a role in whether or not a vehicle overturns in a median barrier accident. (Mr. John Viner of FHWA informed the project staff that a later review of the 1979 California registration data compiled by R. L. Polk indicated that the Volkswagon Beetle comprised 55 percent of all vehicles, weighing less than 1,951 in model year 1966 and later. Thus, the VW Beetle may not be significantly overrepresented as reported in this paper.)

Critique:

The author did not comment on the data shown in table 10 which show some interesting trends. The percentage of passenger car rollovers for CMBs (6.8%) is almost twice that for cable rail median barriers (3.6%) and over 3.5 times that for metal beam median barriers (1.8%). For nonpassenger car rollovers, the percentages still follow the same order (3.0% vs. 2.6% vs. 2.0%), but the differences are much smaller. This suggests that the propensity for rollovers for passenger cars is more sensitive to barrier types than nonpassenger cars.

The differences in mean vehicle curb weights among the barrier types are disturbing, indicating possible differences in exposure between the barrier types. The small sample size for metal beam median barrier rollover accidents may have also contributed to this difference. This apparent difference in exposure between the barrier types should be taken into account when interpreting the results of comparisons between the barrier types.

The paper presented one of the very few data sources available in the literature. Also, some interesting and important trends can be gleaned from the data.

Citation:

Viner, J. G., "Implications of Small Cars on Roadside Safety," Proceedings of the 27th Annual Conference of the American Association For Automotive Medicine, Arlington Heights, Illinois, October 1983, pp. 357-374.(18)

Study Purpose:

This paper was presented at the 27th Annual Conference of AAAM on the general topic of "The Roadway and Roadside".

Research Approach:

The information presented was mostly synthesized from existing literature, with limited new data or analysis.

Findings:

A roadside feature was judged to be the most harmful event in 35.1 percent traffic fatalities and 37.5 percent of fatalities on the Interstate System in 1981, based on FARS data. Overturn is the leading cause of roadside fatalities, accounting for 33.8 percent of roadside fatalities and 44.7 percent of Interstate roadside fatalities.

Existing data indicate that the severity for rollover accidents is generally higher than that of nonrollover accidents. NASS data indicate that fatalities are 5.7 times more likely in single vehicle rollover accidents as compared to nonrollover single vehicle accidents. In single vehicle police reported accidents in Texas in 1981, 2.32 percent of overturn accidents resulted in driver fatality, as compared to 1.11 percent (1.21 percent was incorrectly cited in the paper) for nonrollover accidents, a ratio of 2.1 (a ratio of 1.9 was incorrectly cited in the paper). However, no vehicle size effect was found in driver fatalities or incapacitating injuries in overturn accidents (see figure 5 of paper).

The following table (table 4 of the paper) presents the rollover outcome of all 1979 police reported median barrier accidents for the three most common designs used on California freeways.

	Median Barrier Type					
	Concrete (MB5)		Cable (MB1)		Metal Beam (MB4W)	
Accident Type	No.	%	No.	%	No.	%
Total	1796	100	2305	100	2004	100
Total Rollover	177	9.9	143	6.2	78	3.9
Passenger Vehicle Rollover	123	6.8	83	3.6	37	1.8
Non-Pass. Vehicle Rollover	54	3.0	60	2.6	41	2.0

Passenger vehicle rollovers on the shaped concrete barrier occurred at 1.9 the rate of the cable median barrier and at 3.8 times the rate of the metal beam barrier. For all vehicle classes, rollovers occurred on the shaped concrete barrier at 2.5 times the rate of the metal beam barrier.

Comparisons were made between the cumulative weight distribution of the 123 passenger vehicles that overturned in collision with the shaped concrete median barrier and the weight distribution of passenger vehicles registered in California in 1979. (see Figure 7 of paper) Fifty-one percent of the overturned vehicles weighed less than 2,250 lb although these vehicles only account for 24 percent of passenger car registrations. The overturn and registration curves diverge up to a weight of about 2,700 lb and converge as weight increases, which means that concrete median barrier accidents are overrepresented for vehicle lighter than 2,700 lb.

The cable median barrier also shows a vehicle size effect, 50 percent of overturns occurring at weights less than 2,250 lbs. The vehicle curb distribution for metal beam barrier accidents is closet to the registration weight distribution. (see figure 8 of paper)

Critique:

The analyses presented in the paper are cursory in nature, but do illustrate the rollover problem potentially associated with shaped concrete barriers, especially for small vehicles. The author correctly indicates that vehicle weight distribution data based on vehicle registration are only a surrogate to actual exposure. A number of other factors not considered in the analyses could also affect the results. First, no distinction is made between urban and rural freeways. Significant differences are found in rollover rates between urban and rural freeways in Texas (unpublished data from an ongoing study). Second, no consideration is given to the differences in roadway design for the different barrier types. For example, cable median barriers are no longer used in new installations and are present only on older freeways with relatively wide medians. The CMBs are more likely to be used in new construction on urban freeways with high traffic volumes and narrow medians.

Citation:

Welch, R. E., "Validation and Application of the Guard Computer Program", Federal Highway Administration, Final Report on Contract No. DOT-FH-11-9460, January 1984.(25)

Welch, R. E., "Concrete Safety Shape Simulations with Program GUARD", Federal Highway Administration, FHWA/RD-78/90, May 1977.(26)

Study Purpose:

These two reports describe efforts to validate the use of the GUARD computer program for simulation of automobile-barrier collisions. The later report represents a repetition of validation efforts undertaken after modification of the GUARD program to improve simulation performance. Therefore the two reports are discussed simultaneously.

Research Approach:

The GUARD program was used to simulate six full-scale crash tests of New Jersey and GM shaped concrete barriers. Four tests involved subcompact vehicles impacting at angles ranging from 7.5 to 16 degrees. The remaining tests involved full-size vehicles impacting a New Jersey barrier at angles of 7.5 and 16 degrees.

Measures of simulation correlation with test results included peak and average accelerations, heading and roll angle time histories, barrier exit angle, and maximum vehicle roll angle.

Findings:

The simulation program gave unreliable predictions of 50 ms average accelerations. Relatively good correlation between measured average accelerations and simulation predictions was obtained for low impact angles while very poor correlation was obtained for impact angles above 14 degrees. There appeared to be no correlation between measure peak accelerations and simulation predictions.

Predicted heading angle time histories correlated relatively well with measured data. However, correlation for tests involving low impact angles appeared to be much better than for those involving high angles of impact. Correlation of exit angle predictions with measurement was very similar to that for heading angle time histories.

Correlation between predicted and measured roll angle time histories was poor. Correlation for maximum roll angle was only marginally better.

Critique:

Problems with vehicle acceleration predictions have been reportedly traced to coding errors involving tire/terrain interaction algorithms. Most of the other problems encountered during this effort could potentially be a result of this same coding error.

Another potential cause for lack of correlation between predicted and measured heading angles is the lack of a steering degree of freedom in the computer model to account for the change in steer angle during impact. The model assumes that front tires are held straight during the entire impact event. Further, problems associated with roll angle predictions are likely to arise from the very simple tire model used in the GUARD computer model.

The reports did not include any information regarding height of vehicle climb or pitch angles during testing. Both of these parameters are believed to be good indicators of potential rollover events.

Citation:

Wright, P. H., and Zador, P., "Study of Fatal Rollover Crashes in Georgia," Transportation Research Record 819, Transportation Research Board., Washington, D. C., 1981, pp. 8-17.(27)

Study Purpose:

The purpose of the study was to examine the hypothesis that the roadway and roadside characteristics at the sites where rollover crashes occurred are more adverse than for the road system in general. A separate but similar study was also conducted in New Mexico by Hall and Zador.

Research Methodology:

The methodology used was designed to compare the roadway and roadside characteristics at the sites of fatal rollover crashes with similar characteristics for a matched set of comparison sites, located 1 mile in advance of the crash sites. Field surveys were conducted at the crash and comparison sites to take such measurements as curvature, superelevation, and gradient. Other characteristics of the sites, including road and shoulder widths, roadside slopes, pavement friction, speed limit, and number of intersections and driveways, were also recorded. Roadside spot objects were enumerated and elongated objects were measured. At the crash sites, measurements were also made of the lateral and longitudinal distances traveled off the roadway by the overturning vehicle.

The analyses were mostly descriptive in nature. Statistical comparisons were made on average values using t-test with 0.05 level of confidence and chi-square test.

Findings:

- Single-vehicle fatal rollover crashes are more likely to occur:
  - Along nonlocal (especially arterial) than local roads.
  - Along curved sections turning to the left than along straight sections or right curves.
  - Along downhill slopes than along level of uphill sections.
  - Along the outside of curves (especially left-turning curves) than along the inside, and/or in the area downstream from a curve than in the area upstream.
- The largest difference between the crash and comparison sites was in horizontal curvature. Approximately 40 percent of the crash sites had a maximum curvature greater than 6 degrees whereas only 13 percent of the comparison sites had a maximum curvature greater than 6 degrees.

- Steep gradients were also found to be associated with rollover crash locations, with negative slopes occurring upstream and positive slopes downstream.

- Sites of rollover crashes were characterized by significantly larger changes in lateral slope at the shoulder edge than were found at comparison sites. The crash sites were also more likely to have embankments along the roadside than the comparison sites but less likely to have trees and certain other spot fixed objects.

Critique:

While the research methodology used in the study is generally appropriate, there are some questions and comments on specific analyses and conclusions:

- An implicit assumption was made that there is a cause and effect relationship between fatal overturning accidents and roadway and roadside characteristics. There are many factors that could affect the severity outcome of accidents that are not considered, such as vehicle type and size, restraint usage, impact conditions, etc.

- The use of average value in analyzing the effects of curvature and gradient is bothersome, especially when there are a substantial number of zeros (i.e., tangent or level) and with signed (i.e., + and -) values. A categorical type of analysis may be more appropriate than the t-test used.

- The small sample size limits the level of detail in the analyses and precludes the examination of interaction terms.

- No consideration is given to other factors that might affect the study results, such as highway type and differences in design standards.

Citation:

Young, R. D., Post, E. R., Ross, H. E. Jr., and Holcomb, R. M., "Simulation of Vehicle Impact With the Texas Concrete Median Barrier, Volume I: Test Comparisons and Parameter Study", Research Report 140-5, Texas Transportation Institute, Texas A&M University System, College Station, Texas, June 1972.[28]

Study Purpose:

This report describes efforts to use the HVOSM program to simulate impacts with concrete safety shaped barriers for determination of impact severity under various impact conditions.

Research Approach:

The HVOSM program was used to simulate three full-scale crash tests of New Jersey shaped concrete barriers. The crash tests involved a 4,000-lb vehicle impacting the barrier at angles of 7, 15, and 25 degrees and 60 mi/h. The simulation was then used to predict barrier performance under other impact conditions.

Measures of simulation correlation with test results included acceleration time histories, height of climb, heading and roll angle time histories, barrier exit angle, and maximum vehicle roll angle.

Findings:

The HVOSM simulation program gave reasonably good predictions of peak accelerations for the two high angle impacts and generally the shapes of the acceleration curves corresponded with the curves generated during testing. Although not tabulated, other measures of simulation correlation with testing were reported to have been good. Simulated heading and roll angle time histories appear to give good predictions of vehicle motions when vehicle graphics are compared with sequential photos.

Simulations of other impact conditions indicated that full-size sedans weighing approximately 4,500 lb can sustain impacts with standard shaped concrete barriers at speeds up to 70 mi/h with little chance for vehicle rollover. For simulated impact conditions of 80 mi/h and impact angles of 15 degrees or more, vehicle rollover was predicted.

Critique:

Much of the vehicle data and barrier friction data used in the simulations is not reported thereby limiting the usefulness of the report. As expected, the simulation gave much better correlation for high impact angles than low impact angles. Problems with simulation of tire barrier interaction for low impact angles has been reported during simulation of curb impacts. These problems may have been addressed with McHenry's recent modifications to the HVOSM tire model.

Vehicle body hard points were added to the HVOSM model during this study to enable the simulation to accurately predict vehicle motions during impact with rigid barriers. Analysis of the HVOSM program code indicates a significant error in the procedure for calculating vehicle sheet metal/barrier interaction forces. This error may have been the source of initial problems with the simulation.

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APPENDIX B
RESULTS OF MANUAL CHECK ON TEXAS BARRIER ACCIDENT DATA FILE

A number of questions were raised during the preliminary analysis of the Texas barrier accident data file, concerning the accuracy in the identification of concrete median barriers and rollover involvements using the computerized accident data. An effort was undertaken to manually review hard copies of police accident reports on a small sample of highway sections with concrete median barriers as a check against the computerized accident data.

The San Antonio District of the Texas State Department of Highways and Public Transportation, which maintained a file of police accident reports on all accidents occurring on Interstates and freeways within San Antonio, was contacted for their assistance. Hard copies of all accident reports on urban Interstates and freeways during 1982 were borrowed from the District and reviewed. Two sections of Interstate highways with concrete median barriers, totaling 22.5 miles in length, were selected for this manual check effort.

The accident reports were first screened by matching the locations of median barrier accidents to those of the two selected highways sections with concrete median barriers. Each accident report with matched location was then reviewed manually by reading through the narrative and checking the sketch to determine if the accident actually involved a concrete median barrier.

The concrete median barrier accidents identified from the manual check were then compared to those from the computerized accident data file for accuracy and validity, especially on the correct identification of concrete median barriers and rollover involvements. The results from the manual checks are very interesting, but also very disturbing. Details of the results are presented as follows.

A total of 159 accidents involving CMBs were identified from the manual check for these two highway sections in 1982, 110 (69.2%) of which involved striking CMBs as the first harmful event (see table 13). In nine of these 110 accidents (8.2%), impact with another vehicle subsequent to the CMB impact was reported.

Impacts with CMBs in the remaining 49 accidents (30.8%) were secondary collisions, mostly subsequent to impacts with other vehicles (45 of 49 accidents or 91.8%). It is interesting to note that, in some previous studies, the number of scuff marks on barriers was compared to the number of reported barrier accidents and the difference was attributed to unreported accidents. Given the inability to identify secondary collisions from computerized police level accident data, it is conceivable that some of the differences between the number of scuff marks on the barriers and the number of reported barrier accidents are actually the result of secondary collisions and not unreported accidents.

Table 13. Results of manual check on concrete median barrier accidents

Impact with Concrete Median Barrier	Total Number of Accidents	Rollovers Number	Rollovers Percent
First Harmful Event			
Single Vehicle	101	14	13.9
Multi-Vehicle*	9	1	11.1
Subtotal	110	15	13.6
Secondary Collision			
Single Vehicle**	4	0	0.0
Multi-Vehicle***	45	6	13.3
Subtotal	49	6	12.2
Total	159	21	13.2

* Vehicle impacted concrete median barrier, then another vehicle.
** Vehicle struck another object, then concrete median barrier.
*** Vehicle struck another vehicle, then concrete median barrier.

The computerized accident data file identified only 58 accidents on these two highway sections in which impacting a CMB was the first harmful event, as compared to 110 such accidents from the manual check. Comparisons were then made between each of these 58 accidents identified from the computerized accident data file and hard copies of the 110 accident reports identified from the manual check by matching the date, time of day, and location of the accidents and, to a lesser extent, vehicle information.

The results of the comparisons showed that only 47 of the 58 accidents identified from the computerized data file were matched with hard copies of accident reports. No corresponding accident reports were found for the remaining 11 accidents. On the other hand, there were 63 CMB accidents with accident reports that were not included in the computerized accident data.

The biggest problem appears to be the incorrect use of terminology. For the 110 accident reports reviewed, 18 different names were used by the reporting officers to describe the CMB, as summarized in table 14. The term "guardrail" was used most frequently, either by itself or in conjunction with other descriptors, such as "concrete", "inner", "median", etc., in 44 of the 110 accidents (40.0%). Only 10 of these 44 accidents (22.7%) were correctly identified as median barrier accidents.

The term "wall" was used in 38 accidents (34.5%), again with various descriptors, such as "retaining", "divider", "median", etc. Over half (21 of 38 accidents or 55.3%) of these accidents were correctly identified as median barrier accidents. Overall, only 47 of the 110 accidents (42.7%) were correctly identified.

Data from the manual check showed that, of the 110 accidents in which impacting a CMB was the first harmful event, there were 15 rollovers for a rollover rate of 13.6 percent. In comparison, only 3 of the 58 accidents (5.2%) from the computerized data file were identified as rollovers using top damage to the vehicle as the surrogate for overturning.

Of the 49 accidents in which impacting a CMB was a secondary collision, there were 6 rollovers for a rollover rate of 12.2 percent. It appears that the potential for rollover does not change significantly for secondary impacts, although the sample size is really too small for any definitive conclusions.

For the 47 accidents that had matched accident reports to the computerized data records, three were identified as rollovers based on the vehicle damage rating. A review of the narrative and sketch of the accident reports identified three more rollovers for a total of six rollovers.

The problem is with incorrect coding of the vehicle damage rating or the TAD scale by the reporting officer. Of the six CMB accidents that resulted in rollovers, only two were correctly coded to indicate top damage to the vehicle. For the other four rollovers, two coded the damage from the primary impact with the barrier. One coded "RO" to presumably indicate rollover. However, this was not recognized by the transcribing clerk since

Table 14. Description of concrete median barrier in accident reports

Barrier Description	Total Number of Accident Reports	Matched Accidents Number	Matched Accidents Percent
Guardrail	28	3	10.7
Center Guardrail	2	1	50.0
Median Guardrail	2	0	0.0
Inner Guardrail	4	2	50.0
Concrete Guardrail	6	4	66.7
Guard	1	0	0.0
Guard Rail Protected Concrete Wall	1	0	0.0
Guardrail Total	44	10	22.7
Center Concrete Wall	7	3	42.9
Median Wall	12	8	66.7
West Wall	1	0	0.0
Retaining Wall	13	7	53.8
Divider Wall	5	3	60.0
Wall Total	38	21	55.3
Concrete Center Railing	3	1	33.3
Concrete Median	5	4	80.0
Cement Divider	8	5	62.5
Concrete Barrier	1	1	100.0
Center Median	10	5	50.0
Concrete Embankment	1	0	0.0
Other Total	28	16	57.1
Total	110	47	42.7

"RO" is not a valid vehicle damage rating code and was entered into the computerized data record as unknown. The remaining report did not have a vehicle damage rating; instead, the description of "totalled" was entered. Fortunately, the correct vehicle damage rating was entered by the transcribing clerk and rollover was correctly identified.

In fact, for the 15 rollover CMB accidents for which accident reports are available, only three were coded correctly. Six show coded damages from the primary impacts with the CMB; two are coded "RO" to presumably indicate rollover; two indicate "totalled"; one has "all over"; and one has the damage rating left blank. There is clearly a problem with the correct coding of the vehicle damage rating. In turn, the use of top damage to the vehicle as the surrogate for rollover when rollover is not the first harmful event or the primary impact is not a good or reliable measure.

There are other extenuating circumstances that could also have contributed to the incorrect identification of median barriers. The median barrier code was added to the list of objects struck in 1981. Some of the errors may be the result of unfamiliarity with the definition of median barrier by both the reporting officers and transcribing clerks. Also, the San Antonio Police Department uses an accident reporting form that is different from that used by the State Department of Public Safety. "Object Struck" is not actually coded on the accident report, but has to be ascertained from the narrative. This use of a nonstandard accident reporting form could also have contributed to the problem identified.

APPENDIX C
SUPPLEMENTAL DATA COLLECTION FOR TEXAS CMB ACCIDENT DATA FILE

Hard copies of police accident reports for the 1,964 accidents in the Texas CMB accident data file were requested from the Texas Department of Public Safety. The police accident reports were reviewed manually to:

1. Determine if the involved barrier was indeed a concrete median barrier.

2. Determine whether the vehicle rolled over after impact with the concrete median barrier.

3. Make sure that the police accident reports actually match with the computerized accident data by comparing selected identification data elements between the police accident reports and a listing from the computerized data file. The identification data elements used for the comparison included the accident report number, county where the accident occurred; and the year, month, day and time of the accident.

4. Collect supplemental data not available from the computerized accident data file, including impacts with the end or near the end of the median barrier, the impact sequence and whether the vehicle was spinning or skidding sideways prior to impact with the concrete median barrier.

A copy of the coding form and accompanying instructions used for this manual review are shown in this appendix.

ROLLOVER CAUSED BY CONCRETE SAFETY SHAPED BARRIER
CODING INSTRUCTIONS

Instructions for completing the coding form, an example of which is attached, are described herein. Each line or record pertains to one accident. There are eight data elements for each accident on the coding form, as follows:

- Accident Report Number
- Match
- Median Barrier
  - Barrier End
  - Impact Sequence
- Spinning/Skidding Sideways
  - Rolled Over
- Vehicle Identification Number

Space is also provided for comments on unusual or atypical conditions. If the space is insufficient for the comments, continue on the back of the page.

A listing of the accidents by the DPS accident report number is provided. The following information on each accident is also provided for matching purposes: County, and Month, Day, and Time of the Accident.

Code the eight entries for each accident, based on review of the police accident report. Of particular importance are the narrative description and sketch of the accident and vehicle damage ratings. Brief descriptions and coding instructions for the data elements are provided as follows.

Accident Report Number

The DPS accident report number. The accidents should be listed sequentially by year and by accident report number as in the listing for ease of retrieval.

Match

Does the information on County, and Month, Day, and Time of the accident match between the listing and the accident report? Note any discrepancy under Comments.

0 -- No
1 -- Yes
2 -- Accident report not available - driver self-reports

Median Barrier

Did the accident occur in the median and involve the median barrier? Is the median barrier a permanent or a temporary installation? A median is the area separating opposite directions of traffic on a divided roadway. Read the narrative description and check the sketch on the accident report.

0 -- No, Not a Median Barrier
1 -- Yes, Temporary Median Barrier
2 -- Yes, Permanent Median Barrier

Barrier End

Was the impact with the end or near the end of the median barrier? Read the narrative description and check the sketch on the accident report.

0 -- No, Impact Not With Barrier End
1 -- Yes, Impact With End of Barrier
2 -- Yes, Impact Near End of Barrier (Within 25 Feet)

Impact Sequence

Code the first four impacts in the accident chronologically, using the most appropriate code from the following list. Read the narrative description and check the sketch on the accident report. Also check the vehicle damage ratings and any entry on property damage.

0 -- None
1 -- Another Vehicle
2 -- Roadside Structure/Object Other Than Barrier
3 -- Median Barrier
4 -- Other Longitudinal Barrier
5 -- Rollover
6 -- Other
9 -- Unknown/Unsure

Spinning/Skidding Sideways

Was the vehicle spinning or skidding sideways prior to impact with the median barrier? Read the narrative description and check the sketch on the accident report. Also, check the vehicle damage ratings for indication of non-tracking impacts.

0 -- No
1 -- Yes
9 -- Unknown/Unsure

Rolled Over

Did the vehicle roll over after impact with the median barrier? A vehicle is considered as rolled over if, at any time during the accident sequence, the vehicle did not remain upright on its tires, e.g., on its side or top. Read the narrative description and check the sketch on the accident report. Also check the vehicle damage ratings for indication of rollover.

0 -- No
1 -- Yes
9 -- Unknown/Unsure

Vehicle Identification Number

Copy the vehicle identification number for the vehicle that struck the median barrier.

Accident Report No.	Match	Median Barrier	Barrier End	Impact Sequence				Spinning/ Skidding Sideways	Rolled Over	Vehicle Id. No.
				1	2	3	4			

APPENDIX D
SIMPLIFIED RECONSTRUCTION PROCEDURE

A simplified reconstruction procedure was developed for use in reconstructing the National Accident Sampling System (NASS) Longitudinal Barrier Special Study (LBSS) concrete median barrier (CMB) cases to estimate impact speeds. Brief descriptions of the conceptual framework and individual components of the procedure are presented herein. The procedure is based on the principle of conservation of energy, utilizing empirical relationships derived from full-scale crash test results. Also, the procedure uses some of the subroutines from the CRASH3 (Calspan Reconstruction of Accident Speeds on the Highway) program to reduce developmental effort. In fact, the CRASH3 program is used as the starting point for coding of the reconstruction procedure.

It should be borne in mind that, while every effort is made to assure that reasonable accuracy and validity is achieved, numerous assumptions and simplifications were made in the development of the procedure to keep it simple and inexpensive to use. Empirical relationships developed for use with the procedure are based on available data, including full-scale crash test data and results from other simulation models, such as HVOSM (Highway-Vehicle-Object Simulation Model). However, it is recognized that there are limitations associated with these data sources, e.g., full-scale crash tests are limited to a few impact conditions and vehicle types.

Conceptual Framework

The accident sequence is divided into two phases: impact and post-impact. The impact phase goes from the point of initial contact with the barrier to the point where the vehicle separates from the barrier. The post-impact phase goes from the point of separation to the point of final rest. The reconstruction procedure starts at the point of final rest. Vehicle speed at separation from the barrier is first estimated from the post-impact trajectory. The impact speed is then estimated based on the separation speed and the energy loss during the impact phase.

Post-impact trajectories are divided into two classes, rollover and nonrollover. For nonrollover cases, energy loss during the post-impact phase is strictly from the tire/pavement interactions and is estimated using the SPIN2 subroutine from the CRASH3 program. Factors such as coefficient of friction between the tires and pavement surface, distance traveled during the post-impact phase, percent braking, and amount of vehicle rotation are included in the calculation. The separation speed is then estimated by summing the total energy loss after impact and dividing it among rotational and translational velocities.

If rollover occurs during the post-impact phase, the speed at the start of rollover is estimated using empirical curves relating roll distance to roll speed. These curves, shown in figure 1, were developed by using HVOSM to simulate vehicle rollover accidents.[(1)] It should be noted that roll distance was found to be relatively unrelated to tripping mechanism.

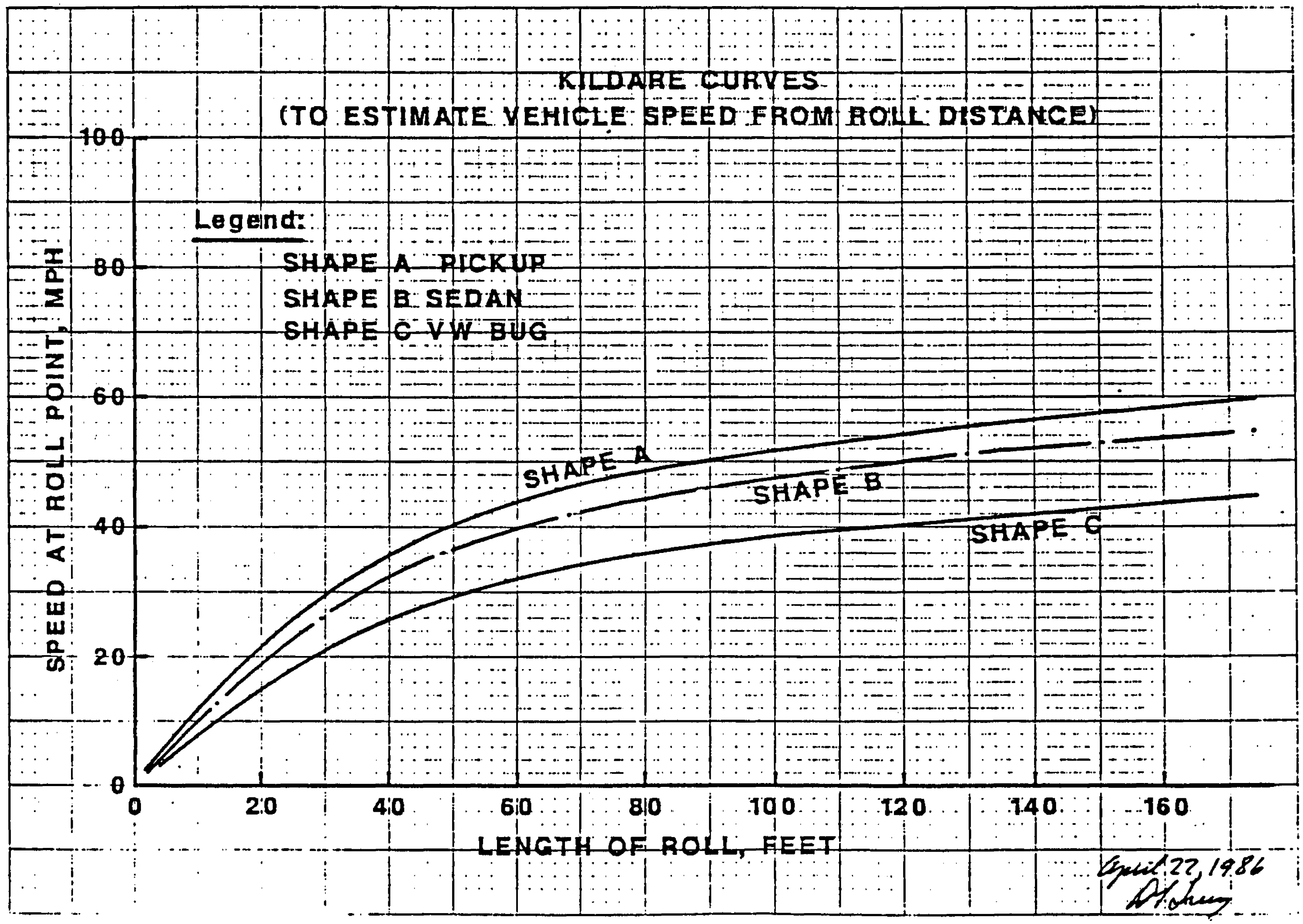

Figure 1. Curves developed by using HVOSM to simulate vehicle rollover accidents.

In other words, roll distance was not greatly affected whether high tire side forces were applied instantanously or tire side forces were applied slowly. The energy loss from the point of separation to the initiation of rollover is estimated using the SPIN2 subroutine. The roll speed and the trajectory energy loss are then combined to estimate separation speeds.

Energy loss during impact is broken into two components: vehicle crushing and frictional loss. It is assumed that no energy is absorbed by the rigid barrier. Further, frictional energy loss between tires and pavement surface is assumed to be negligible. These assumptions should be reasonably accurate when energy losses associated with vehicle crush and vehicle/barrier friction are compared to those associated with the barrier damage and tire frictions. Even for nontracking or rotating vehicles, tire frictional losses over short contact distances are not significant. However, when barrier contact occurs over long distances, these assumptions are suspect.

The amount of energy dissipated due to crushing of the vehicle sheet metal and structure is estimated using the DAMAGE subroutine of the CRASH3 program. This takes into account the size, weight, and stiffness of the vehicle and the damage dimensions sustained by the vehicle. The estimate should be reasonably accurate for most impacts since the damages tend to be in a vertical plane, i.e., relatively uniform crush.

The barrier/sheet metal frictional energy loss is a function of the normal force and the length of contact between the barrier and the vehicle. In turn, the normal force is a function of the impact speed and angle. This poses somewhat of a problem since impact speed is not known. In fact, impact speed is what we are trying to estimate with the reconstruction procedure. To resolve this problem, an iterative process using empirical relationships was developed.

Energy loss during impact is first assumed to be solely a function of vehicle sheet metal crushing. An initial estimate of vehicle kinetic energy at impact is then obtained by summing the vehicle's kinetic energy at separation with crush energy. Impact speed can then be estimated by assuming that most of the kinetic energy at impact is associated with translational velocity.

Frictional energy losses are then be estimated by calculating average lateral accelerations during impact and multiplying by the weight of the impacting vehicle and the length of barrier contact. Average lateral accelerations are calculated from an equation presented by Olson as shown below:[2]

$$G_{lat} = \frac{V^2 \sin^2 \Theta}{2g(AL\sin\Theta - B(1 - \cos\Theta) + D)}$$

where G_{lat} = Average lateral acceleration (ft/sec^2)

V = Vehicle impact velocity (ft/sec)

0 = Vehicle impact angle (deg)

g = Acceleration due to gravity (ft/sec^2)

AL = Distance from vehicle's front end to center of mass (ft)

B = 1/2 vehicle width (ft)

D = Effective lateral displacement of barrier (ft)

The average lateral acceleration is related to frictional force by the coefficient of friction between the barrier and the vehicle sheet metal. The coefficient of friction was estimated by comparing predictions of the impact phase of the reconstruction procedure to full-scale crash test results. Figure 2 shows a plot of measured versus predicted frictional energy losses. As shown in this figure, the predicted values correlated reasonably well with crash test results and the findings corresponded with a coefficient of friction of approximately 0.8. The correlation equation shown in figure 2 was incorporated into the reconstruction procedure rather than a coefficient of friction in the interest of maintaining as much accuracy as possible.

After a revised estimate of impact energy dissipation is obtained by summing calculated frictional and vehicle crush energy, a new impact speed is calculated in the same manner as before. The revised impact speed is then used to calculate new frictional energy dissipation and the process is iterated until the impact velocity converges.

Validation of the reconstruction procedure involved comparing measured impact velocity to impact velocities predicted for four full-scale CMB crash tests from reference.[3] Note that all of these tests involved relatively small cars and moderate impact angles. As shown in table 15, the reconstruction procedure accurately predicted impact speeds for most of the crash tests. The average percent difference in velocity change (delta V) between the test and reconstruction results is roughly 13 percent, with a range from 2.9 to 24.8 percent. If one looks at the difference in the actual delta V, the difference ranges from 0.2 to 3.3 mi/h, which is rather small considering an impact speed of 60 mi/h. The trajectory portion of the reconstruction procedure, which is unchanged from the CRASH3 program, plays a much more critical role in the accuracy of the impact speed estimation than the reconstruction phase. Overall, the validation results were considered satisfactory given the simplified nature of the reconstruction procedure.

Reconstruction Procedure

A brief descriptions of the individual steps of the reconstruction procedure, based on the framework discussed above, are presented in this section a schematic diagram illustrating the key steps and components of

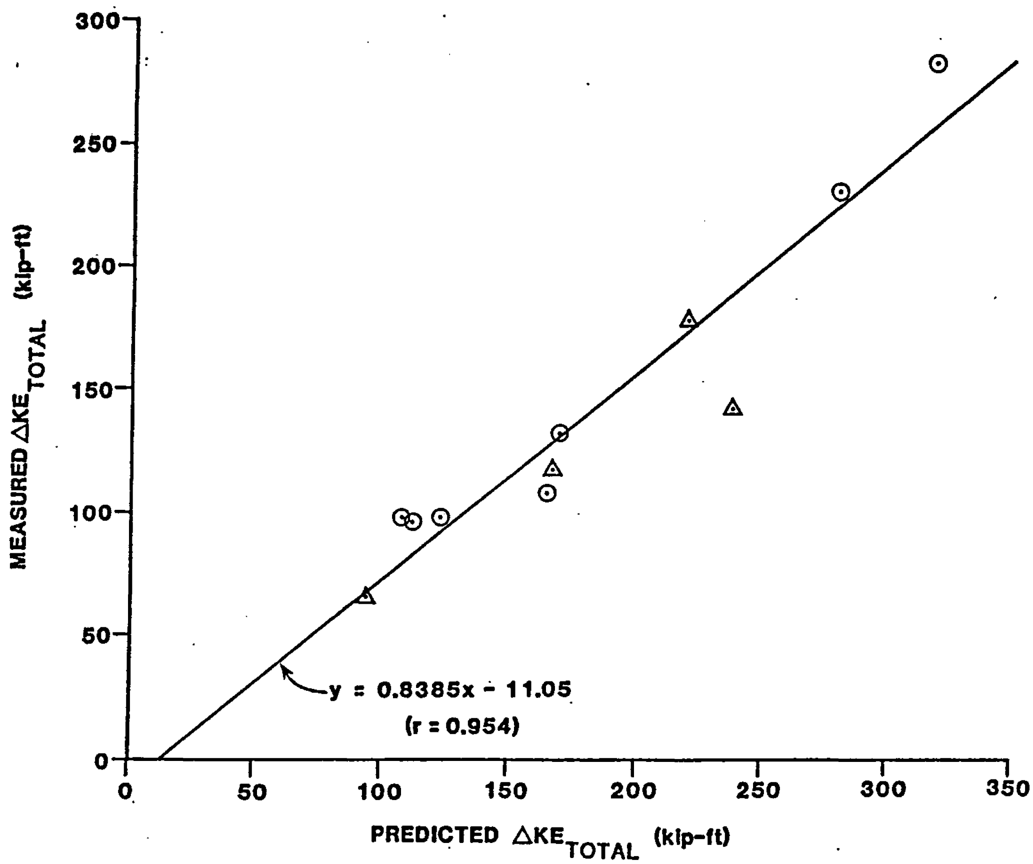

Figure 2. Measured vs. predicted frictional energy losses.

Table 15. Summary of validation results.

Test No.	Crash Test Results: Impact Speed (mi/h)	Crash Test Results: Exit Speed (mi/h)	Crash Test Results: ΔV (mi/h)	Reconstruction Results: Impact Speed (mi/h)	Reconstruction Results: Exit Speed (mi/h)	Reconstruction Results: ΔV (mi/h)	% Difference* ΔV
7043-1	58.4	51.6	6.8	58.8	51.8	7.0	2.9
7043-2	59.9	46.6	13.3	56.9	46.9	10.0	-24.8
7043-3	60.0	53.2	6.8	60.4	53.1	7.3	7.4
7043-4	61.6	56.2	5.4	62.5	56.2	6.3	16.7

$$* \quad \% \text{ Difference} = \frac{\Delta V_{Reconstruction} - \Delta V_{Test}}{\Delta V_{Test}} \times 100\%$$

the procedure is shown as figure 3:

1. The reconstruction starts with a check on whether the vehicle rolled over or not during the post-impact phase.

2. If no rollover occurs, the separation speed, V_s, is determined using the SPIN2 subroutine from the CRASH3 program.

3. If rollover occurs, the roll speed, V_r, at the initiation of rollover, is determined from the roll distance, S_r, using an empirical relationship as shown in figure 1. Separation speed is then determined by combining the roll speed with the trajectory energy loss from the point of initiation of rollover to the point of separation.

4. Energy loss due to vehicle crushing, KE_v, is estimated using the DAMAGE subroutine from the CRASH3 program.

5. An initial estimate of the total energy loss during the impact phase, $KE_t(0)$, is approximated as being equal to the energy loss due to vehicle crushing.

6. An initial estimate of the impact speed, $V_i(0)$, is calculated from the total energy loss during the impact phase and the separation speed,

$$KE_t(0) = \frac{1}{2} M_v \left(V_i(0)^2 - V_s^2\right) \quad (1)$$

or

$$V_i(0) = V_s^2 + \frac{2\,KE_t(0)}{M_v} \quad (2)$$

where M_v = Mass of impacting vehicle.

7. An iterative process is introduced and continues until convergence in the estimate for total energy loss during impact phase is attained. Steps for the first iteration are shown as follows. The frictional energy loss is calculated as a function of the average lateral acceleration, the vehicle mass, and the length of contact between the vehicle and the barrier, S_i,

$$KE_f(1) = M_v\, G_{lat}(1)\, S_i \quad (3)$$

Average acceleration is calculated based on estimated initial impact conditions as shown below,

$$G_{lat} = \frac{V^2 \sin^2\theta}{2g(AL\sin\theta - B(1 - \cos\theta) + D)} \quad (4)$$

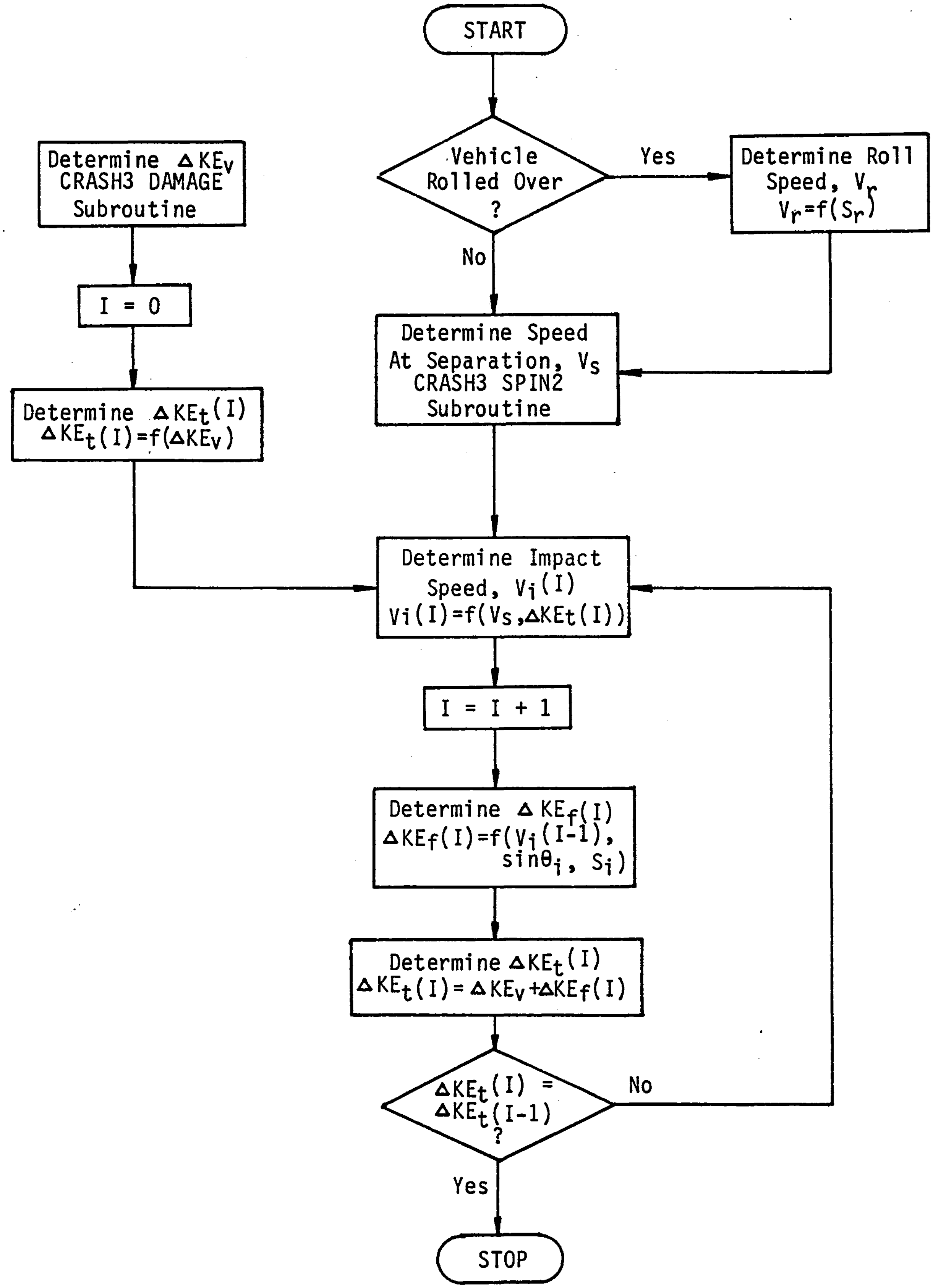

Figure 3. Schematic diagram of simplified reconstruction procedure.

Frictional energy loss is then adjusted according to the empirically determined equation shown below,

$$KE_f(1) = 0.8385 * KE_f(1) - 11050 \qquad (5)$$

8. A revised estimate of total energy loss, $KE_t(1)$, is calculated by summing the energy losses from friction and vehicle crushing,

$$KE_t(1) = KE_f(1) + KE_v \qquad (6)$$

9. The revised estimate of total energy loss, $KE_t(1)$, is compared to that of the initial estimate, $KE_t(0)$. If the two estimates are the same or within acceptable limits, the initial impact speed estimate, $V_i(0)$, is considered correct and the program is terminated. If the two estimates are different, a revised impact speed, $V_i(1)$, is calculated using the revised estimate of total energy loss, $KE_t(1)$. The process described in steps (7) through (9) is repeated for the second iteration and will continue until convergence is attained in the estimate of total energy loss. For subsequent iterations, simply replace (1) with (I) and (0) with (I-1) in all the calculations. The general forms of the equations are shown as follows:

$$V_i(I-1) = V_s^2 + \frac{2\ KE_t(I-1)}{M_v} \qquad (2a)$$

$$G_{lat} = \frac{V^2 \sin^2 O}{2g(AL\sin O - B(1 - \cos O) + D)} \qquad (4a)$$

$$KE_f(I) = M_v\ Glat(I)\ S_i \qquad (3a)$$

$$KE_f(I) = 0.8385 * KE_f(I) - 11050 \qquad (5a)$$

$$KE_t(I) = KE_f(I) + KE_v \qquad (6a)$$

APPENDIX E
QUALITY REVIEW OF NASS LBSS ACCIDENT CASES

Summary of Assessment

One of the data files used in the accident studies was the National Accident Sampling System (NASS) Longitudinal Barrier Special Study (LBSS) data file. A total of 130 NASS LBSS cases involving impacts with concrete safety shaped barriers were identified and hard copies of these cases were provided to the project staff by FHWA for analysis.

Each case was first reviewed by a member of the project staff and reconstructed, if possible, to estimate the vehicle impact speed with the barrier. All cases resulting in vehicle rollovers (a total of 31) were clinically analyzed in-depth in an effort to identify factors that may have contributed to the rollover.

Based on the general review of all 130 cases and in-depth analysis of the 31 cases involving rollovers, an assessment was made by the project staff concerning the quality of the NASS LBSS cases.

Comments

- The quality of the data varies greatly among Primary Sampling Units (PSUs) and among investigators within individual PSUs. A few of the cases should not have been accepted for inclusion into the data base. For example, one case had the wrong accident scene documented and the error was noted by the Zone Center. In another case, the investigator wrote on the data form that he was not paid enough to go out into the traffic to collect the data. Nevertheless, both cases were still included in the data file, even though they are probably invalid and of no use.

- A considerable proportion of the cases involved impacts with other vehicles or fixed objects prior to impact with the barrier. Such accident cases are usually more difficult to analyze and of little value as far as evaluation of barrier performance is concerned.

- The reproduced copies of the cases are generally of poor quality. There are frequently missing pages and some of the copies are not legible. The slides are not numbered, making it difficult to use with the slide indices. The slide indices in many cases are too general to be of aid in identify the slides.

- Some useful information is deleted due to sanitization, including the police accident report and description of accident sequence by the driver.

- The scene diagram is the only source of information indicating the vehicle dynamics and trajectory. Reconstruction of accidents without this is not possible. Police sketches on the accident reports would be helpful, if available. The following problem areas are noted with the scene diagrams:

- Diagrams are not to scale, thus necessitating the preparation of scaled scene diagrams prior to reconstruction.

- Pre-crash travel of the vehicle is either omitted or not depicted incorrectly.

- The final rest position of the vehicle is either identified incorrectly.

- Dynamics of the vehicle are incorrect.

- Scene measurements are not made with proper technique. This becomes a problem when roadway geometric information is needed, e.g., horizontal curvature.

- The quality of the photographs varies greatly from case to case. Some of the problems noted with the photography are as follows:

  - The slide index is too general e.g. slides 1 through 10 show path of vehicle.

  - Lack of reference points, such as station markings complicate matching photographs to the scene.

  - Coverage of vehicle damage is frequently insufficient. Vehicles are often photographed inside a garage or junk yard which does not provide sufficient space for the needed camera angles. Investigators may not be able to recognize what photographic coverage is important.

- Vehicle damage data has the following short comings:

  - Crush measurements is lacking on rollover.

  - Crush measurements are lacking or incorrect in cases with masking damages, i.e., two or more impacts in same area.

  - Collision Deformation Classification (CDC) is incorrectly coded. Similar problem exists for the Principal Direction of Force (PDOF).

Discussions

It appears that because PSU investigators and Zone Center personnel lack are trained principally in data collection and not accident investigation they lack sufficient experience and expertise on barrier accidents, particularly in the area of accident dynamics and angle measurements. This is to be expected given the setup and direction of the NASS program.

However, part of the problem also lies with the individual investigators and the quality control process. It is evident from reviewing the cases that some of the investigators spent the necessary effort to think through the accident dynamics, drew a good scene diagram, and gave a good effort in measuring or estimating the angles. On the other hand, there were other investigators that simply filled out the forms with little thought given to the quality of the data.

The quality control, or lack thereof, is very disappointing. Some of the cases should not have been accepted for inclusion into the data base, such as the case with the wrong accident scene or the case in which the investigator refused to collect the data. Obvious the errors with the dynamics and angle measurements should have been detected in the quality control process. On the other hand, there are cases in which the Zone Center changed the angles by some negligible amount, such as one degree, which is beyond the level of accuracy that can be reasonably expected. (In that case the angles were actually way off from the correct values).

The poor quality found with some of the NASS LBSS cases raised concern with FHWA and, at its request, a quality review was conducted on the remaining non-rollover cases. A coding form and accompanying instructions were developed for this quality review process. A clinical analysis of the non-rollover accidents was also conducted at the same time to determine why rollover did not occur in these cases, especially those with impact conditions similar to those identified as contributory to rollover.

A copy of the coding form and accompanying instructions is attached to this appendix. The results of the quality review were compiled and entered into a Lotus data file for analysis on microcomputers.

C M B CASE REVIEW FORM

IDENTIFICATION

Year of Accident __ __

PSU __ __

Case Number __ __ __ __

Investigator __

GENERAL INFORMATION

Roadway Type __ __

First digit of variable pertains to land use and second digit pertains to roadway function class

Land Use	Roadway Function Class
(1) Urban	(1) Principal arterial - Interstate
(2) Rural	(2) Principal arterial - Other urban freeway or expressway
(9) Unknown	(3) Principal arterial - Other
	(4) Minor arterial
	(5) Urban collector
	(6) Major rural collector
	(7) Minor rural collector
	(8) Local road or street
	(9) Unknown

Barrier Type __

(1) Median barrier, NJ Shape
(2) Median barrier, GM Shape
(3) Roadside barrier, NJ shape
(4) Roadside barrier, GM shape

Barrier Location __

(1) Median
(2) Roadside
(3) Ramp
(4) Other

Vehicle Year __ __

(99) Unknown

Vehicle Make __ __

____

Vehicle Model __ __

____

Vehicle Curb Weight __ __ __

(001) Less than 150 pounds
(997) 99,650 pounds or more
(999) Unknown

CMB Review Form

OVERALL QUALITY ASSESSMENT

Overall quality assessment portion of the form pertains to the entire case and needs to be completed only once for each case.

Scene Diagram	poor		average		excellent	
Pre-Crash Travel	1	2	3	4	5	___
Impact Configuration	1	2	3	4	5	___
Impact Sequence	1	2	3	4	5	___
Post-Impact Trajectory	1	2	3	4	5	___
Final Rest Position	1	2	3	4	5	___

Comments ____

____

Photography	poor		average		excellent	
Accident Site	1	2	3	4	5	___
Barrier Damage	1	2	3	4	5	___
Vehicle Damage	1	2	3	4	5	___
Slide Index	1	2	3	4	5	___

Comments ____

____

Reproduction	poor		average		excellent	
Forms	1	2	3	4	5	___
Slides	1	2	3	4	5	___

Comments ____

____

Overall Quality	poor		average		excellent	
CSS Forms	1	2	3	4	5	___

Comments ____

____

CMB Review Form

OVERALL QUALITY ASSESSMENT (Continued)

Overall Quality	poor		average		excellent	
LBSS Form						
Impact Sequence	1	2	3	4	5	___
Longitudinal Barrier Characteristics	1	2	3	4	5	___
Roadside Data	1	2	3	4	5	___
Impact and Trajectory Data	1	2	3	4	5	___

Comments ____

____

CMB Review Form

SPECIFIC QUALITY ASSESSMENT

Specific quality assessment portion of the form pertains to individual impacts and needs to be completed once for each barrier impact.

For each data element being assessed, the coded value is first shown. The reviewer then indicates agreement or disagreement with the coded value:

(0) Disagree
(1) Agree
(9) Unsure/Insufficient information

If the reviewer disagrees (code = 0) with the coded value, a revised value will be given. If the reviewer agrees with or is unsure about (code = 1 or 9) the coded value, the revised value will be coded as not applicable (N/A).

Impact Number _ _

Vehicle Damage Data	Coded	Agree/ Disagree	Revised
CDC	_ _ _ _ _ _ _	_	_ _ _ _ _ _ _
PDOF	_ _ _	_	_ _ _
Barrier Damage Data			
Length of Contact/Damage	_ _ _	_	_ _ _

Comments ____

____

Impact and Trajectory Data	Coded	Rating	Agree/ Disagree	Revised
Impact Angle	_ _	_	_	_ _
Vehicle Yawing at Impact	_ _ _	_	_	_ _ _
Separation Angle	_ _	_	_	_ _
Vehicle Separation to Final Rest Distance	_ _ _	_	_	_ _ _
Rollover	_		_	_

Comments ____

____

CMB Review Form

IMPACT SPEED RECONSTRUCTION

Impact Speed (mph) __ __

(97) 97 mph or higher
(99) No reconstruction

Reason for No Reconstruction __

(0) Not applicable
(1) Missing scene diagram
(2) Missing/incorrect final rest position
(3) Missing/incorrect vehicle damage data
(4) Non-passenger vehicle
(5) Other

Confidence Level __

(0) Not applicable
(1) None
(2) Low
(3) Fair
(4) Good
(5) Excellent

Reason for Poor Confidence __

(0) Not applicable
(1) Poor scene diagram
(2) Questionable final rest position
(3) Questionable vehicle Trajectory
(4) Questionable vehicle damage data
(5) Poor photographic documentation
(6) Other

Comments ____________________

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Clinical Review ____________________

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CODING INSTRUCTIONS FOR CMB CASE REVIEW FORM

Identification

Year of Accident - Code last two digits of the year of the accident, e.g., 1982 is coded as 82.

PSU - Enter number of Primary Sampling Unit (PSU).

Case Number - Enter case number. Note that the combination of year of accident, PSU number and case number provide an unique identification for each case.

Investigator - Enter the number of the investigator that investigated and completed the case.

General Information

Roadway Type - This variable is a combination of two data items. The first digit of the variable pertains to land use and the second digit pertains to the roadway function class.

Land Use - Same as CSS data item A20.

(1) Urban
(2) Rural
(9) Unknown

Roadway Function Class - Same as CSS data item A23.

(1) Principal arterial - interstate
(2) Principal arterial - other urban freeway or expressway
(3) Principal arterial - other
(4) Minor arterial
(5) Urban Collector
(6) Major rural collector
(7) Minor rural collector
(8) Local road or street
(9) Unknown

Barrier Type - Enter the appropriate code for the barrier type.

(1) Median barrier, NJ shape
(2) Median barrier, GM shape
(3) Roadside barrier, NJ shape
(4) Roadside barrier, GM shape

Barrier Location - Enter the most appropriate code for barrier location.

(1) Median
(2) Roadside
(3) Ramp
(4) Other

Coding Instructions

Vehicle Year - Same as CSS data item V11. Enter last two digits of model year.

Vehicle Make - Same as CSS data item V12. Refer to CSS Coding and Editing Manual for appropriate codes.

Vehicle Model - Same as CSS data item V13. Refer to CSS Coding and Editing Manual for appropriate codes.

Vehicle Curb Weight - Same as CSS data item V75. Code weight to nearest 100 pounds.

(001) Less than 150 pounds
(997) 99,650 pounds or more
(999) Unknown

Overall Quality Assessment

Subjective assessment on the quality of the following items is to be made, using a simple ordinal scale of 1 (poor) to 5 (excellent). This portion of the form pertains to the entire case and needs to be completed only once for each case.

- Scene Diagram

  Pre-crash travel
  Impact configuration
  Impact sequence
  Post-impact trajectory
  Final rest

- Photography

  Accident site
  Barrier damage
  Vehicle damage
  Slide index

- Reproduction

  Forms
  Slides

- Overall quality

    CSS forms
    LBSS form
      Impact sequence
      Longitudinal barrier characteristics
      Roadside data
      Impact and trajectory data

Coding Instructions

For all items rated as below average, i.e., rating of 1 or 2, comments on the problem or deficiency should be provided in the space provided.

Scene diagram - Assessment of the scene diagram is based primarily on its utility in reconstructing the accident. The criteria to be considered in making this subjective assessment include such questions as:

- Is the sequence of events portrayed in the scene diagram logical, reasonable, complete and accurate?
- Is the information provided in the scene diagram consistent with other available sources of information, e.g., photographic evidence, scene evidence, barrier and vehicle damage data, etc.?
- Is the information well presented, e.g., scale drawing, annotation of key features, etc., to allow for determination and checking of specific data items, such as angles and distances?

A rating of 1 (very poor) would indicate gross errors in many data items so that reconstruction of the accident is not possible or no confidence can be attached to the reconstruction. A rating of 2 (poor) would indicate a few gross errors and/or many minor errors so that the results of the reconstruction would be somewhat questionable. A rating of 3 (average) would indicate some minor errors and the reconstruction is acceptable. A rating of 4 (good) would indicate very few errors and much confidence can be attached to the reconstruction. A rating of 5 (excellent) would indicate no errors and great confidence can be attached to the reconstruction.

The quality of presentation could move the rating up or down one point. For example, a rating of 4 based on accuracy alone may be upgraded to 5 for an excellent presentation or downgraded to a rating of 3 for very poor presentation.

Photography - Assessment of the quality of the photography is again based primarily on its utility for reconstructing the accident. The criteria to be considered in making this subjective assessment include such questions as:

- Are all evidence properly documented with photographs?
- What is the quality of the photographs?
- Are the photographs properly indexed for easy reference?

The ratings would reflect primarily the quality of the documentation of evidence. The quality of the photographs and indexing is secondary and may move the rating up or down one point as appropriate.

Reproduction - Assessment on the reproduction of the case, including such consideration as legibility of the copies and photographs, missing forms or pages, etc.

Coding Instructions

Overall Quality - An overall subjective assessment of the quality of the case.

A rating of 1 (very poor) would indicate gross errors in many data items and no confidence in the data. A rating of 2 (poor) would indicate a few gross errors and/or many minor errors and questionable confidence in the data. A rating of 3 (average) would indicate some minor errors and an acceptable case. A rating of 4 (good) would indicate very few errors and good confidence in the data. A rating of 5 (excellent) would indicate no errors and great confidence in the data.

Specific Quality Assessment

Assessment on specific data items pertaining to the impact and trajectory of each barrier impact is to be made. This portion of the form pertains to individual impacts and needs to be completed once for each barrier impact.

For each data item, the coded value (as it appears in the computerized data file) and the confidence level on the field measurement (as coded by Zone Center personnel when applicable) are given first, followed by an indication of whether the reviewer agrees or disagrees with the coded value:

(0) Disagree
(1) Agree
(9) Unsure/Insufficient information

If the reviewer disagrees (code = 0) with the coded value, a revised value will be given. If the reviewer agrees with or is unsure about (code = 1 or 9) the coded value, the revised value will be coded as not applicable (N/A).

These specific data items to be assessed are as follows:

- Vehicle damage data

  Collision Deformation Classification (CDC)
  Principal direction of force

- Barrier damage data

  Length of Direct Contact/Damage (LBSS Data Item B60)

- Impact and trajectory data

  Impact angle (LBSS Data Items B62 and B71)
  Vehicle yawing angle at impact (LBSS Data Items B63 and B72)
  Separation angle (LBSS Data Items B65 and B73)
  Vehicle separation to final rest distance (LBSS Data Item B74)
  Rollover (LBSS Data Item B69)

Coding Instructions

Impact speed reconstruction

Impact speed - Enter the reconstructed impact speed for each barrier impact in miles per hour. Code 99 if reconstruction of the impact is not conducted and enter the most important reason for why no reconstruction is conducted in the space provided.

Confidence level - Enter the confidence level associated with the reconstruction, using an ordinal scale of 1 (none) to 5 (excellent). Code 0 (not applicable) if no reconstruction is conducted for the impact. If the confidence level rating is 1 (none) or 2 (low), enter the most important reason for this lack of confidence in the space provided.

Reason for no reconstruction - Enter the most important reason for why no reconstruction is conducted.
(0) Not applicable
(1) Missing scene diagram
(2) Missing/incorrect final rest position
(3) Missing/incorrect vehicle damage data
(4) Non-passenger vehicle
(5) Other

Reason for poor confidence - If the confidence level rating is 1 (none) or 2 (low), enter the most important reason for this lack of confidence.
(0) Not applicable
(1) Poor scene diagram
(2) Questionable final rest position
(3) Questionable trajectory
(4) Questionable vehicle damage data
(5) Poor photographic documentation
(6) Other

APPENDIX F. MODIFICATIONS TO HVOSM

This Appendix contains a synopsis of corrections and modifications to the RD2 version of the HVOSM computer program made during research efforts described in reference 1. In the interest of completeness, descriptions of the modification effort are reprinted here in a slightly condensed form. Comprehensive details of the changes and modifications can be found in reference 2.

1. Improvements to Sprung-Mass-Impact Routines

1.1 Existing Model and Errors Therein

Model for the Crush of the Vehicle Structure. In HVOSM, the vehicle sprung mass is treated as a rigid mass surrounded by a layer of isotropic, homogeneous material which exhibits plastic behavior. As shown in figure 4, the dynamic pressure of the plastic flow process in the peripheral layer of material is assumed to increase linearly with the depth of penetration.(3) With these assumptions, the force F_N normal to the contact interface with an obstacle is given by,

$$F_N = k_v \int \delta dA \qquad \qquad (1)$$

where A is the contact area as illustrated in figure 5. Even though equation 1 is found in HVSOM documentation to describe the crush model, a careful review of the method of evaluation of F revealed that equation 2 below is followed rather than equation 1.(3)

$$F_N = k_v \int A d\delta \qquad \qquad (2)$$

It should be noted that equation 2 would give the same result as equation 1 if the area A is selected such that it is always perpendicular to the crushing direction.

Method Used to Find the Normal and Tangential Forces at the Contact Area. To find the impact forces at time t_i, the program allows the vehicle to move during the period t_{i-1} to t_i with the contact force at t_{i-1}. The barrier is also assumed to move with the vehicle but without rotation as shown in figure 6. Then the barrier is moved to its actual position in a number of steps, and the contact area and deformation at each of these steps are multiplied to find the integral $\int A d\delta$, which is converted to a force by multiplying with k_v.

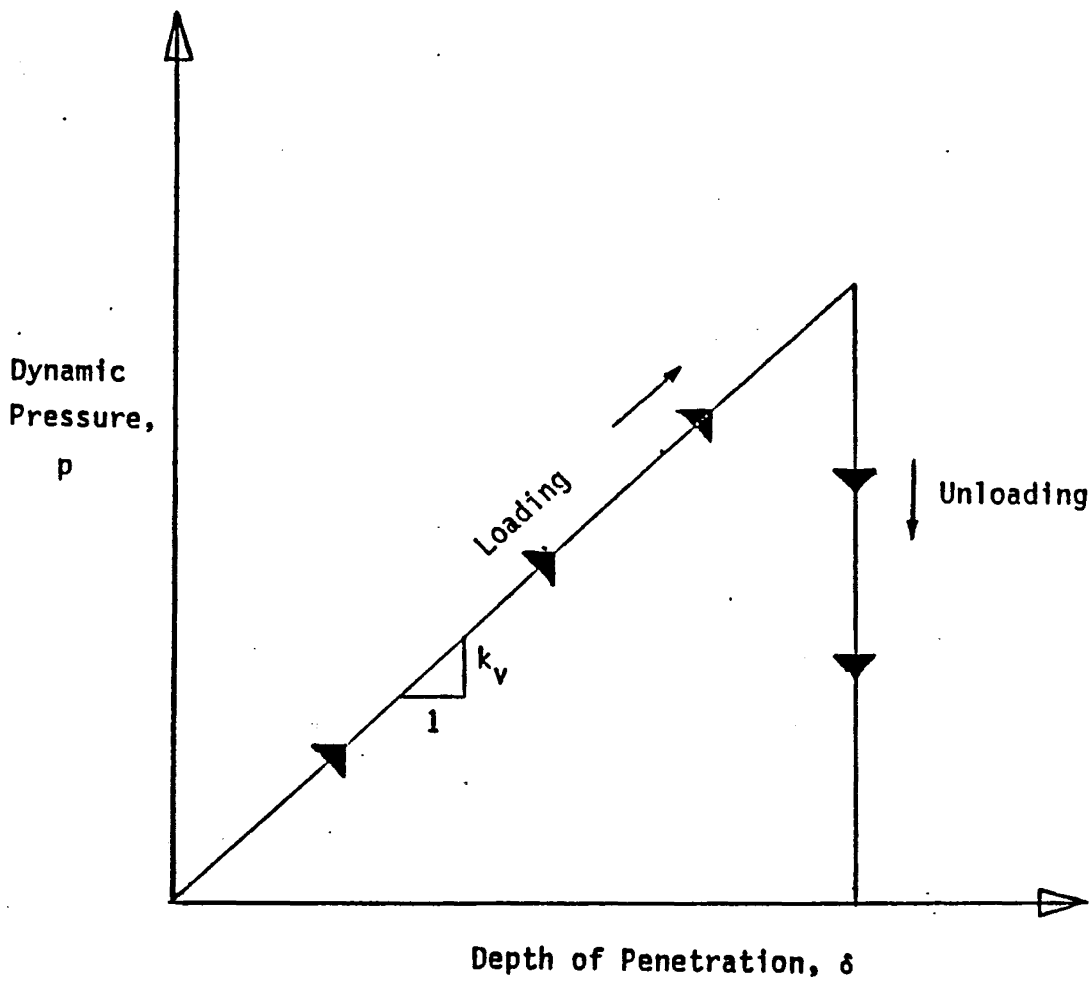


Figure 4. Existing HVOSM mathematical model for collision properties of vehicle periphery.

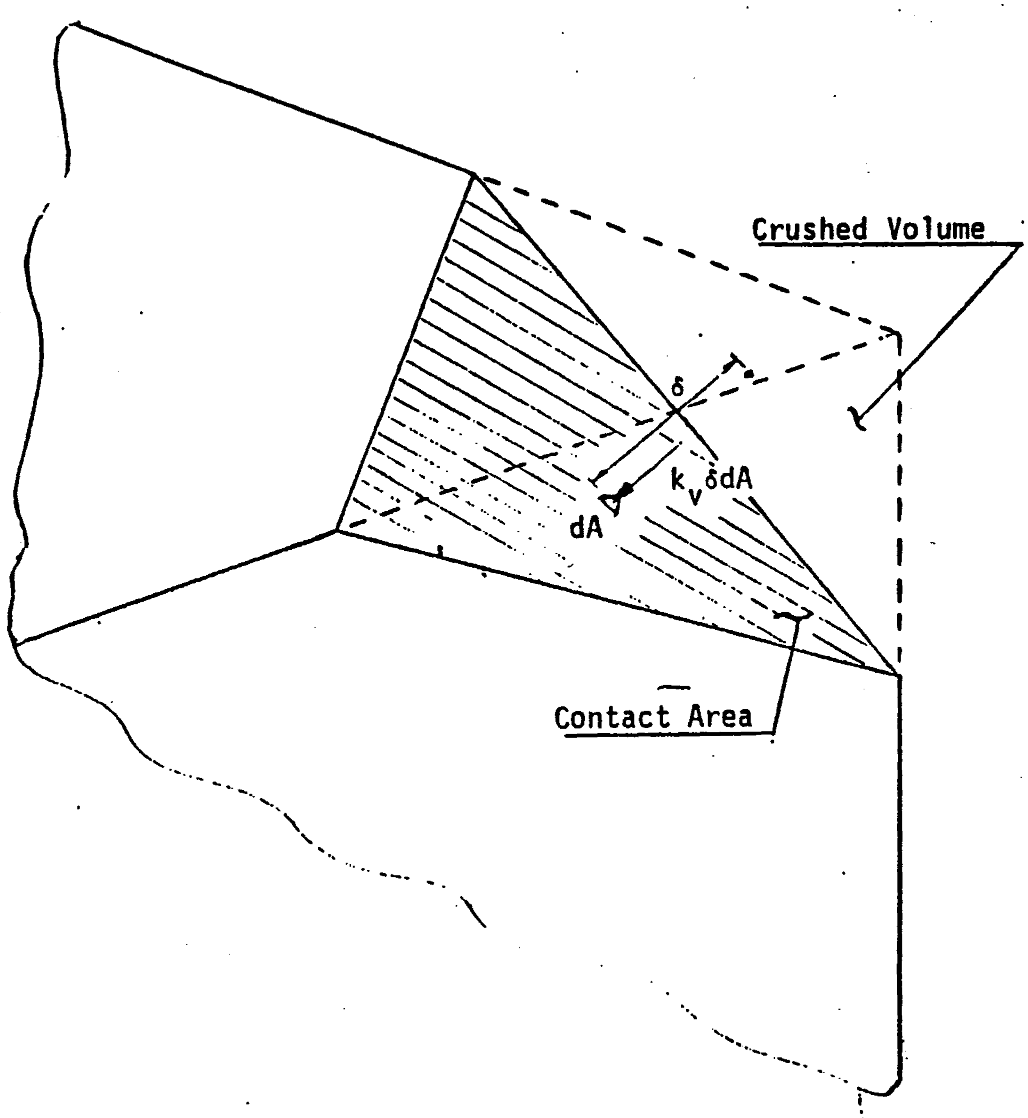


Figure 5. Force intensity due to the crush of the vehicle periphery.

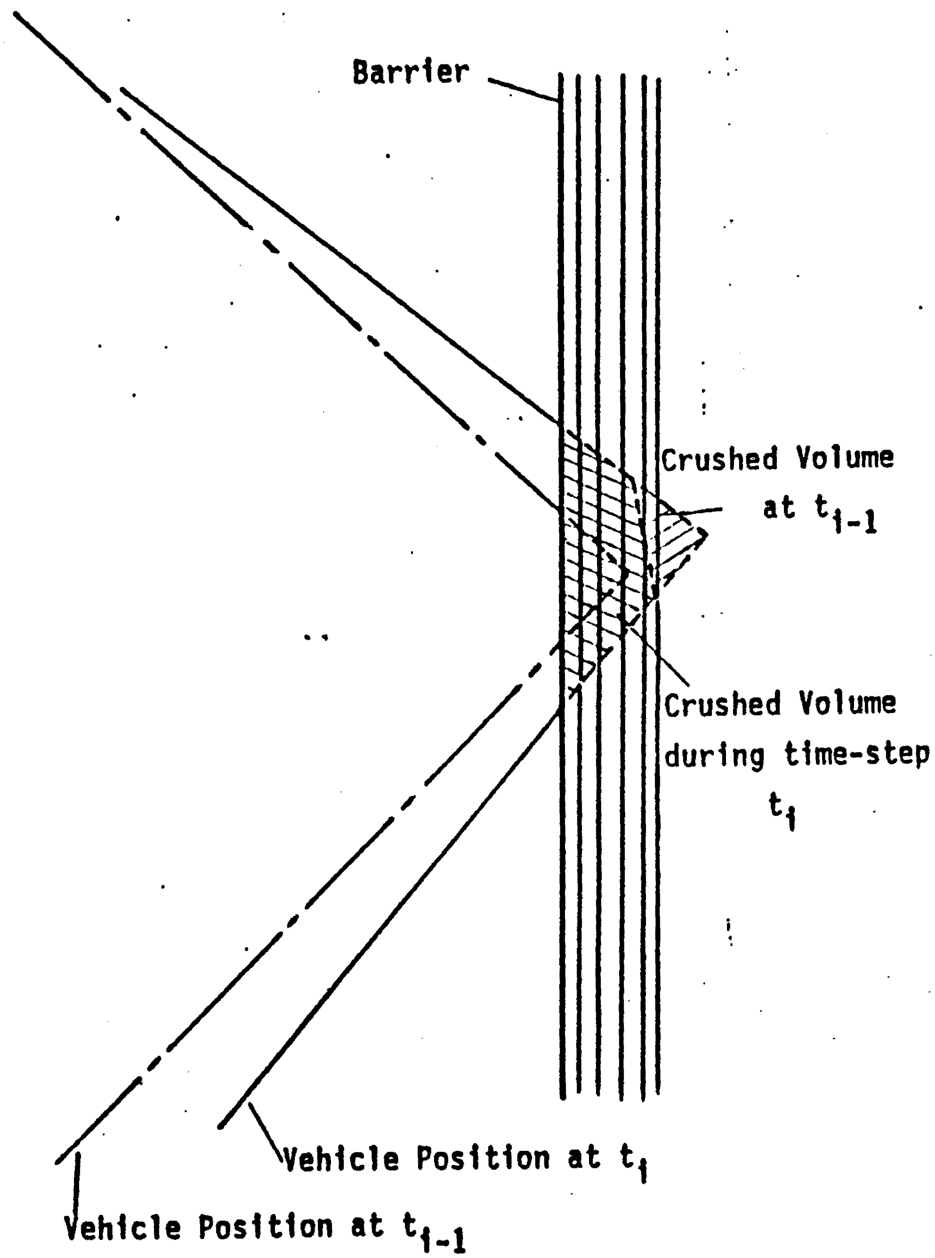


Figure 6. Existing method for the determination of crushing force by slicing the crushed volume.

The point of action of each of these forces is taken to be the centroid of each contact area. Then the total normal force increment during t_{i-1} to t_i is the resultant of these forces. Tangential friction force is also found by multiplying the normal force by a friction coefficient, assuming slip occurs. When the tangential velocity of the vehicle relative to the barrier at the point of action of the normal force is less than a very small value ϵ_v, the friction force is assumed to be zero.

Errors in the Existing Method. Force vs. crush results of frontal crash tests performed by NHTSA showed that dynamic pressure at the vehicle barrier interface depends not only on deformation, but also on deformation rate.(4) In other words, the damping characteristics of the vehicle body also have a considerable contribution to the interface force.

In addition to the shortcoming of the existing crush model in HVOSM mentioned above, the method used to determine the force F has the following limitations:

(a) Equation 2 gives the same result as equation 1 only if the vehicle is moving perpendicular to the barrier without any rotation. In most barrier impacts the vehicle rotates.

(b) The possibility of a frictional moment due to the relative rotation of the vehicle with respect to the barrier is not considered.

(c) When the contact area decreases in going from t_{i-1} to t_i, either due to the vehicle sheet metal going over a finite barrier or due to the rotation of the vehicle around a line passing through the contact area at t_{i-1}, the force F_N at t_{i-1} will not fully contribute to the force F_N at t_i. It is impossible to account for this reduction with the existing method.

1.2 Modifications

Limitations "a" and "b" mentioned above can be overcome by changes to the existing method of finding the interface force. However, the last limitation cannot be overcome within the present formulation and integration procedures of HVOSM.

Furthermore, to simulate a sloped concrete barrier, HVOSM should be capable of analyzing a multifaced barrier instead of just a vertical wall as presently assumed. However, the limitations mentioned above also preclude this modification within the present formulation.

Based on these findings the following objectives were set forth for the development of a method of analysis and an improved set of sprung-mass-impact subroutines for HVOSM for the simulation of vehicular impacts with rigid barriers.

(a) Develop a general crush model which accounts for the effects of both the deformation and deformation rate of the vehicle body on the vehicle barrier interface force.

(b) Develop a method for determination of the interface force according the new crush model.

(c) Modify the sprung-mass-impact subroutines of HVOSM to simulate a multifaced, fixed barrier according to the new crush model and using the new force determination method.

(d) Validate the modified program using closed-form hypothetical solutions and existing crash test results.

New Crush Model. A typical force vs. deformation curve obtained from a frontal crash test is shown in figure 7. It should be noted that the dynamic pressure is also a function of the deformation rate, and this curve is the resulting force vs. deformation due to some form of a pressure vs. deformation and deformation rate relationship. The deformation vs. time and the deformation rate vs. time curves from the same test are shown in figures 8 and 9. As a first step to determine an expression for dynamic pressure, certain characteristics of these data were identified and were imposed as constraint conditions in the development of the model.

Data values of force in figure 7 were obtained by multiplying vehicular acceleration by the vehicle's mass and the deformation was obtained by integrating the acceleration twice. Figure 7 shows a finite force at zero deformation. However, accelerometer results usually consist of sharp spikes, and locating the zero time point is very difficult. Therefore, the finite force at zero deformation was neglected in the development of the crush model. Then the conditions to be met were:

(1) At $s = 0$ and $v = v_o$, $p = 0$ and the slope of p vs. s is finite.

(2) At $s = s_m$ and $v = 0$, the slope of p vs. s is negative infinity.

where,

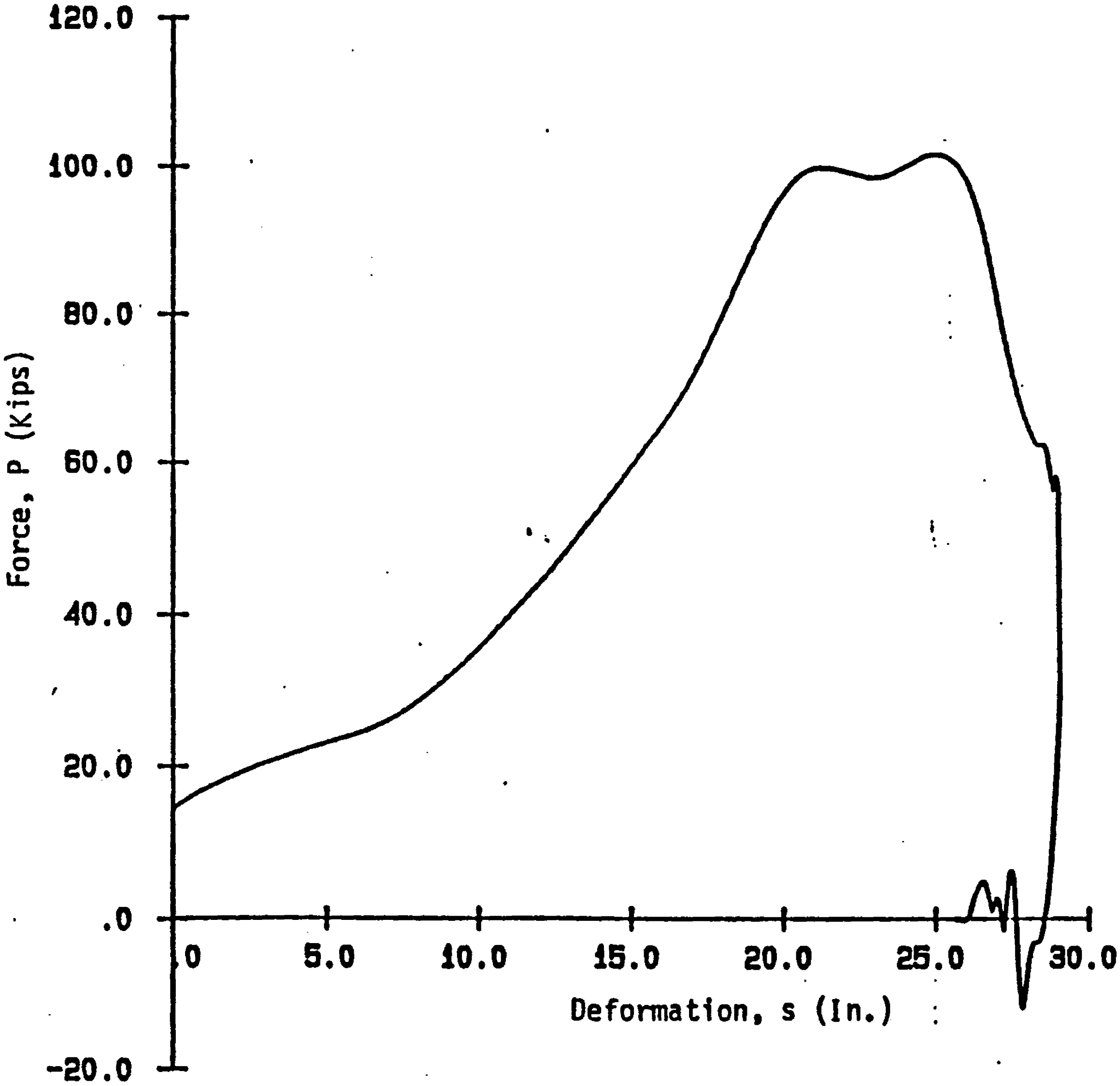


Figure 7. Force vs. deformation curve of a frontal crash test.
(NHTSA 1987)

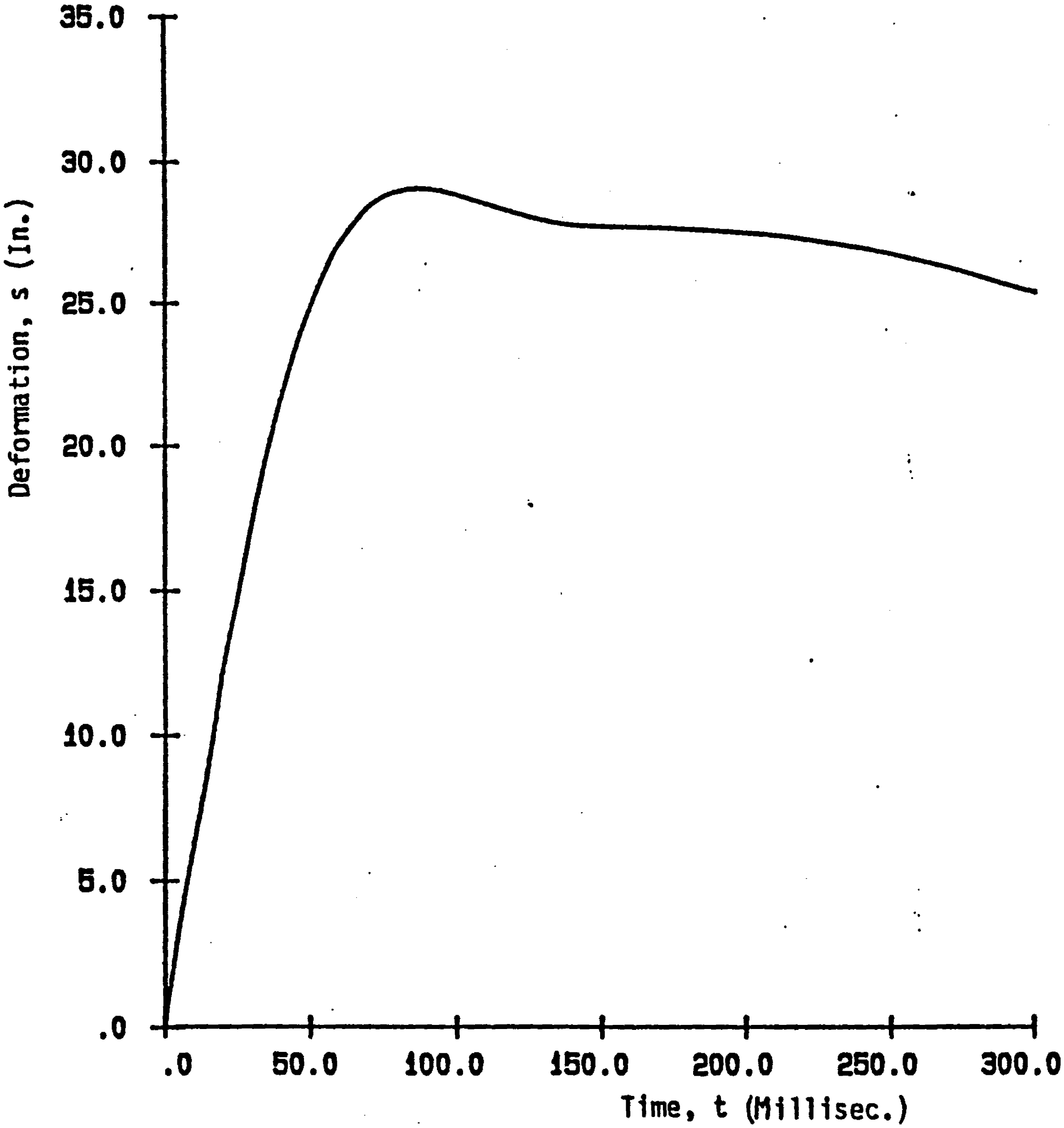


Figure 8. Deformation vs. time curve of a frontal crash test. (NHTSA 1987)

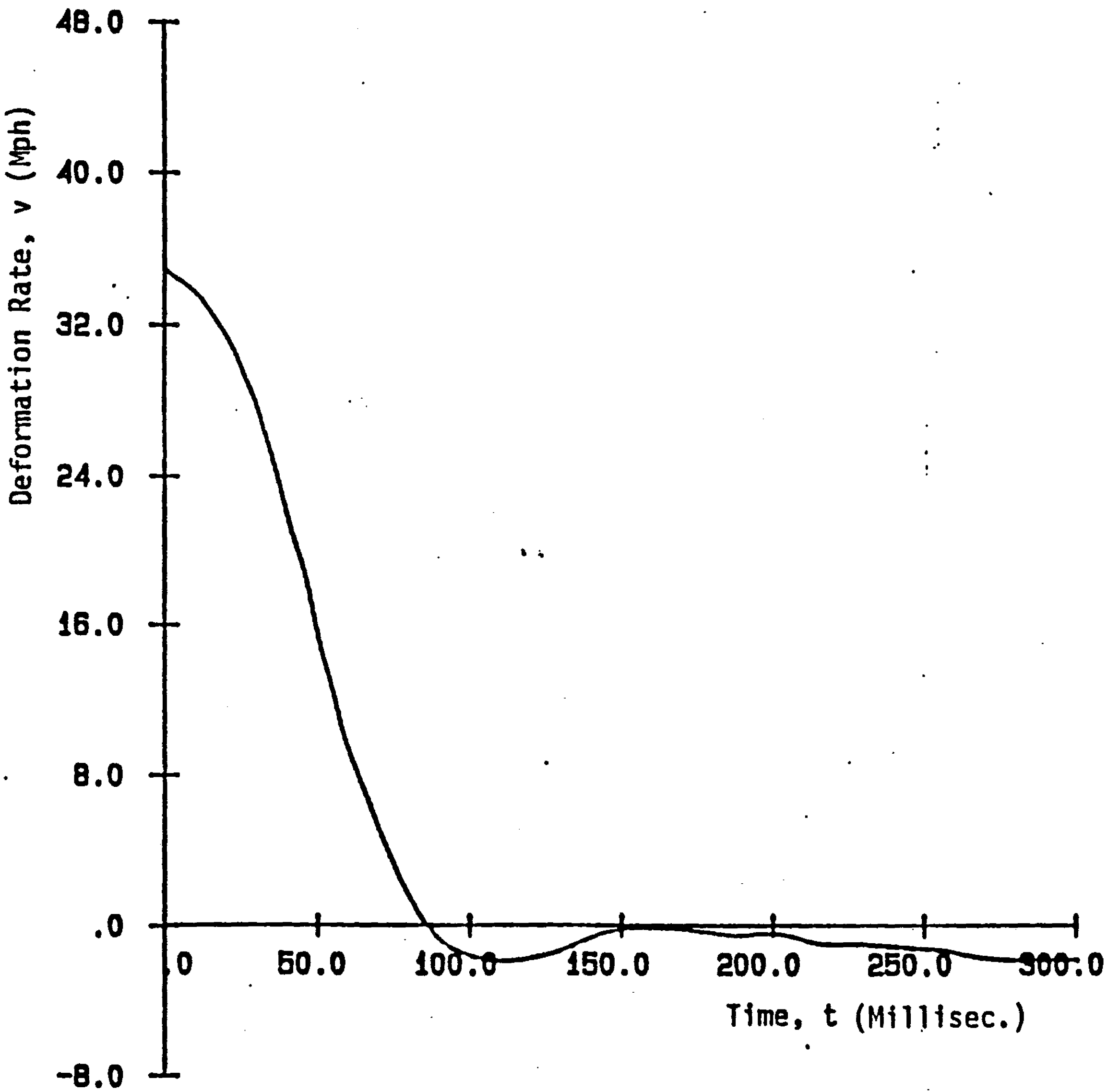


Figure 9. Deformation rate vs. time curve of a frontal crash test. (NHTSA 1987)

s = deformation of the front end of the vehicle;
v = deformation rate of the front end of the vehicle;
p = dynamic pressure at the vehicle/barrier interface;
s_m = maximum deformation;
v_o = initial deformation rate (in a frontal crash the initial velocity of the vehicle).

The portion of the force vs. deformation curve after attaining the maximum deformation is due to a nonzero coefficient of restitution, e. However, in an angular impact the loss of contact between the vehicle and the barrier is progressive, unlike the instantaneous loss of contact that occurs in a frontal crash. Therefore, the effects of coefficient of restitution are negligible and only the portions before $s = s_m$ or $v = 0$ of the curves in figures 7, 8, and 9 were simulated.

To satisfy the above conditions, the following model for the dynamic pressure p at the vehicle/barrier interface was chosen as the new crush model.

$$p = k_v s\left[1 + c_v(v/v_{ref})^{n_v}\right] \qquad 0 < n_v < 2 \qquad . . (3)$$

where k_v, c_v, and n_v are constant parameters for a particular vehicle, and v_{ref} is a reference velocity which makes the velocity term dimensionless. The constant k_v is a force per volume, whereas c_v and n_v are dimensionless. It should be noted that the constant c_v is not a damping coefficient. The reference velocity v_{ref} here was chosen to be 1 in/sec.

A series of 10 frontal crash tests performed for NHTSA's New Car Assessment Program were simulated with the use of the new crush model given in equation 3.(4) Since the force depends on both the deformation and the deformation rate, a numerical integration method had to be used to determine the force vs. deformation curve. A simple numerical integration program, incorporating the crush model shown in equation 3, was written to integrate the single DOF equation of motion of a vehicle. The purpose of the simulations was to determine appropriate ranges of the parameters k_v, c_v, and n_v. For estimation of these parameters, the simulated force vs. deformation curves were first assumed to have the same initial slope and maximum deformation as the measured curve. These two conditions provided two equations relating k_v, c_v, and n_v. Then the value of n_v was adjusted between 0 and 2 until a good correlation was acheived between measured and simulated force curves. Mass of the vehicle, initial velocity, maximum deformation in each test, k_v, c_v, n_v values and frontal cross-sectional area used in each simulation are tabulated in table 16.

The range of k_v, c_v, and n_v values for frontal impacts estimated using these simulations is from 0.4 through 1.3 kip/in^3, 0.004 through 0.04, and 0.65 through 1.0 respectively.

An attempt was made to correlate the crush parameters k_v, c_v, and n_v with the mass of the vehicle. However, a useful relationship could not be found due to scattering of estimated values when plotted against the mass m. More data are needed to cover the whole range of vehicle masses from small to large automobiles.

Tracking Vehicular Deformations. According to the crush model given by equation 3 the normal force on the interface between the kth barrier surface and the vehicle, F_{Nsk}, is given by,

$$F_{Nsk} = k_v \int \delta \left[1 + c_v (\dot{\delta}/\dot{\delta}_{ref})^{n_v} \right] dA_{sk} \qquad . \; . \; . \; . \; . \; . \quad (4)$$

where,

- A_{sk} = interface area between the vehicle and the kth barrier surface;
- δ = deformation of the vehicle periphery;
- $\dot{\delta}$ = deformation rate of the vehicle periphery;
- $\dot{\delta}_{ref}$ = reference deformation rate taken as 1 in/sec, to make the deformation rate term dimensionless.

It should be noted that δ, $\dot{\delta}$, and $\dot{\delta}_{ref}$ are used in place of s, v, and v_{ref} in equation 3 since the direction of deformation is not the same as the direction of motion of the vehicle in an angular impact. In the equations that follow, $\dot{\delta}$ denotes nondimensional deformation rate, and $\dot{\delta}_{ref}$ does not appear.

The deformation rate $\dot{\delta}$ at any point on the contact area A_{sk} is the velocity of the vehicle at that point in the direction of the outward normal to the kth barrier surface. This can be easily determined for a given position, orientation, and translational and

Table 16. Input parameters of frontal crash test simulation.

Vehicle	mass $\left[\frac{lb\text{-}s^2}{in.}\right]$	v_o (mph)	s_m (in.)	A_f (in.×in.)	k_v $\left[\frac{kips}{in.^3}\right]$	c_v	n_v
Yugo (3-Dr. Hatchback)	6.004	35.1	23.4	60.7×25	1.03	0.02	0.75
Buick LeSabre (2-Dr. Sedan)	9.446	35.5	35.1	72.1×24	0.47	0.033	0.75
Buick Century (4-Dr. Sedan)	8.411	35.2	33.7	67.7×25	0.80	0.005	0.90
Buick Century (2-Dr. Coupe)	8.696	35.1	32.4	67.7×25	0.65	0.005	1.00
Mazda (3-Dr. Hatchback)	6.496	35.2	27.8	64.8×25	1.20	0.014	0.65
Plymouth Colt Vista Stn Wgn	7.712	34.7	27.8	64.6×25	1.26	0.004	0.90
Olds. Delta 88 (4-Dr. Sedan)	9.601	35.4	36.2	72.1×24	0.43	0.015	0.90
Volks. Sciroc. (3-Dr. Hatch.)	8.773	35.0	29.0	64.0×25	1.01	0.022	0.70
Chevrolet Nova (5-Dr. Hatch.)	6.677	35.2	27.9	64.4×23	1.11	0.006	0.85
Toyota Celica (2-Dr. Coupe)	7.635	34.9	30.7	65.5×25	0.72	0.006	0.95

Note: v_o = Initial velocity ; s_m = Maximum deformation

A_f = Frontal cross-sectional area

rotational velocity of the vehicle. However, to find the deformation δ, the deformation history of each vehicle point on A_{sk} is needed.

To accomplish the task of tracking the deformation history of the vehicle periphery during the crash, a set of points was introduced on the vehicle periphery. It will be referred to herein as deformation tracking (DT) points.

It is assumed that friction between the vehicle and the barrier causes no tangential deformations to the vehicle sheet metal. Based on this assumption the DT points will slide along a barrier surface subject to the friction force. During the rotation of a barrier surface around its axis of rotation within a time step, the surface is assumed to move the DT points in contact with it in a normal direction. In other words, the points are assumed to move in a circular arc whose center is on the axis of rotation of the barrier surface as shown in figure 10. The total deformation of a certain DT point at a certain time is the sum of the lengths of all the circular arcs it is moved along from the time it started moving.

Determination of the Vehicle/Barrier Interface Shape. To find the normal forces on the vehicle/barrier surface interfaces, the integration in equation 4 has to be performed over its region of integration. The region of integration is the contact area between the vehicle and each barrier surface. The existing HVOSM analysis for the simulation of an impact with a vertical wall assumes that the vehicle is a rectangular box. For simplicity of determining the interface polygons, this assumption is retained in the revised model. This assumption guarantees that the shape of each vehicle/barrier interface is a polygon with sides formed by the upper and lower boundaries of the barrier surface and/or the intersection of vehicle surfaces with the barrier surface. The procedure used for the determination of corner points of these polygons is as follows: First, the intersection points of the vehicle edges with the plane of the barrier surface are found assuming that both the vehicle edges and the barrier surface plane are unbounded. Then the points falling outside the vehicle are rejected. This defines a polygon lying on the unbounded barrier surface plane. Finally, the points falling outside the barrier surface edges are rejected after finding necessary intersections of the edges of the polygon with the upper and lower barrier surface edges.

It should be noted that there are two types of vehicle surfaces. They are the original undeformed vehicle surfaces and the vehicle surfaces that are created during the impact. The latter type of surfaces are partially deformed. Figure 11 shows a plan view of the vehicle and the possible movements of the k^{th} barrier surface (assumed

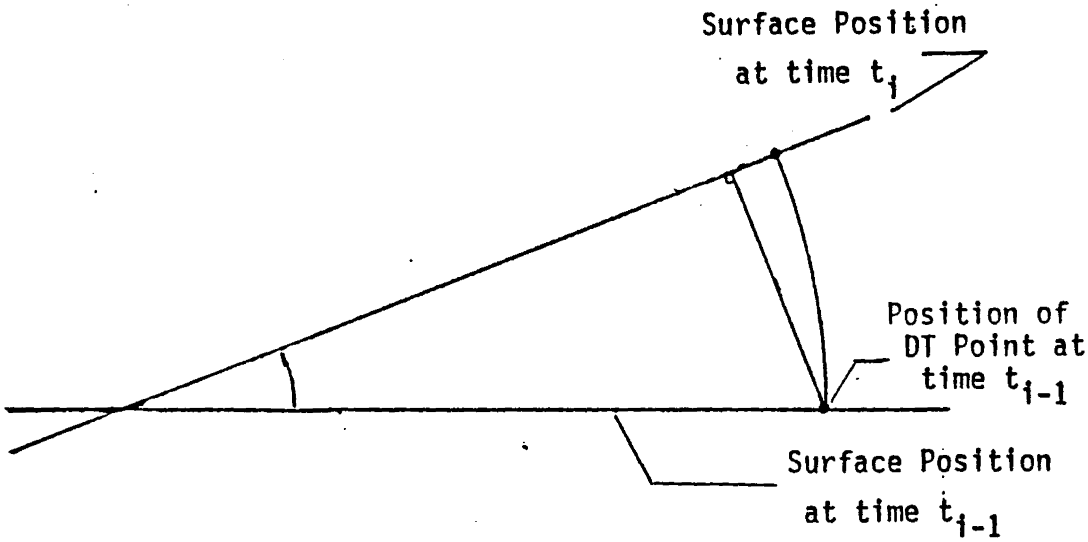


Figure 10. Schematic for deformation and positioning of a previously undeformed DT point.

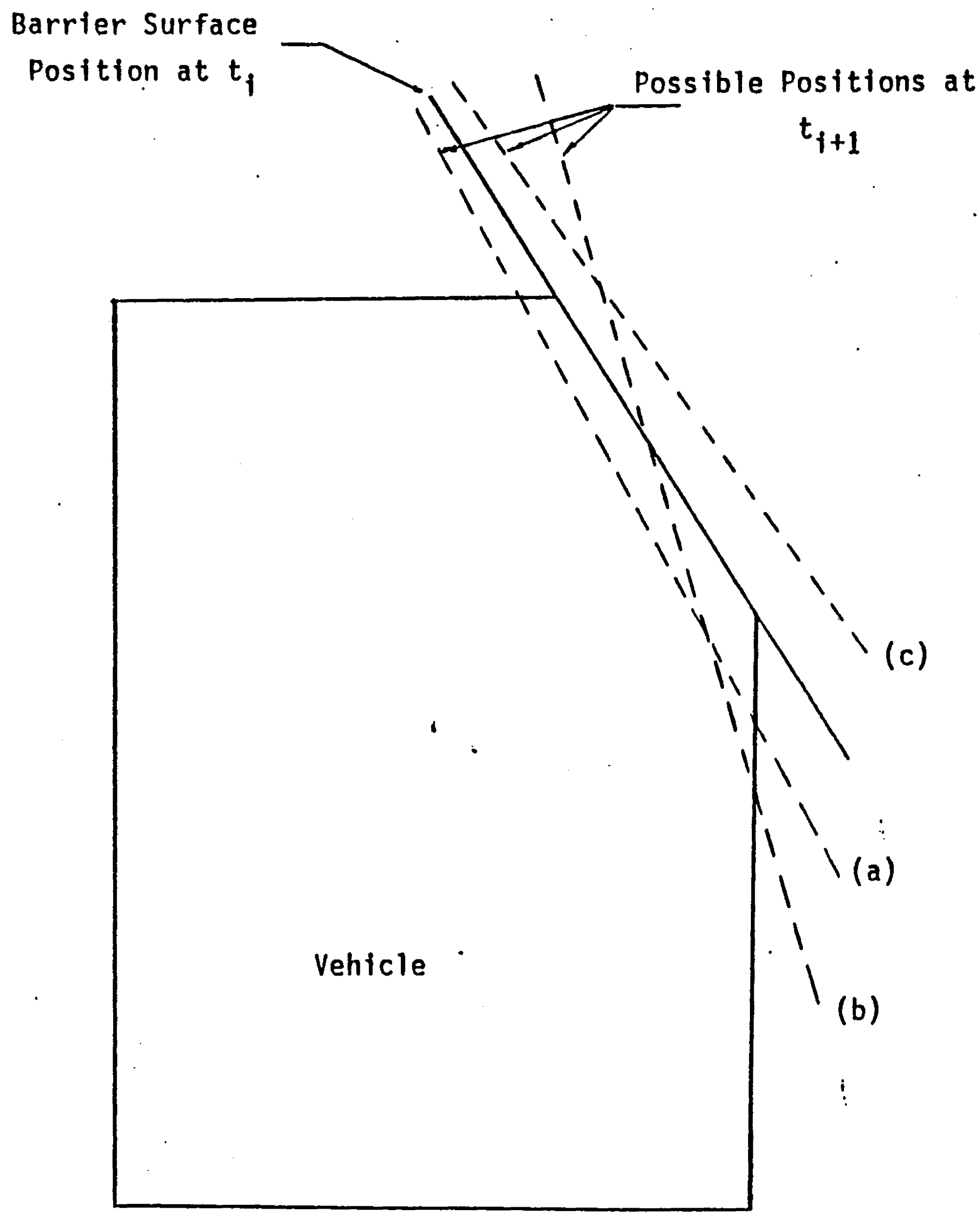


Figure 11. Possible movements of a barrier surface with respect to the vehicle during a time step.

vertical in the illustration) relative to the vehicle from time t_i to t_{i+1}. These are:

(a) The vehicle staying in touch with the k^{th} surface, from t_i to t_{i+1}.

(b) The vehicle leaving the k^{th} surface partially, during the time step.

(c) The vehicle leaving the k^{th} surface fully, during the time step.

It is obvious that the cases (b) and (c) are creating a partially deformed but currently unloaded vehicle surface. These partially deformed vehicle surfaces may take a part in forming the corner points of vehicle/barrier surface interfaces for time steps after time t_{i+1}. Therefore, if it is found that any such partially deformed surfaces exist, the equations of the vehicle edges formed by the intersection of these planes with the original vehicle surfaces are found, and these new vehicle edges are also considered in the corner point determination of the subsequent time steps.

Determination of the Interface Force. The normal and tangential impact force, or moment on the interface between the k^{th} barrier surface and the vehicle, are found by integrating force or moment intensities which are functions of deformations δ and deformation rates $\dot{\delta}$ (see equation 4) over the interface area, A_{sk}. As mentioned earlier, the deformation rate $\dot{\delta}$ at any point on the contact area (needed only at the DT points) is the velocity of the vehicle at that point in the direction of the outward normal to the barrier surface it is in contact with. In addition to this component of the velocity, the direction of the component tangential to the barrier surface is also needed to find the direction of the friction force intensity at that point. Therefore, to find forces or moments on the k^{th} the barrier surface, the velocities (components both normal and tangential to the surface) of all DT points that are in contact with the surface must be found.

The normal force vector, $\mathbf{F}_{Nsk}$ on the k^{th} barrier surface, can then be expressed as,

$$\mathbf{F}_{Nsk} = n_k k_v \int \delta \left[1 + c_v \dot{\delta}^{n_v}\right] dA_{sk} \qquad \ldots\ldots (5)$$

where,

n_k = unit outward normal vector to the k barrier surface.

Also, the total friction force vector, F_{Fsk} on the k^{th} barrier surface, is given by,

$$F_{Fsk} = -\mu_B k_v \int \delta\left[1 + c_v \dot{\delta}^{n_v}\right] \frac{v_{tk}}{|v_{tk}|} dA_{sk} \qquad \ldots\ldots \quad (6)$$

where:

μ_B = friction coefficient between the barrier and the vehicle;

v_{tk} = tangential velocity (to the barrier surface) vector of each vehicle point in touch with the k^{th} barrier surface.

By combining equations 5 and 6 the total force vector, F_{sk} on the k^{th} barrier surface can be expressed as,

$$F_{sk} = k_v \int \delta\left[1 + c_v \dot{\delta}^{n_v}\right] \left[n_k - \mu_B \frac{v_{tk}}{|v_{tk}|} \right] dA_{sk} \qquad \ldots \quad (7)$$

The total moment vector, M_{sk}, acting at the vehicle center of gravity due to the force, F_{sk}, is given by,

$$M_{sk} = k_v \int r_{sk} \times \delta\left[1 + c_v \dot{\delta}^{n_v}\right] \left[n_k - \mu_B \frac{v_{tk}}{|v_{tk}|} \right] dA_{sk} \qquad \ldots \quad (8)$$

where, r_{sk} = position vector of each vehicle point in touch with the k^{th} barrier surface.

In evaluating the integrals in equations 7 and 8, the deformation δ is known only at deformation tracking points even though the deformation rate and the rest of the variables can be found at any vehicle point contacting the barrier. Moreover, these DT points are scattered over the interface. Therefore, a curved surface has to be fitted to the values of the integrand at these scattered DT points to perform the integrations. The volume under this surface is then the value of the integral. A survey of methods for fitting surfaces to scattered data indicated that the best method for the problem in hand was triangularization of the points.(5) A very efficient computer code performing the triangularization was developed.(6) The code first triangulates the data point locations and then calculates the volume under a linear piecewise surface or a cubic spline surface fitted on any set of data values at the points. The integrals over each barrier surface interface found in this manner are summed to find the total forces and moments.

Structural Hard Points. The existing HVOSM mathematical model for sheet metal crush shown in figure 4 was not intended to represent anything more than sheet metal crush of moderate penetration. However, during high-angle impacts, stiff automobile structural components (hard points) slam into the barrier and generate high impact forces.(7) To account for these high impact forces, the HVOSM sprung-mass-impact model was later modified to include a set of three hardpoints with user defined locations and stiffnesses. Deformation of these hardpoints normal to the wall creates a normal force perpendicular to the barrier and a proportional friction force parallel to it. The hard points are not allowed to deform tangential to the barrier.

Several changes were made during the course of this research to the structural hard points of HVOSM to better simulate impacts with rigid barriers. In an angular impact with a rigid barrier, most significant generation of high impact forces are due to the contact of front and rear vehicle axles slamming into the barrier. Therefore, it was assumed that the user defines the initial position of the hardpoints always to be at the end of an axle. The hard points numbered 1, 2, and 3 should be at the right front, right rear, and left front axle ends respectively. In an impact with a CSSB, the first point rigidly connected to the axle that comes into contact with the barrier is the bottom point of the wheel rim. However, in a vertical wall impact the midpoint of the rim can be assumed to come into contact first.

Even though axle deformations usually occur both parallel and perpendicular to the barrier surface, the hard point is assumed to deform only in a direction parallel to the longitudinal axis of the axle. However, since axle deformations parallel to the vehicle are usually relatively small, hardpoint deformation is considered to be along the axis of the axle when its roll angle is zero. As the wheel moves up and down due to suspension deflections or due to rolling of the axle (if solid), the hardpoint also is considered to change its position vertically up or down in the vehicle-fixed frame by an amount equal to the wheel center vertical displacement.

The force between the vehicle and the barrier at a hardpoint due to its deformation is assumed to have components both normal and tagential to the barrier surface. The tangential component F_{ht} is equal to the normal component F_{hn} times the coefficient of friction μ_B.

$$F_{ht} = \mu_B F_{hn} \qquad \ldots\ldots\ldots \qquad (9)$$

When resolved in the direction of deformation, these two produce the force F_h required to deform the hard point which depends both on the deformation and the deformation rate of the hard point. Hence,

$$F_h = F_{hn}\cos\alpha_n + F_{ht}\cos\alpha_t \qquad \ldots\ldots\ldots \qquad (10)$$

where α_n is the angle between the force F_h and the force F_{hn} which acts normal to the barrier surface, and α_t is the angle between the force F_h and the force F_{ht} (see figure 12) which acts in the direction opposite to the velocity of the hard point tangential to the barrier surface. It should be noted that α_n and α_t may not add up to 90 degrees.

The model assumed for the force required to deform the hard point is similar to the model used to find the force intensity at a general point on the vehicle surface. According to this model, the force F_h can be expressed as,

$$F_h = k_{st}\delta_h\left[1 + c_{st}\dot{\delta}_h^{\,n_{st}}\right] \qquad \ldots\ldots\ldots \qquad (11)$$

where k_{st}, c_{st}, and n_{st} are constant parameters for the hard point, δ_h is the total deformation of the hard point, and $\dot{\delta}_h$ is the deformation rate of the hard point. The constant k_{st} has the dimensions of stiffness (force per unit length), whereas c_{st} and n_{st} are dimensionless.

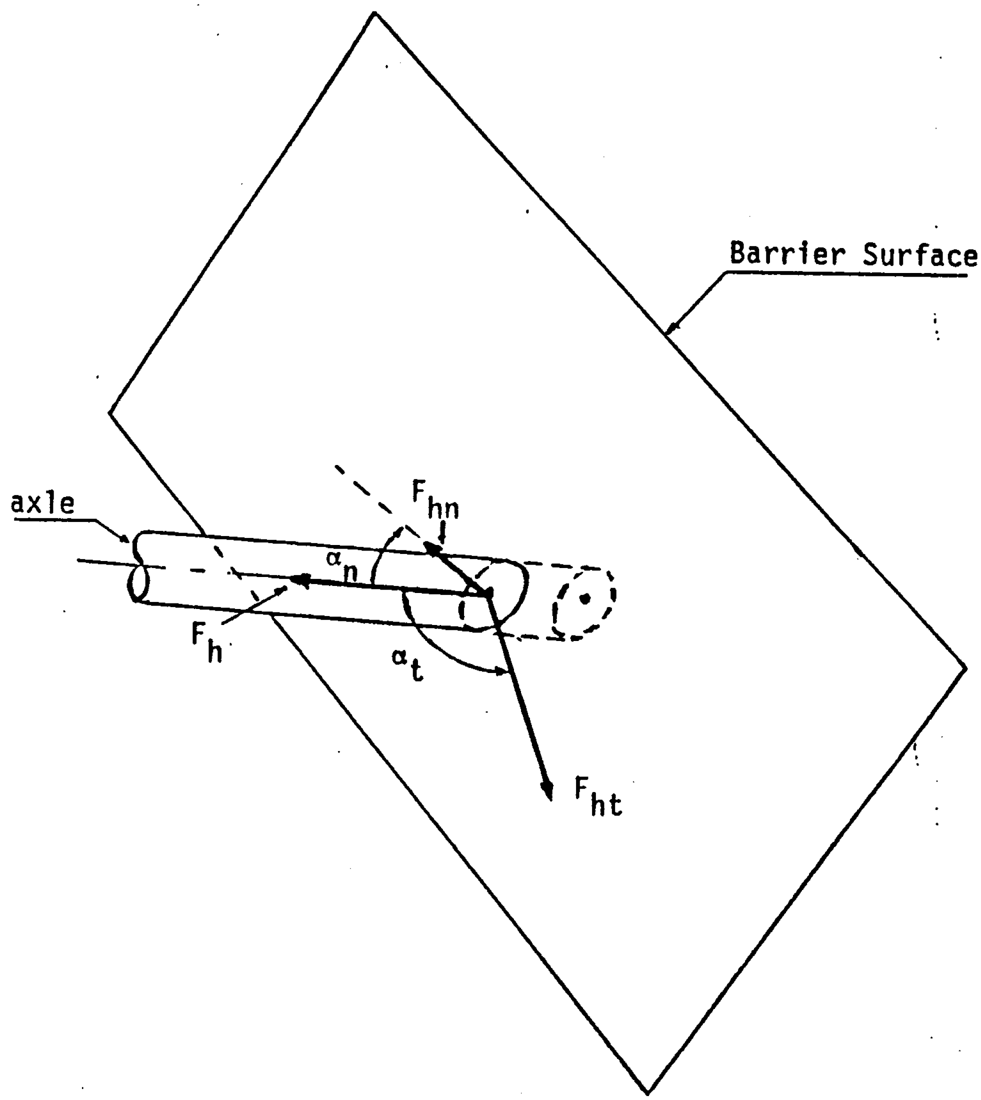


Figure 12. Schematic of the determination of forces at a structural hard point in contact with a barrier surface

By equating the right hand sides of equations 10 and 11, and then substituting for F_{ht} from equation 9, and finally solving for F_{hn},

$$F_{hn} = \frac{k_{st}\delta_h\left[1 + c_{st}\dot{\delta}_h^{\,n_{st}}\right]}{\left[\cos\alpha_n + \mu_B\cos\alpha_t\right]} \quad \ldots\ldots\ldots \quad (12)$$

Then the other component of the force F_{ht} is found by equation 9.

Improved Set of Sprung-Mass-Impact Subroutines. The SFORCE subroutine which simulates a vertical-wall impact for HVOSM was replaced with a set of subroutines that are written to find the forces and moments in an impact with a multi-faced rigid barrier. The main subroutine of this new set of subroutines which calls the rest of the set is the new SFORCE subroutine. SFORCE calls the subroutines PTPLMT, PTDFMN, CORNER, FORCIN, and REARNG. PTPLMT and CORNER call the subroutine ERROR, and PTDFMN calls the subroutine PTPOSN. SFORCE also calls the subroutines PERMUT, REORDR, TRMESH, INTRC1, ADNODE, and the function subprogram VOLUME of the triangularization and surface fitting package.

Subroutine PTPLMT is called to place the DT points on side surfaces as explained later in this section. Deformations of any deforming points are calculated by the subroutine PTDFMN. PTPOSN is called by PTDFMN to calculate the new coordinates of the points deformed at each time step. If there are any points moved outside or along the vehicle periphary, these will cause errors to the values of integrals being calculated. Hence, the subroutine REARNG finds such points and rejects them. The corner points of the vehicle/barrier interface polygon are found by calling the subroutine CORNER. Subroutine FORCIN is called to find the force and moment intensities acting on the vehicle at each deforming DT point.

The initial coordinates of the DT points are calculated by the program itself according to user specified spacings. If the sprung mass impact input data are supplied, the main program calculates the initial coordinates of the DT points on the top and bottom vehicle surfaces. When the SFORCE subroutine is called, it first finds the corner of the vehicle closest to the barrier and checks whether it is in contact with the barrier. Once that corner comes into contact, SFORCE calls the subroutine PTPLMT to place the points on the side surfaces on either side of the corner. During the impact, if the vehicle spins and another corner starts crushing against the barrier, then the subroutine PTPLMT is called again to to define new DT points next to the new corner.

A selected number of DT points on each original surface adjacent to the crushing corner of the vehicle are checked by subroutine PTDFMN to see if contact has been made with a barrier surface. The order in which the points are placed on the vehicle makes it possible to be certain that any points other than those carefully selected points cannot be in contact with the considered barrier surface. Once a point is found to be in contact, then that point is considered to stay in contact with that surface until subsequent checks determine that this point has left the surface or has slipped on to another surface. Therefore, it is not checked for contact with any other surface during its stay with this surface. In this manner, at each time step the subroutine PTDFMN collects any new points which have come into contact with each surface and rejects the ones which have left each surface. It then calculates the deformation undergone by each point in contact with a barrier surface during the time step. This is followed by a call to the subroutine PTPOSN to find the new coordinates of each deformed point.

To determine the regions of integration for equations 7 and 8, subroutine CORNER finds the coordinates of each vehicle/barrier surface interface area. The subroutine SFORCE then calls the subroutines REORDR, PERMUT, and TRMESH to triangulate all the DT points on the interface and the zero deformation corner points where the function for which the surface to be fitted is known. It should be noted that some of the corner points that are formed by the intersection of a partially deformed vehicle surface with a barrier surface have unknown deformations. Therefore, the subroutine INTRC1 is called to fit a cubic spline to the known data values and to extrapolate the value of the function at the rest of the corner points. These corner points are then also added to triangulation by calling the subroutine ADNODE and, finally, the function subprogram VOLUME gives the volume under the linear piecewise surface fitted to the function over the interface.

2. Other Modifications

Several modifications to the subroutines other than the sprung-mass-impact routine of HVOSM were made during the course of this research. These changes were made with the intent of improving the model's accuracy. These modifications involved shock absorber and tire models.

2.1 Modifications to Shock Absorber Model

Effects of shock absorbers are taken into consideration in HVOSM by including a viscous damping force at the suspensions. The suspension viscous damping force is equal to a damping constant times the suspension deflection rate.(8) The user can specify two different values for damping constants at front and rear suspensions.

Even though hydraulic dampers used as automotive shock absorbers have traditionally been considered to be viscous dampers, in reality, the force developed by a shock absorber is a nonlinear function of velocity. Researchers have stated that this nonlinear function conforms to a composite of power law relationships of the form

$$F = c\dot{x}^n \quad . \; . \; . \; . \; . \; . \; . \quad (13)$$

with different values for n ranging from 0 to 2.(9) In equation 13 above, F is the damping force, $\dot{x}$ is the piston speed, and c and n are constants. Another observation is that most damper designs provide different flow control valves for jounce ($\dot{x} > 0$) and rebound ($\dot{x} < 0$). Effective damping in jounce is usually much less than in rebound. figure 10 shows a typical damping force vs. piston speed relationship in jounce and rebound.(10)

In order to incorporate these characteristics, the model for the shock absorber in HVOSM was changed to the following form.

$$F = \begin{cases} c_{R1}\dot{x} + c_{R2}(\dot{x}-\dot{x}_{R1}) + c_{R3}(\dot{x}-\dot{x}_{R2}) + c_{R4}(\dot{x}-\dot{x}_{R3}) \\ \qquad + (\dot{x}-\dot{x}_{R3})^n \qquad \text{for} \quad \dot{x} > 0 \text{ and,} \\ c_{J1}\dot{x} + c_{J2}(\dot{x}+\dot{x}_{J1}) + c_{J3}(\dot{x}+\dot{x}_{J2}) \qquad \text{for} \quad \dot{x} < 0 \end{cases} \quad (14)$$

where c_{Ri}(= 0 for $\dot{x}_{Ri} < \dot{x} < \dot{x}_{Rj}$, i = 2,4, j = i-1) and c_{Ji}(= 0 for $-\dot{x}_{Ji} > \dot{x} > -\dot{x}_{Jj}$, i = 2,3, j = i-1) are damping constants in rebound and jounce respectively. It should be noted that $\dot{x}_{Ri}$ and $\dot{x}_{Ji}$ are absolute suspension velocities. Figure 13 shows how this model can be used to approximate typical force vs. piston velocity curves in jounce and rebound. The SUSFRC subroutine of HVOSM was modified according to this new model such that the user can specify different c_{Ri}, c_{Ji}, and n for front and rear suspensions.

Measured force vs. piston velocity curves in jounce and rebound were available to determine the constants c_{Ri}(i = 1,3) and c_{Ji}.

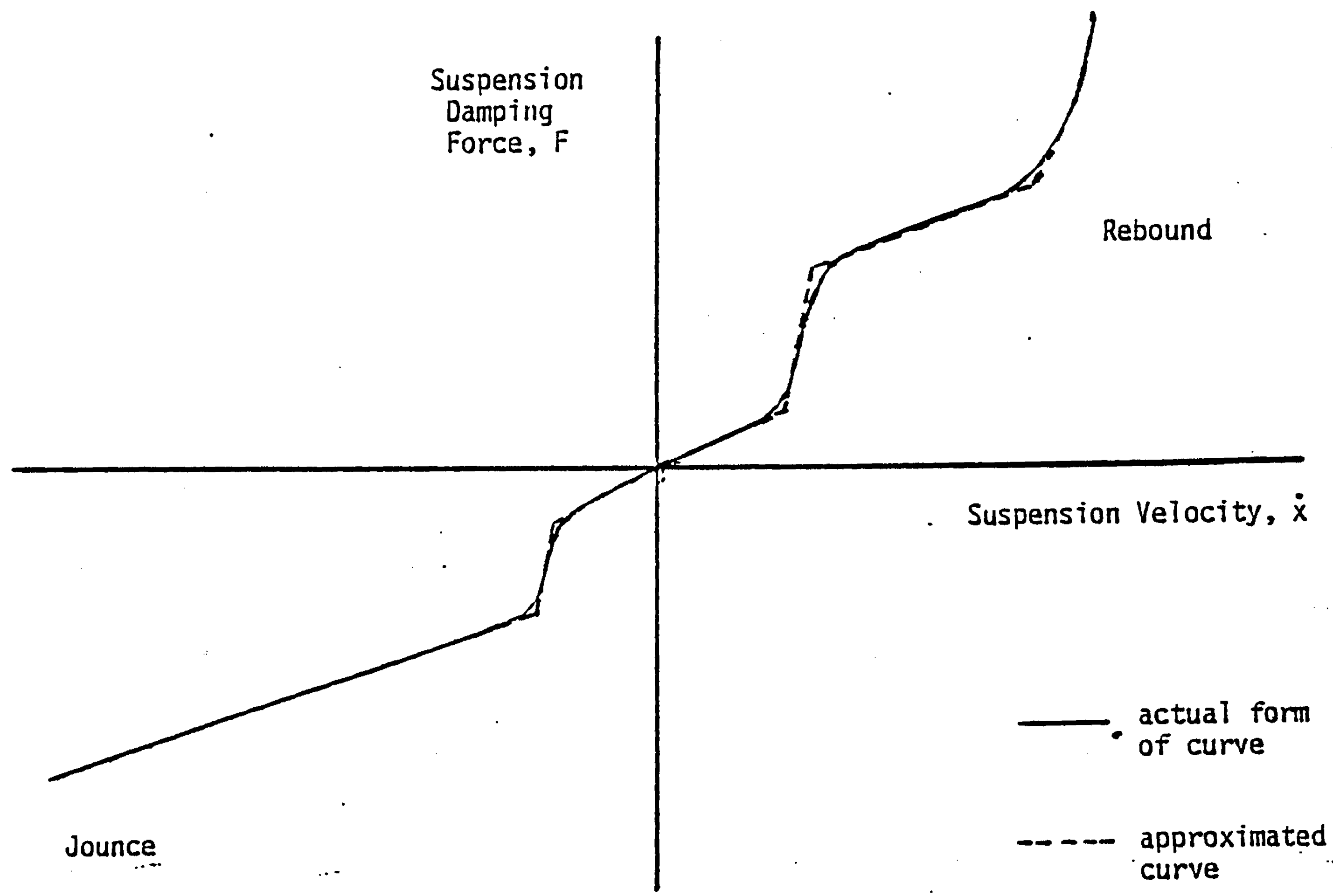


Figure 13. Typical suspension damping vs. suspension velocity curves in jounce and rebound, and the approximated curves.

However, measurements were not available for high enough piston velocities to determine the constants c_{R4} and n. Hence, initial estimates were made and these values were then adjusted during the validation process of the program.

2.2 Modifications to Tire Model

The model of the tire in HVOSM is a disc with nonlinear radial springs as shown in figure 14. Nonlinearity in the force deflection relation of the springs is taken into consideration with the provision of a bilinear curve. This radial spring tire model was modified to include a viscous damper as shown in figure 15. It can be shown from experimental data that

$$F_d = 0.004\ k\ \dot{\sigma} \qquad \text{. . . . . . . (15)}$$

where,

F_d = damping force in the radial damper;

k = radial spring stiffness;

$\dot{\sigma}$ = radial deformation rate.(11)

Equation 15 was included in the modified tire model.

3. Validation of the Modified Program

After completion of the modifications to the HVOSM computer program, an extensive validation effort was undertaken. The validation procedure was conducted in three stages, (1) comparison with known solutions of highly idealized problems, (2) simulation of full-scale crash tests with a rigid vertical wall, and (3) simulation of full-scale crash tests with concrete safety shaped barriers.

3.1 Validation Against Known Solutions

In the first step, sprung-mass-impact subroutines were used to analyze three selected problems with known solutions. Two of the problems have known theoretical solutions and the other an approximate solution. In all of these problems a rigid vertical wall was used as the barrier and vehicular motions were two-dimensional. A simple vehicle model having only the two translational DOFs and a rotational DOF was used. The purpose of this phase of the calibration was to assess the accuracy of the crush model algorithms and the computer subroutines associated therewith. The three problems are described below.

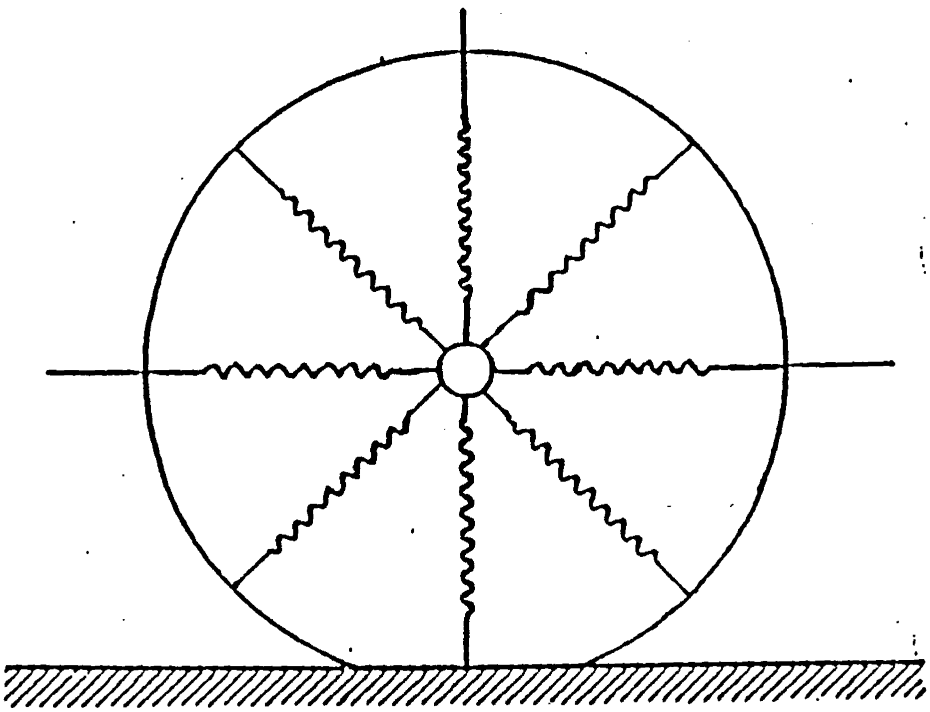


Figure 14. Radial spring model of the tire.

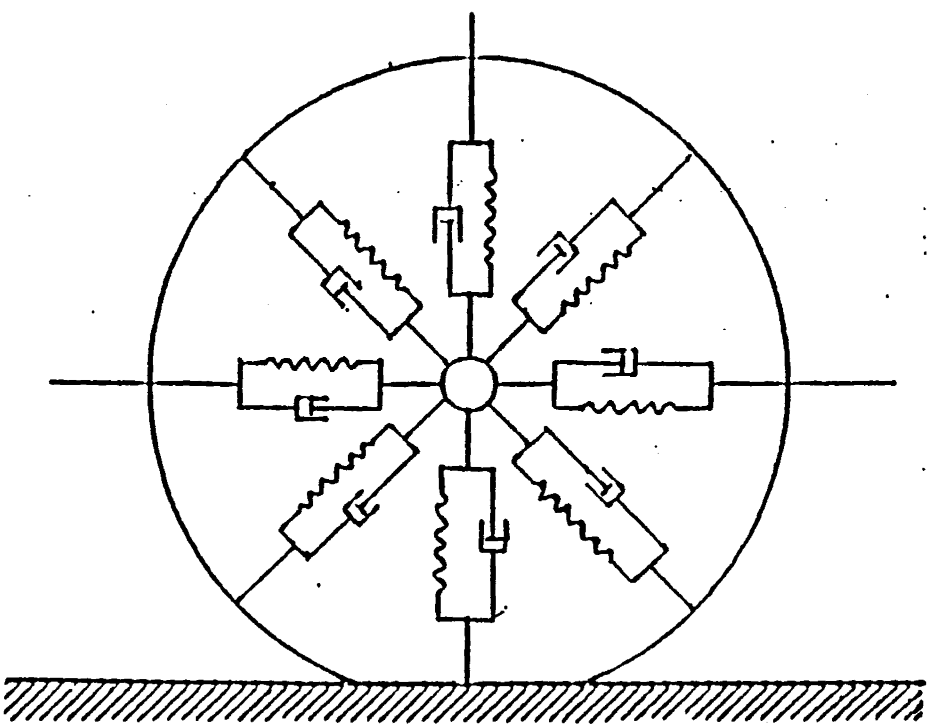


Figure 15. Radial spring-damper model of the tire.

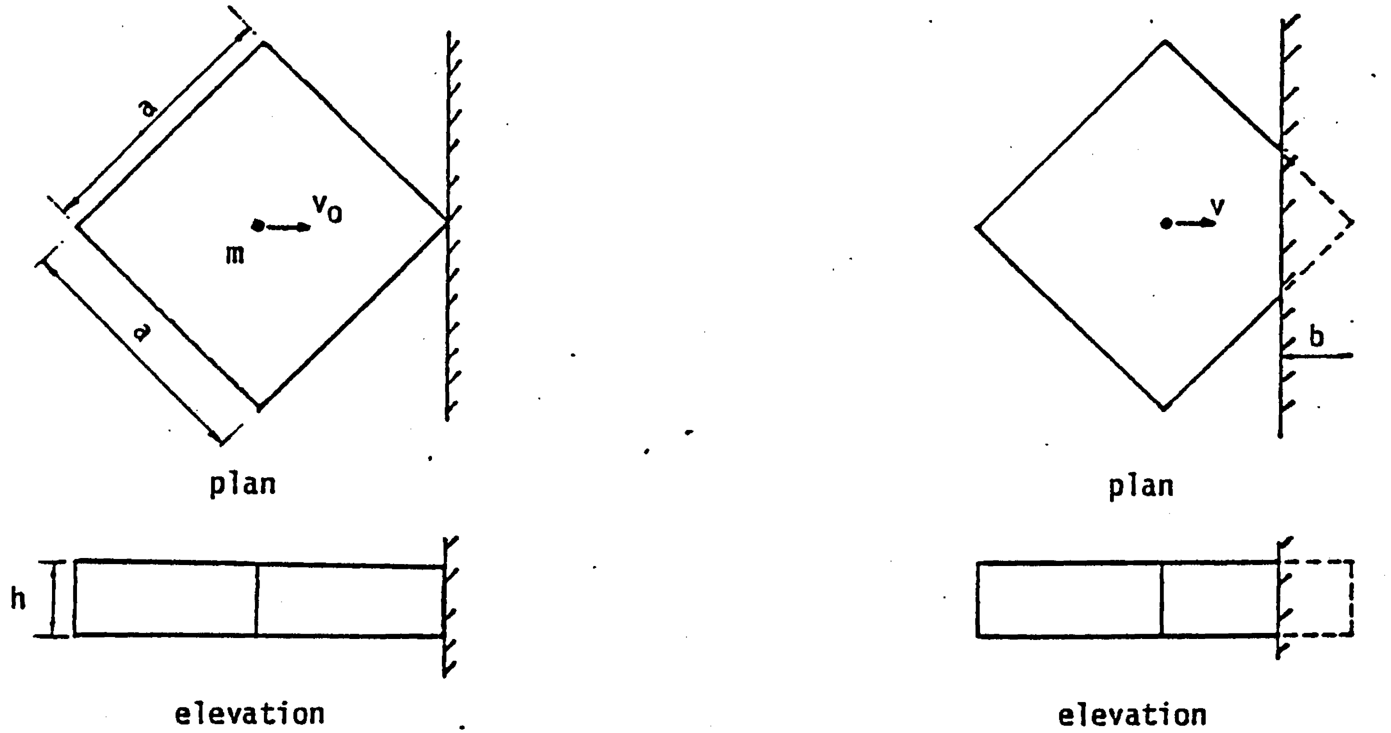
The first is a crushable box with equal length and width hitting one of its corners symmetrically on a wall (see figure 16). The mass of the box was assumed to be concentrated at the center of gravity. The total depth of crush of the box was found theoretically and the time required to stop the box was found through numerical integration. Theoretical exressions for total depth of crush and the force on the box at a certain depth of crush are given in table 17. The dimensions of the box and the impact velocity were selected to obtain a desired duration of impact. This problem was simulated using the modified program and the results obtained are also shown in table 17. Results of the simulation were the same as the theoretical findings. The accuracy of the simulation was not surprising, since the deformation is linear over the interface and the program also linearly connects the deformation of each DT point selected on the box.

The second problem involved the rotation of a crushable rectangular box linked to a point on the wall as shown in figure 17. In this case, an expression for the crushing force was found theoretically, and the motion of the block was found through numerical integration. The expression for the crushing force is given in table 18 along with theoretical results and results obtained by the modified subroutines. Simulation results very closely approximated theoretical findings. Minor deviations from the theoretical solution were expected due to discrepancy between the nonlinear deformation function and the linear piecewise surface fitted by the program.

Finally, the same crushable box was rotated around a point not on the wall (see figure 18). This problem introduced friction forces between the block and the wall that were not present in the first two validation problems. An approximate method was used to determine the force between the wall and the block and numerical integration was again used to find theoretical block motions. The solution of this problem obtained using the program is compared with theoretical findings in table 19. Figures 19 and 20 give theoretical and simulated plots of force and moment on the box vs. time for the motion after impact. As shown in these figures, theoretical and simulated solutions are in close agreement. Slight deviations were expected due to the approximate solution used in the theoretical analysis and the linear piecewise surface fitted by the program to the nonlinear deformation function.

3.2 Validation Against Full-Scale Crash Tests

Validation with full-scale crash testing was conducted in two stages. The first stage involved simulation of crash tests of a vertical wall, instrumented to measure impact loading. The second stage involved simulation of eight full-scale crash tests with a concrete safety shaped barrier. Primary emphasis in the validation effort was placed on determination of proper values for, crush



(a) Just before impact

(b) At time t after impact

Figure 16. First validation problem.

Table 17. Input theoretical expressions and results from first problem.

Input

$m = 124.2236 \text{ lb-sec}^2/\text{ft}$ $\qquad v_o = 88 \text{ ft/sec}$

$a = 10 \text{ ft}$ $\qquad h = 4 \text{ ft}$

Volumetric Stiffness, $k_v = 4 \text{ lb/in.}^3$

Damping Parameter, $c_v = 0$

Theoretical Expressions

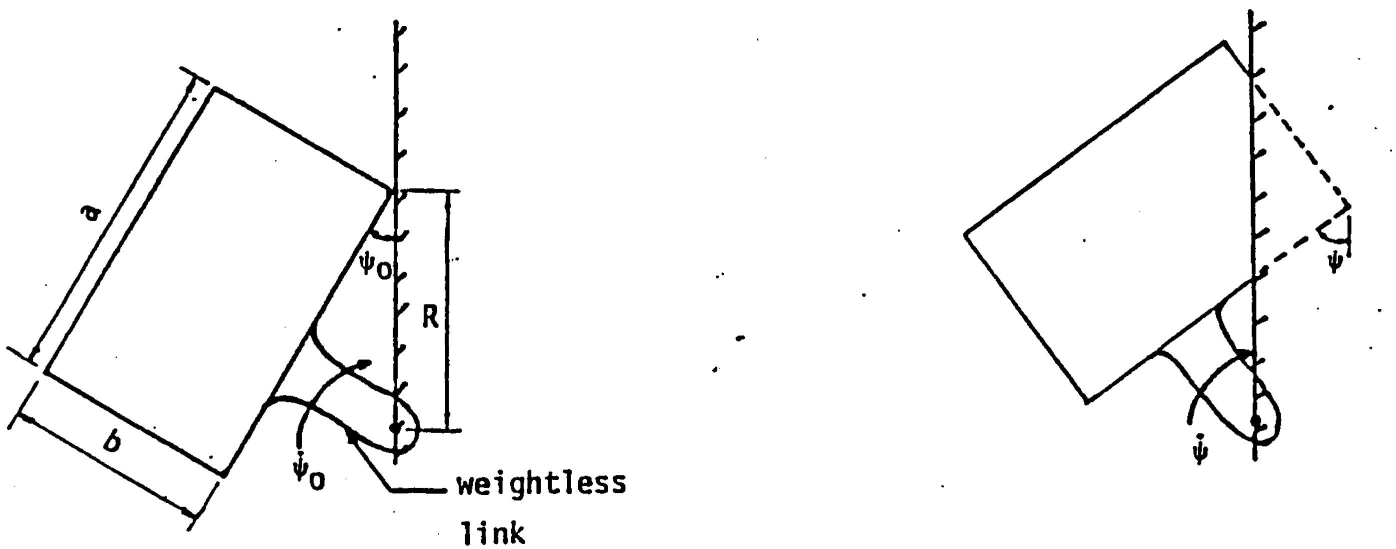
Crushing force at depth of crush $b = k_v h b^2$

Total depth of crush $= \left[\dfrac{3mv_o^2}{2k_v h} \right]^{1/3}$

Results

	Theory	Simulation
Duration of Motion after impact	0.0595	0.0595
Depth of Penetration	3.737 ft	3.737 ft
Force at t = 0.030 sec	1.7649×10^5 lb	1.7649×10^5 lb

Note: Theoretical and simulated forces compared well throughout the motion of the box.



(a) Just before impact

(b) At time t after impact

Figure 17. Second validation problem.

Table 18. Input, theoretical expressions and results from second problem.

Input

$m = 124.2236$ lb-sec^2/ft $\quad$ $I = 2122.153$ lb-ft-sec^2

$\dot{\psi}_o = 5$ rad/sec $\quad$ $\psi_o = 30$ degree

$a = 10$ ft $\quad$ $b = 8$ ft

$R = 20$ ft $\quad$ $h = 4$ ft

Volumetric Stiffness, $k_v = 4$ lb/in.^{3}

Damping Parameter, $c_v = 0$

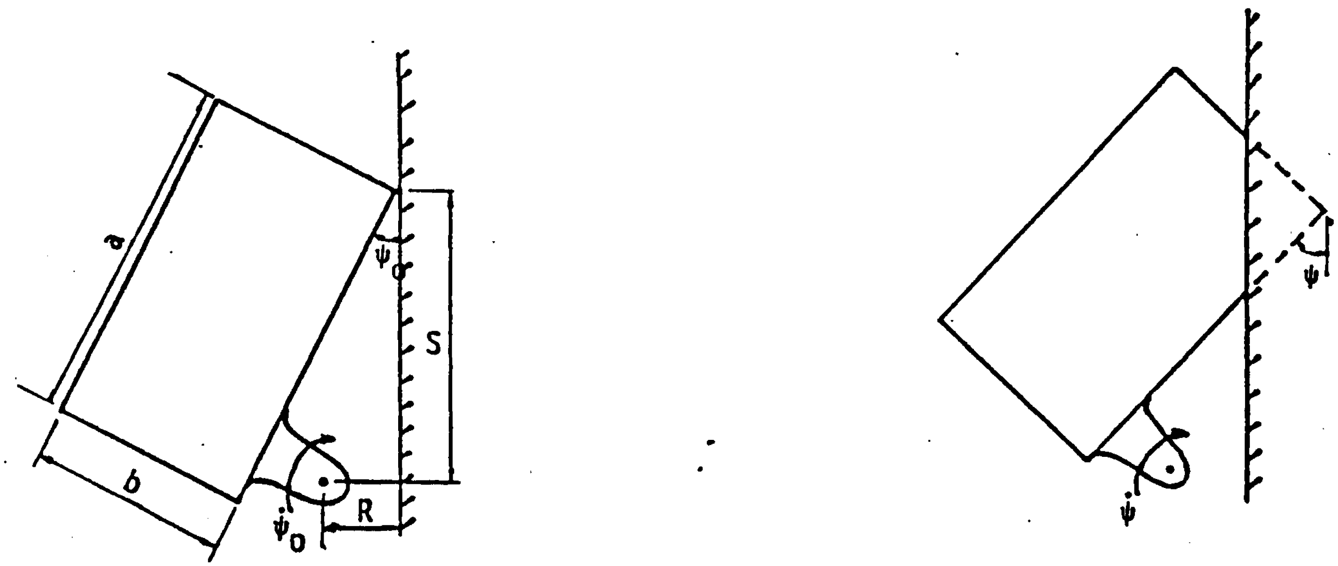
Theoretical Expressions

$$\text{Crushing force} = k_v h R^2 \left[\cos^2\psi_o . \tan\psi + \sin^2\psi_o . \cot\psi - \sin 2\psi_o\right]/2$$

Results

	Theory	Simulation
Duration of Motion after Impact	0.0559 sec	0.0559 sec
Angular Displacement after Impact ($\psi_f - \psi_o$)	11.34 degree	11.34 degree
Force at t = 0.030 sec	2.2717×10^5 lb	2.2717×10^5 lb
Moment of the Force around the Pin, at t = 0.030 sec	4.4009×10^6 lb-ft	4.4051×10^6 lb-ft

Note: Theoretical and simulated forces and moments compared well throughout the motion of the box.



(a) Just before impact

(b) At time t after impact

Figure 18. Third validation problem.

Table 19. Input and results from third problem.

<u>Input</u>

$m = 124.2236$ lb-sec^2/ft	$I = 2122.153$ lb-ft-sec^2
$\dot{\psi}_0 = 4$ rad/sec	$\psi_o = 30$ degree
$a = 10$ ft	$b = 8$ ft
$R = 5$ ft	$S = 8.6603$ ft
$h = 4$ ft	

Volumetric Stiffness, $k_v = 4$ lb/in.^{3}

Damping Parameter, $c_v = 0$

<u>Results</u>

	Theory	Simulation
Duration of Motion after Impact	0.0764 sec	0.0787 sec
Angular Displacement after Impact $(\psi_f - \psi_o)$	12.18 degree	12.55 degree

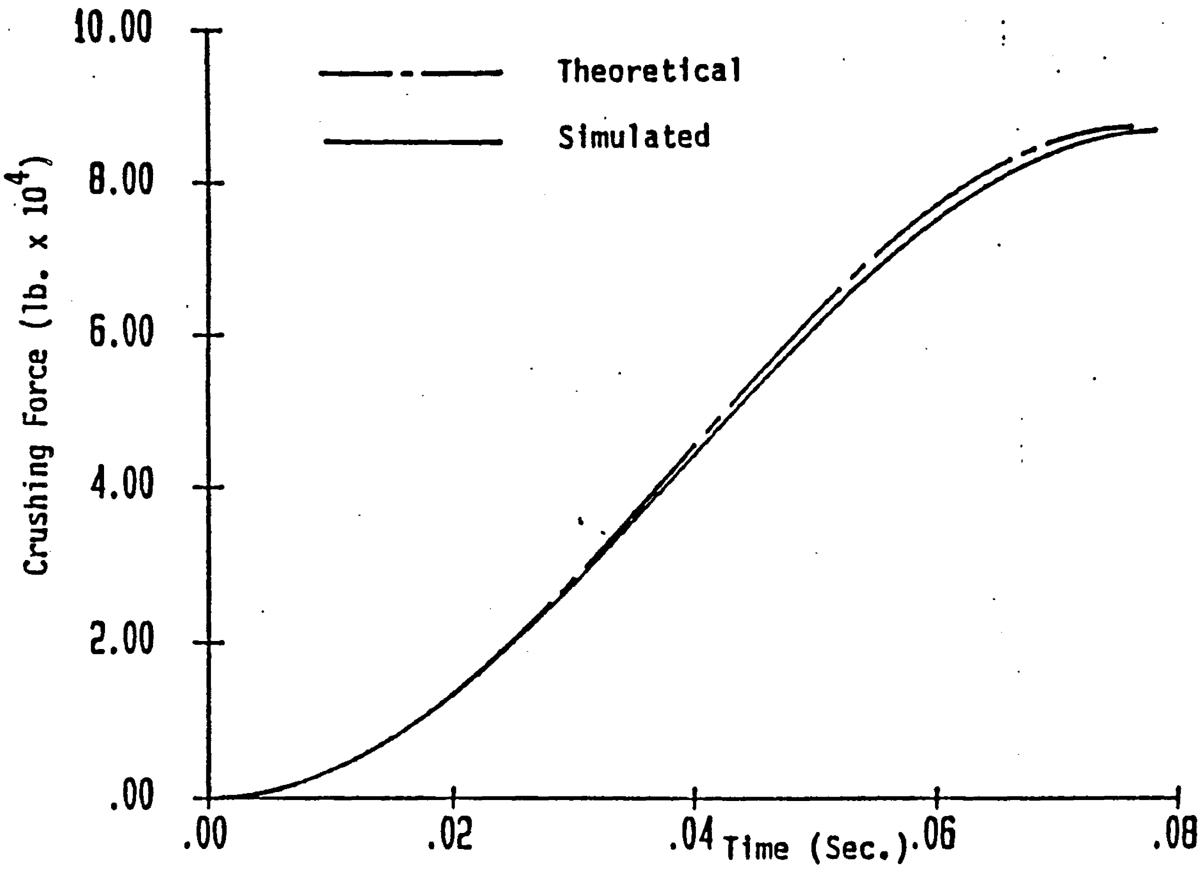


Figure 19. Plot of crushing force vs. time for third validation problem.

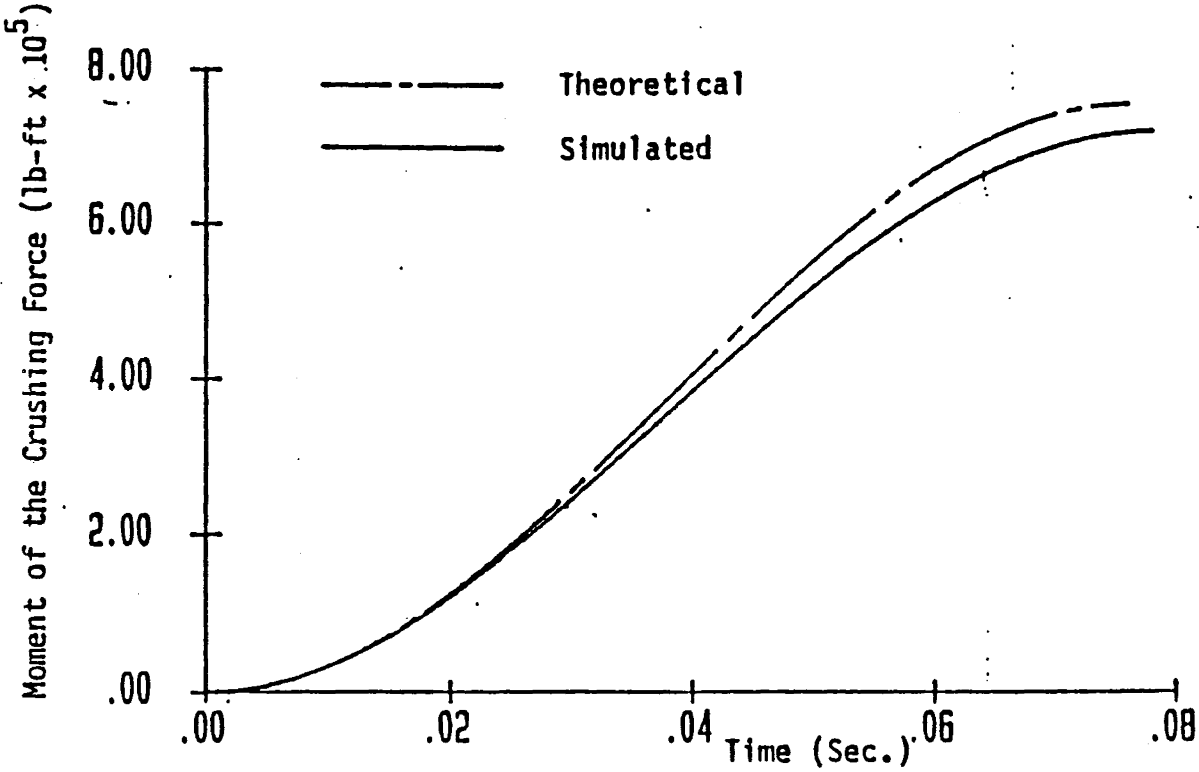


Figure 20. Plot of moment of the crushing force around the pin vs. time for third validation problem.

properties of the sheet metal, structural hard point properties, and the unknown suspension damping coefficients c_{R4} and n. Parameters k_v, c_v, and n_v, estimated using frontal crash tests were adjusted to simulate angular impacts. Initial estimates for the structural hard point parameters k_{sti}, c_{sti}, and n_{sti}, and the suspension damping parameters c_{R4} and n were also made and then adjusted to better simulate the selected full-scale crash test results.

The validation process was iterative in nature and it was quite time consuming. On average, approximately 30 HVOSM runs were required per vehicle to converge on a set of parameters that resulted in a best fit. Actual values of the parameters so derived are given at the end of section 1.

Simulation of Full-Scale crash tests with a Vertical Wall. Two crash tests involving impacts with a vertical wall, instrumented to measure impact forces, were selected from reference 12. One of the tests, 3451-29, involved a small car (1974 Honda Civic) and the other, test 3451-36, involved a large car (1975 Plymouth Fury). The Honda Civic in test 3451-29 was directed at the wall with a speed of 59.0 mi/h at an angle 15.5 degrees to the wall. The Plymouth Fury in test 3451-36 had an impact speed of 59.8 mi/h and an impact angle of 24.0 degrees.

Measured and simulated angular displacements from the test with the Honda Civic are shown in figure 21. The simulation produced excellent correlation for the yaw displacement. Simulated roll and pitch displacement curves show a slight deviation, but the basic shapes appear to be the same as the measured curves. The primary forces affecting vehicle yaw are the forces due to crush of the vehicle body. However, the roll and pitch displacements are affected a great deal more by the tire and suspension forces. Even though the routines in HVOSM for tire and suspensions were improved, slight deviations in roll and pitch can still be expected due to problems associated with tire side forces arising from tire scrubbing on the wall, suspension jams, and unknown suspension damping behavior at high suspension velocities.

Figure 22 shows measured and predicted lateral wall forces from the test with the Honda Civic. These two curves show the same general shape with two large peaks corresponding to the impacts of the front and rear corners of the vehicle. Average magnitudes and the time of separation of the peaks of predicted curve also compare very well with the measured curve.

The simulated angular displacements for the test with the Plymouth Fury are plotted along with the measured curves in figure 23.

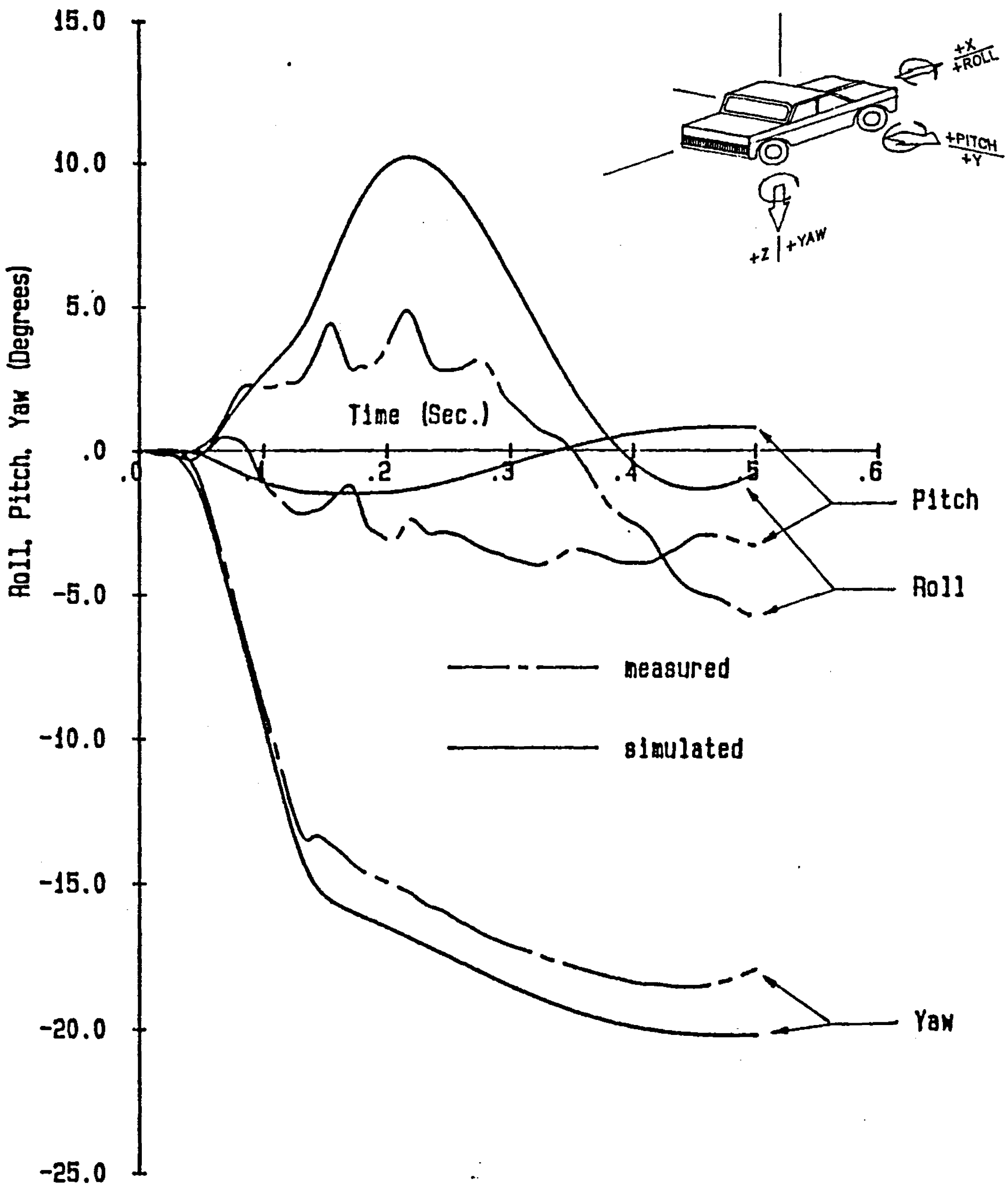


Figure 21. Measured and simulated vehicle angular displacements for test 3451-29 (1974 Honda Civic on an instrumented wall).

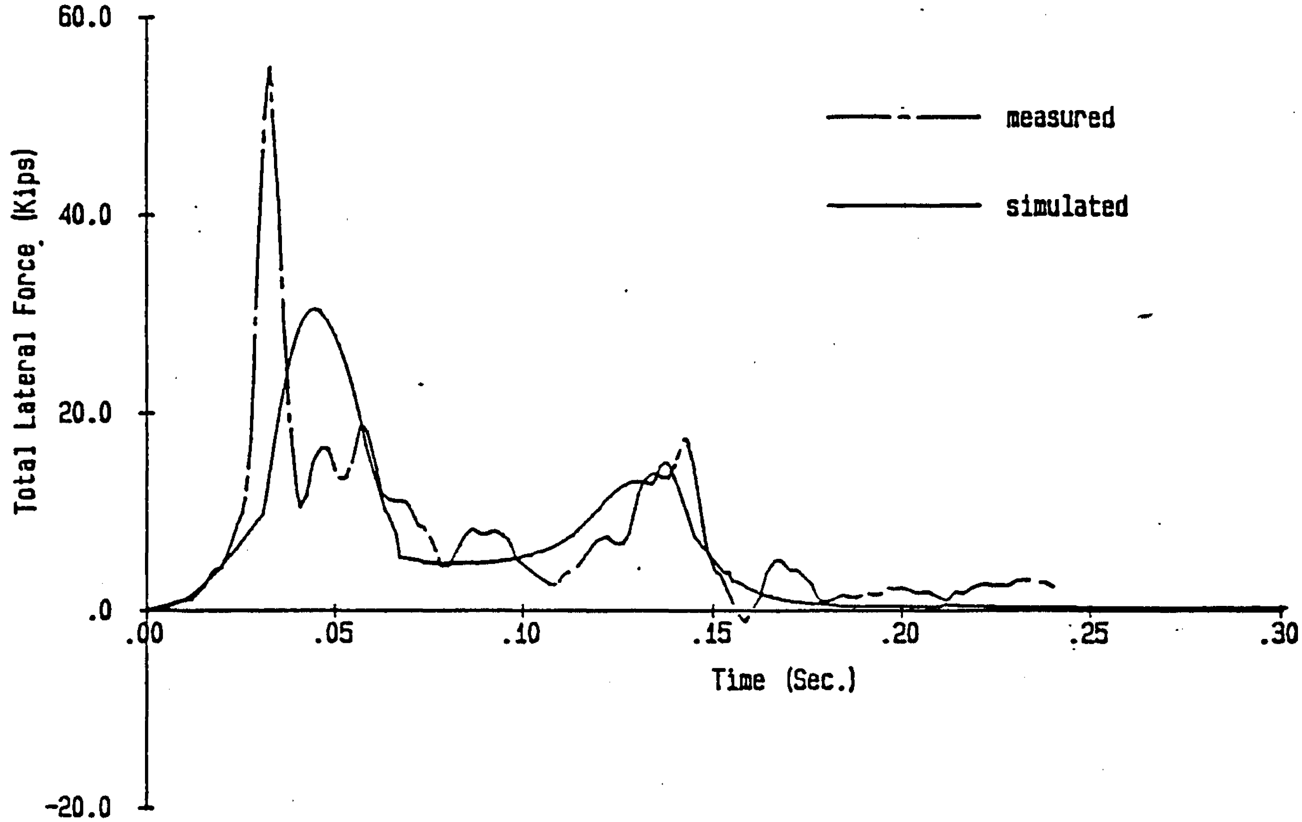


Figure 22. Measured and simulated total lateral force on wall for test 3451-29 (1974 Honda Civic).

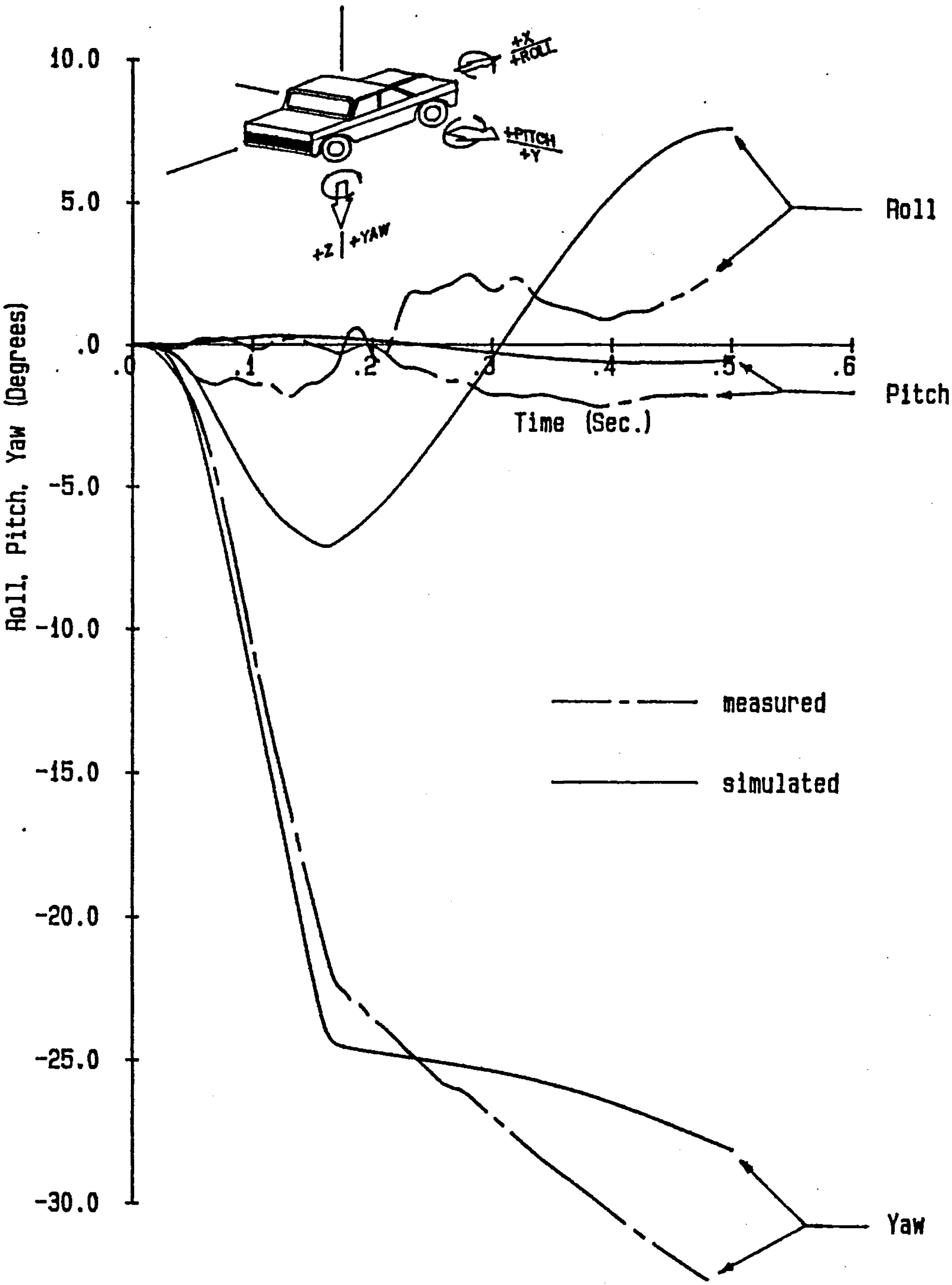


Figure 23. Measured and simulated vehicle angular displacements for test 3451-36 (1975 Plymouth Fury on an instrumented wall).

The basic shapes of the simulated curves for this test are the same as the measured curves. Measured and simulated lateral wall forces for this test are shown in figure 24. Again the curves have the same general shape and peak magnitudes compare well. The time of separation shows a slight deviation.

Measured and predicted maximum 50 ms average longitudinal, lateral, and vertical accelerations for both wall tests are shown as the first two tests in table 20. The simulation slightly underpredicted maximum measured accelerations.

Card images of the HVOSM input used in the final calibration runs for the two vertical wall tests just described are shown in appendix H.

Simulation of Full-scale Crash Tests with CSSB. Eight full-scale crash tests with the CSSB were simulated in this final phase of the validation and calibration process. The first two of these tests were 4798-1 and 4798-3 conducted in an earlier study.(13) Test vehicles were similar to those used in the two instrumented wall tests. These two tests were simulated to further calibrate vehicular crush parameters and structural hard point parameters. Impact angles were 14.5 and 16.5 degrees for tests 4798-1 and 4798-3 respectively, and impact speeds were 59.9 and 58.6 mi/h respectively. Measured and predicted angular displacements for these tests are shown in figures 25 and 26. Again the simulation accurately reproduced the yaw displacement from these tests. The predicted roll and pitch curves show slight deviations from the measured curve due to the limitations in the HVOSM tire and suspension models discussed in the previous subsection. However, the general shapes of the predicted roll and pitch curves were similar to that of measured curves.

Five full-scale CSSB crash tests from reference 1 were then simulated. These tests, 7043-1 through 7043-4 and 7043-12, involved micro-mini size automobiles. A 1985 Fiat Uno impacted a CSSB in tests 7043-1 and 7043-2 with impact angles of 15 and 21.9 degrees respectively. Impact speeds were 58.4 and 61.6 mi/h. Figures 27 and 28 show measured and predicted angular displacements for these tests. As in the previous simulations, correlation between measured and predicted yaw curves was very good while predicted roll and pitch curves showed the same general shape as the measured curves with a slight deviation. During both of these tests it was observed that the front tire on the impact side of the vehicle was jammed into the wheel housing, thereby destroying the suspension system at the wheel. Observed deviations in roll and pitch displacement curves are attributed in large part to this damage.

Measured and predicted longitudinal, lateral, and vertical accelerations for the tests 7043-1 and 7043-2 are shown in figures 29

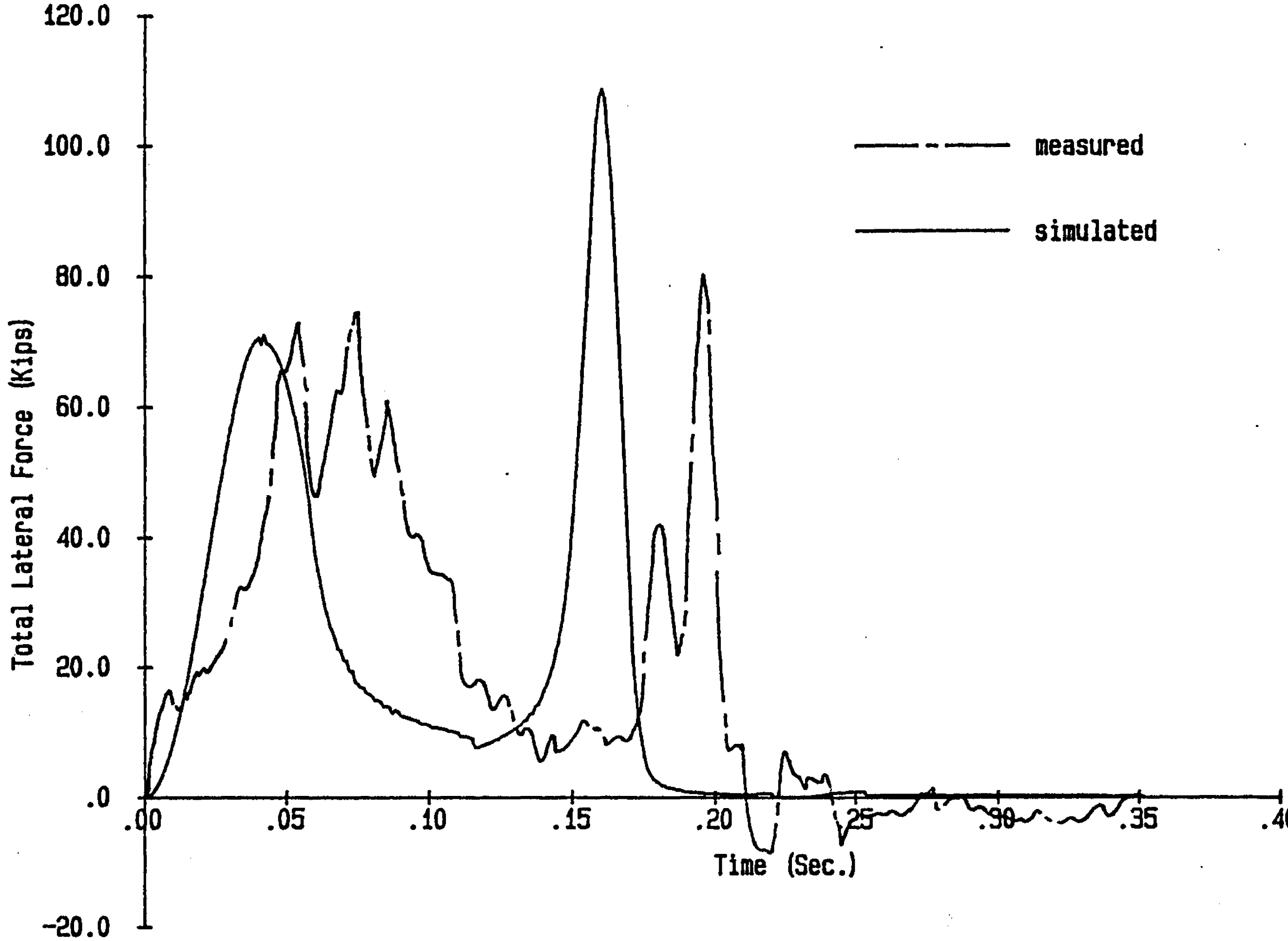


Figure 24. Measured and simulated total lateral force on wall for test 3451-36 (1975 Plymouth Fury).

Table 20. Comparison of measured and predicted maximum 50-ms-average longitudinal, lateral and vertical accelerations of the vehicle in full-scale crash tests.

Test	Longitudinal Acceleration (G-units)		Lateral Acceleration (G-units)		Vertical Acceleration (G-units)	
	measured	predicted	measured	predicted	measured	predicted
3451-29 (Honda Civic on Wall)	-4.0	-4.0	-10.2	-8.7	1.2	0.3
3451-36 (Plymouth Fury on Wall)	-9.1	-6.2	-15.4	-10.8	2.3	0.2
4798-1 (Honda Civic on CSSB)	-4.6	-2.6	-10.0	-7.4	-3.0	-3.3
4798-3 (Plymouth Fury on CSSB)	-4.2	-3.1	-7.9	-7.3	-1.8	-0.8
7043-1 (Fiat-Uno on CSSB at 15 Deg.)	-4.2	-1.9	-9.0	-6.3	-4.5	-3.6
7043-2 (Fiat-Uno on CSSB at 21.9 Deg.)	-7.1	-5.7	-13.8	-12.2	-4.5	-4.8
7043-3 (Daihatsu Domino on CSSB)	-6.0	-2.9	-7.4	-5.8	-3.6	-2.7
7043-4 (Ford Fiesta on CSSB)	-4.5	-2.3	-7.6	-6.3	-3.7	-5.1
7043-12 (Chevrolet Sprint on CSSB)	-6.0	-4.3	-12.1	-10.0	-4.0	-4.6
**** (Honda Civic on CSSB)	-5.5	-5.8	-12.4	-15.6	-3.1	3.8

Note: 1 G-unit = 32.2 ft/s^2

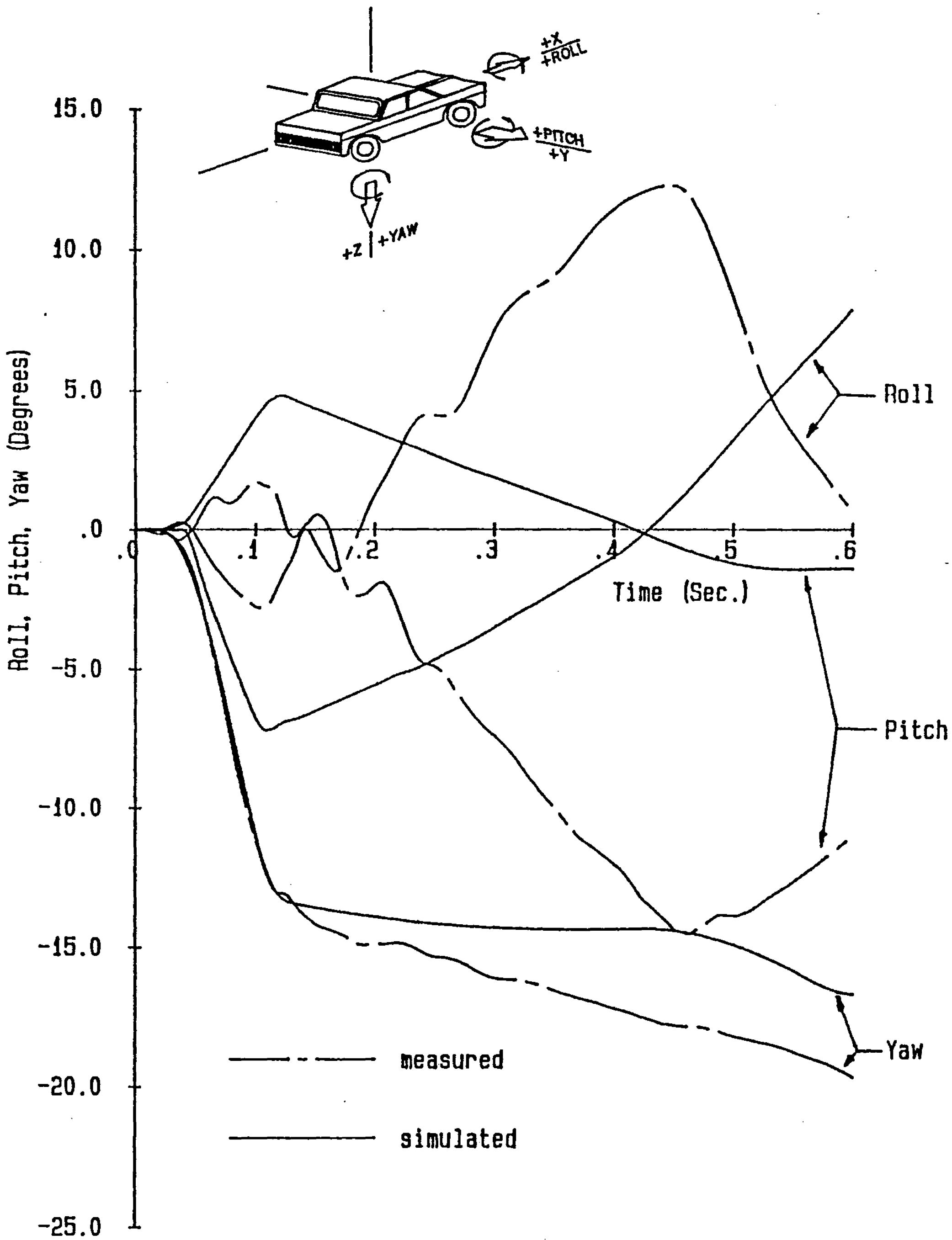


Figure 25. Measured and simulated vehicle angular displacements for test 4798-1 (1977 Honda Civic on a CSSB).

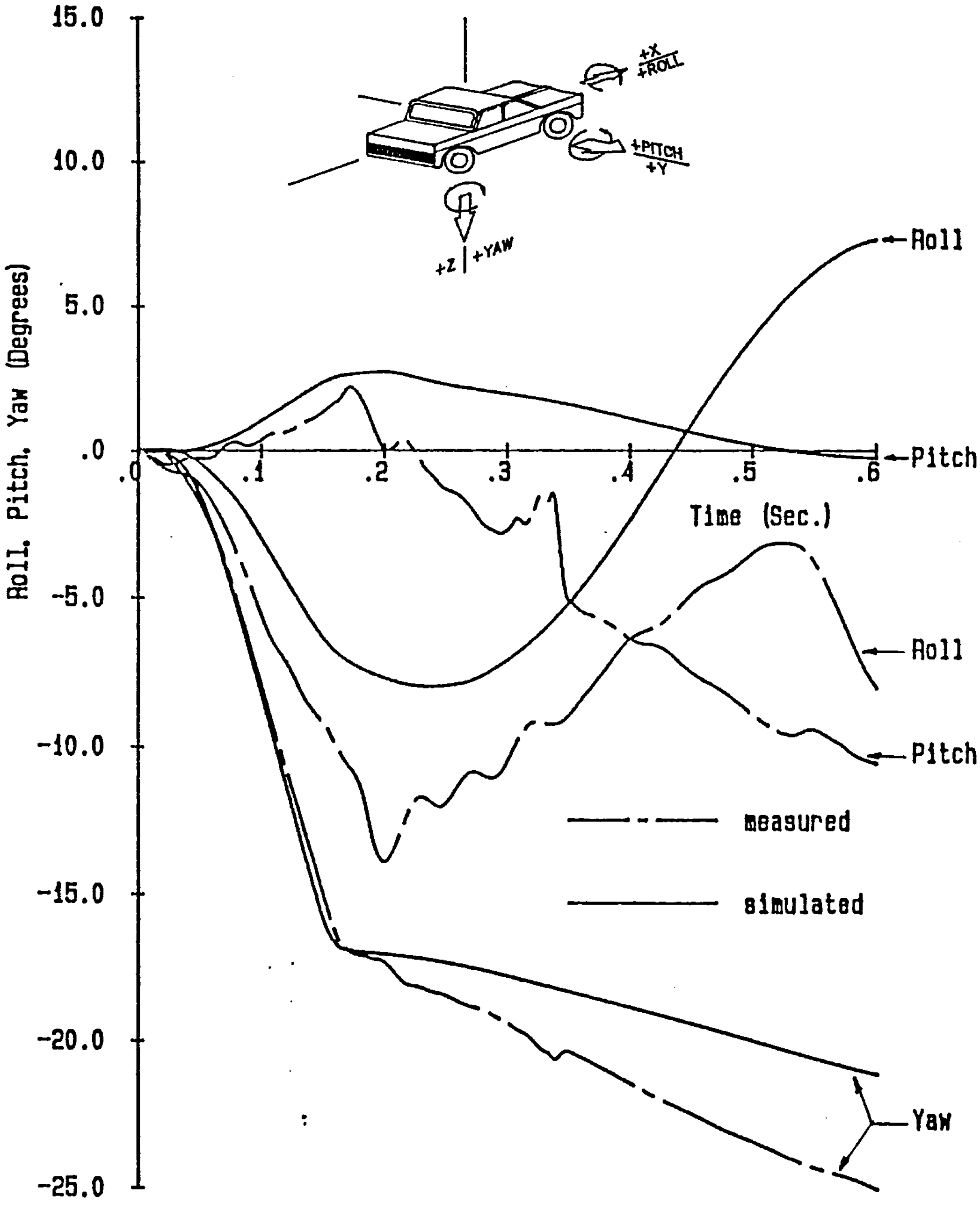


Figure 26. Measured and simulated vehicle angular displacements for test 4798-3 (1977 Plymouth Fury on a CSSB).

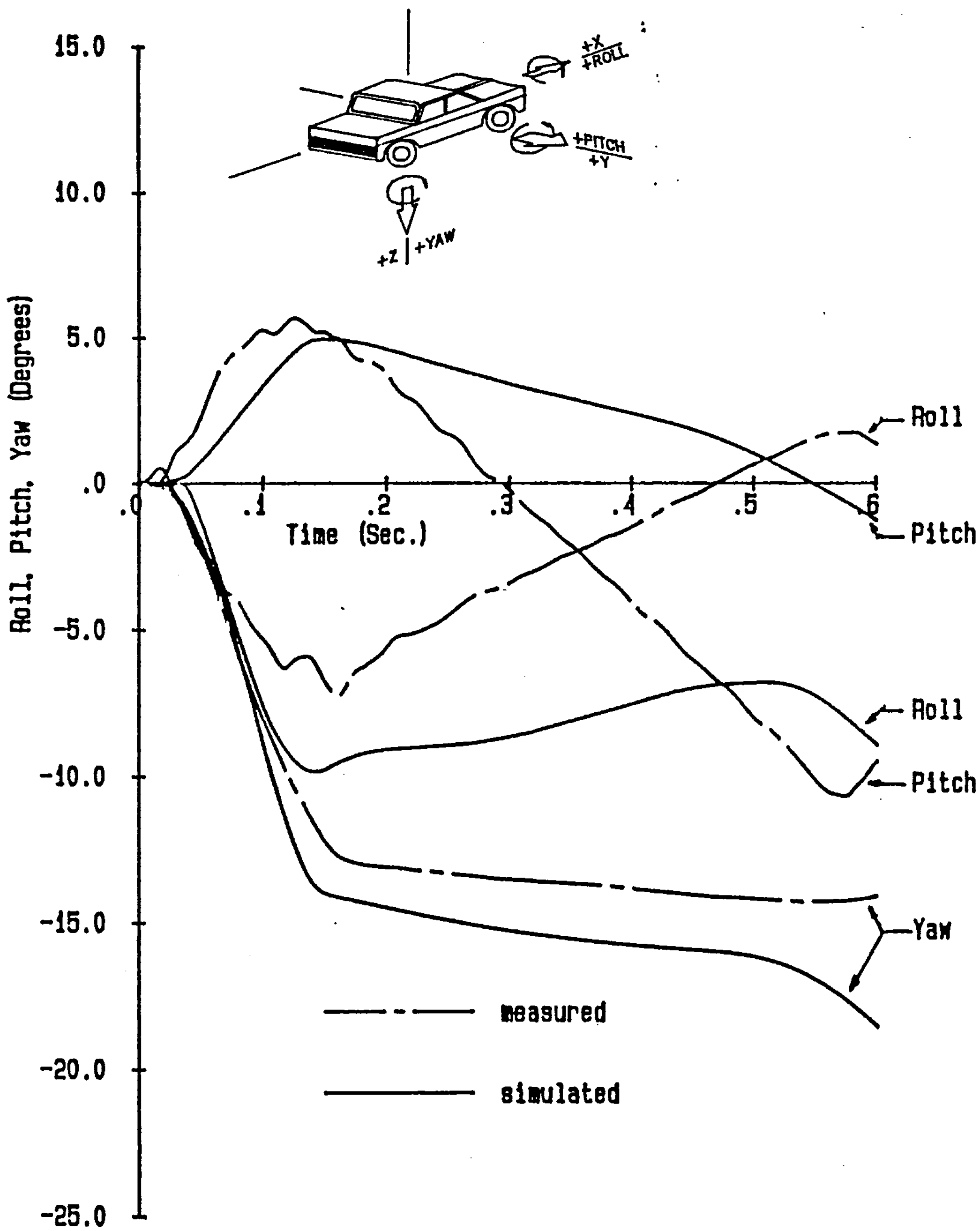


Figure 27. Measured and simulated vehicle angular displacements for test 7043-1 (1985 Fiat Uno-45 on a CSSB at 15 degrees).

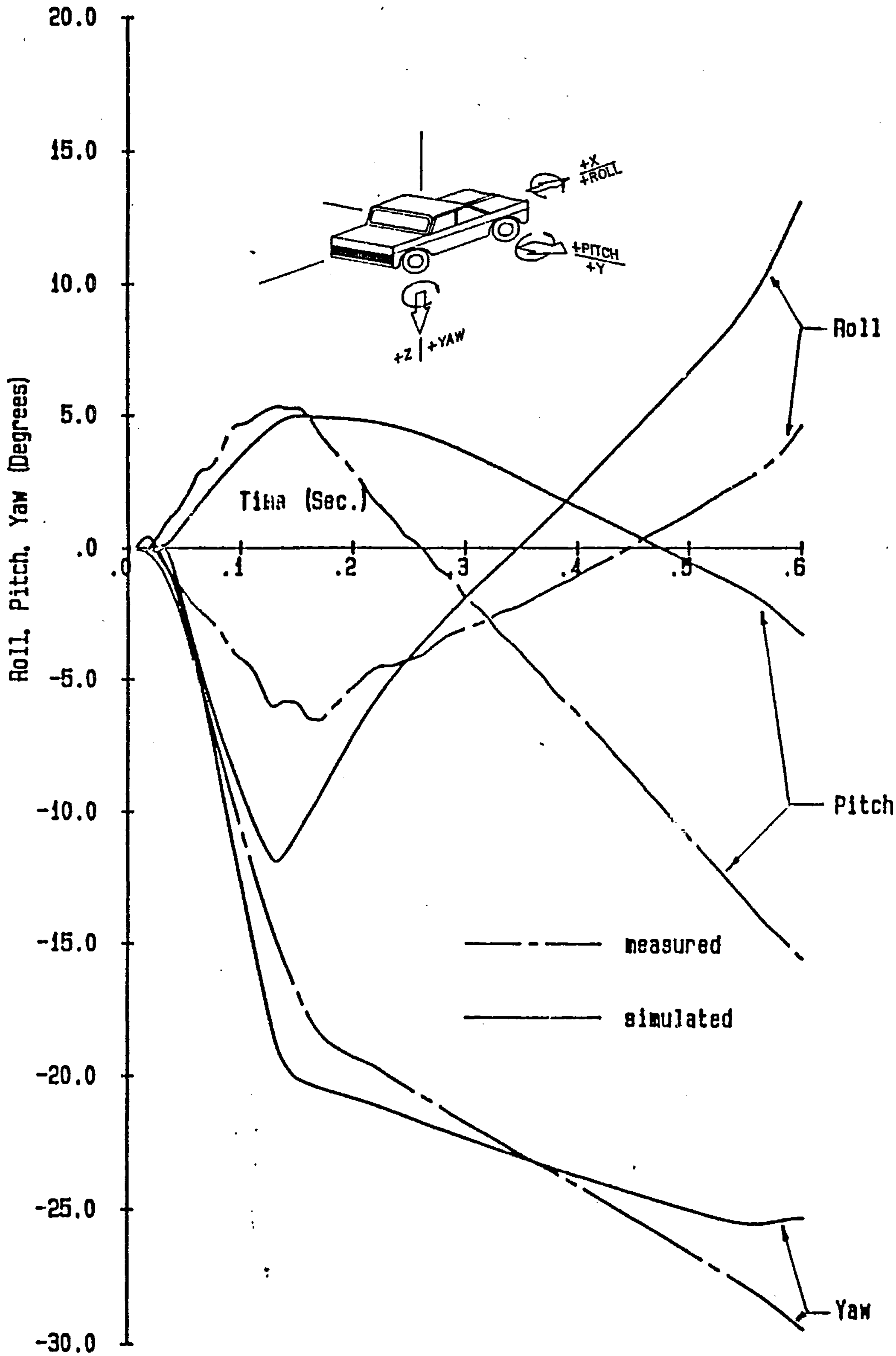


Figure 28. Measured and simulated vehicle angular displacements for test 7043-2 (1985 Fiat Uno-45 on a CSSB at 21.9 degrees).

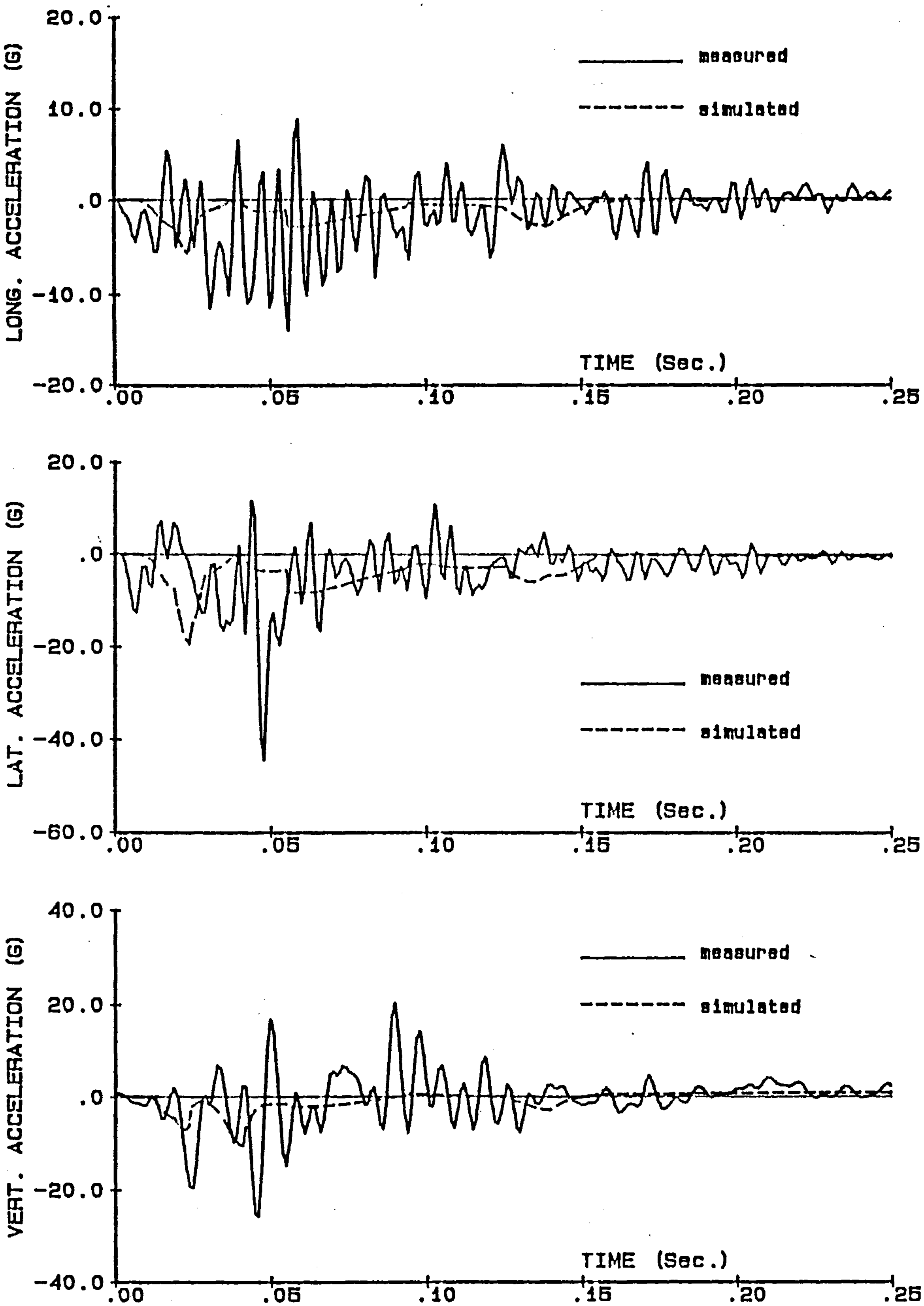


Figure 29. Measured and simulated longitudinal, lateral and vertical accelerations for test 7043-1 (1985 Fiat-Uno on a CSSB at 15 degrees).

and 30. The curves compare reasonably well when the measured curves were averaged to eliminate the spikes caused by high-frequency vibration of vehicular structural elements.

In test 7043-3, a 1985 Daihatsu Domino was directed into a CSSB at 60.0 mi/h and 16.0 degrees. Measured and predicted angular displacements and longitidinal, lateral, and vertical accelerations for this test are shown in figures 31 and 32. Correlation between the simulated and measured curves was similar to the previous two tests. Note that severe suspension damage was again observed at the vehicle's right front wheel. Since HVOSM could not simulate this damage, the correlation between the predicted and measured roll trajectories began to deteriorate after the vehicle returned to the ground.

A 1985 Ford Fiesta impacted the CSSB in test no. 7043-4 at 61.6 mi/h and 16.0 degrees. As shown in figure 33, the program again predicted yaw and roll displacements with a reasonable degree of accuracy. The general shape of measured and predicted roll displacement curves was the same. However, the correlation between predicted and measured pitch displacements was not as good due to vehicle suspension damage and aforementioned limitations in tire and suspension models of HVOSM. Measured and predicted longitudinal, lateral, and vertical accelerations are shown in figure 34. These curves show good correlation as in the previous three tests.

In test 7043-12, a 1985 Chevrolet Sprint was directed into a CSSB at 61.6 mi/h and 20.1 degrees. Measured and predicted angular displacements for this test are shown in figure 35. The program was able to predict both roll and yaw displacements for this test with a reasonable degree of accuracy. The shapes of the measured and predicted pitch displacements were close with a slightly larger deviation than in the tests involving the Fiat Uno and Daihatsu Domino. Figure 36 shows that measured and predicted longitudinal, lateral, and vertical accelerations and the correlation is good, as in previous tests.

Finally, a single high impact angle crash test was simulated in an effort to validate HVOSM as much as possible for impacts outside the range of normal crash test conditions.(14) This test involved a Honda Civic impacting a CSSB at a speed of 27 mi/h and an angle of 52 degrees. When the vehicle impacted the barrier, it did not redirect significantly, but instead began to ride up the face of the barrier until it rolled over. The vehicle rolled slowly away from the barrier until it reached a roll angle of approximately 80 degrees and came to rest on an exterior camera rack mounted to the passenger's side door. The vehicle came to rest with its heading direction making an angle of 69 degrees with the centerline of the barrier, resulting in a net yaw displacement of 17 degrees. HVOSM predicted a slow rollover away from

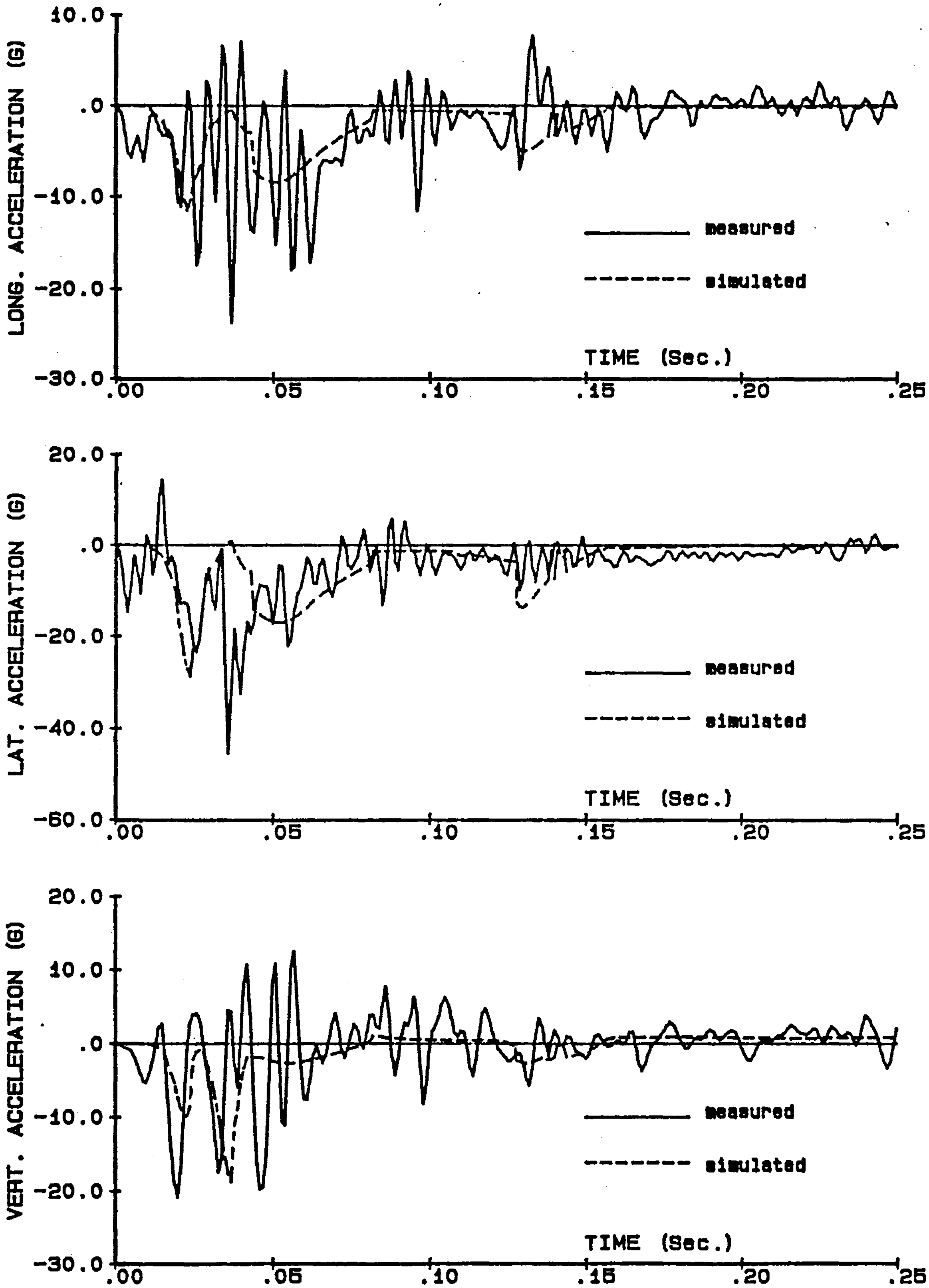


Figure 30. Measured and simulated longitudinal, lateral and vertical accelerations for test 7043-2 (1985 Fiat-Uno on a CSSB at 21.9 degrees).

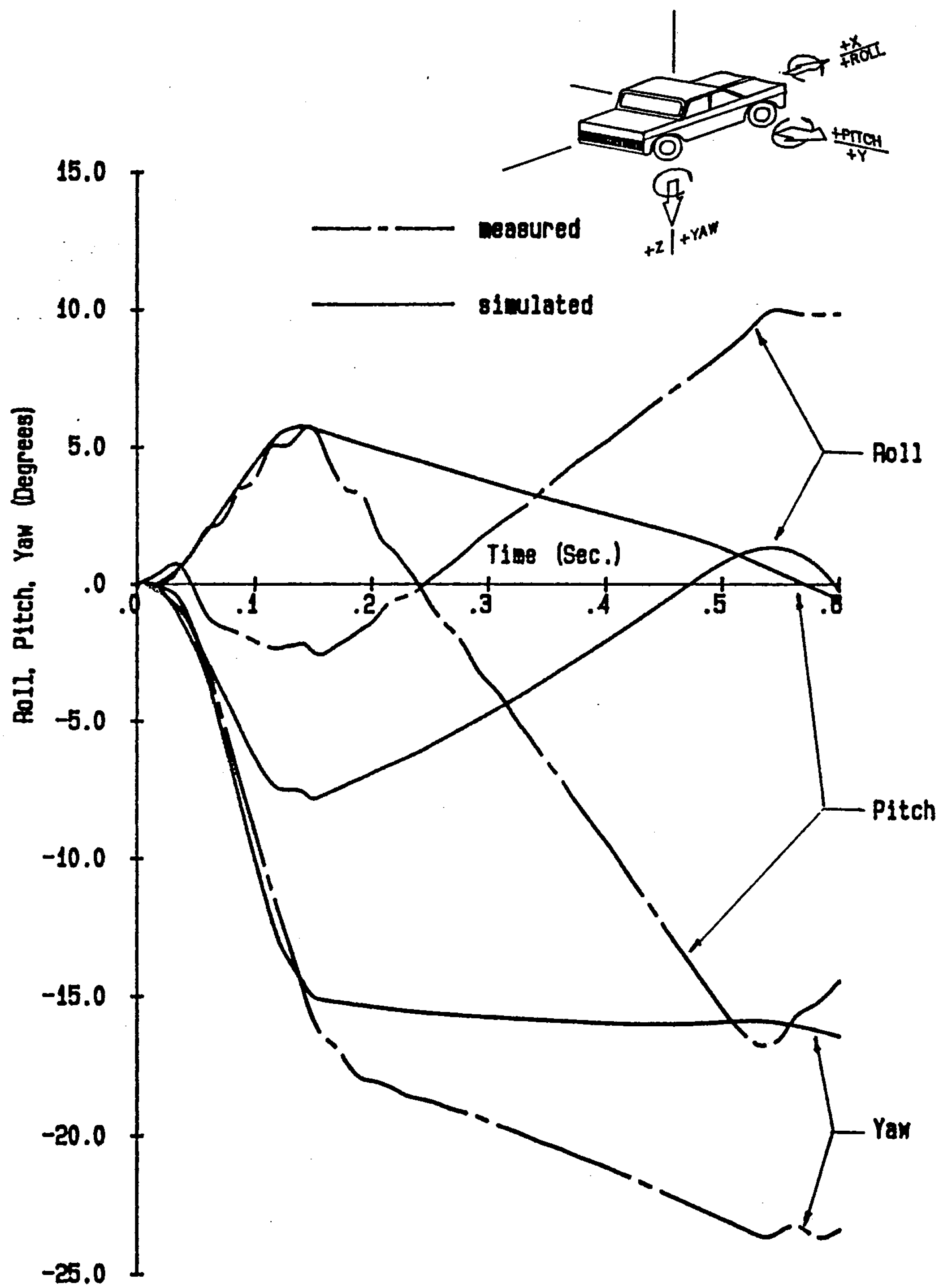


Figure 31. Measured and simulated vehicle angular displacements for test 7043-3 (1985 Dihatsu Domino on a CSSB).

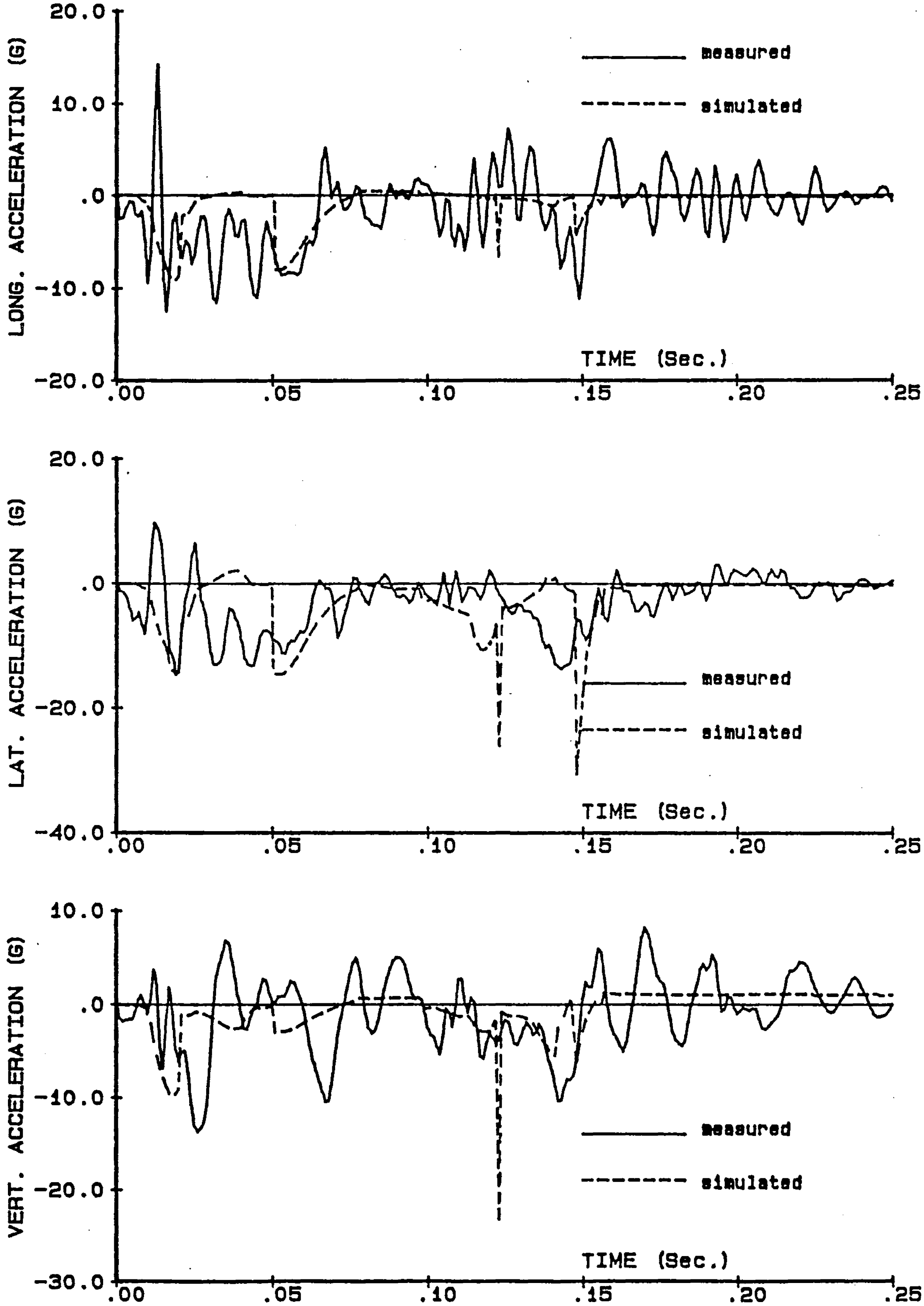


Figure 32. Measured and simulated longitudinal, lateral and vertical accelerations for test 7043-3 (1985 Dihatsu Domino on a CSSB)

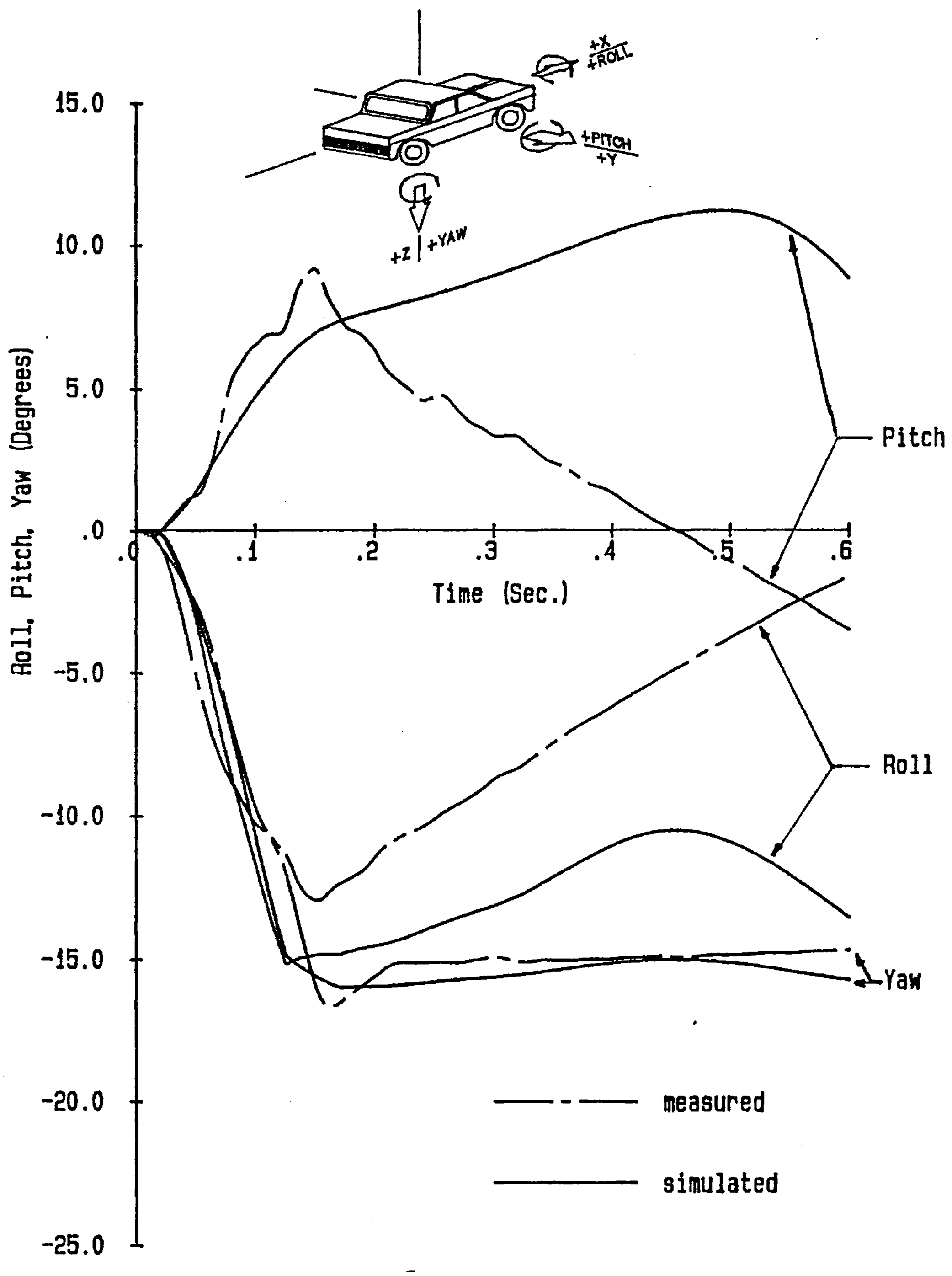


Figure 33. Measured and simulated vehicle angular displacements for test 7043-4 (1985 Ford Fiesta on a CSSB).

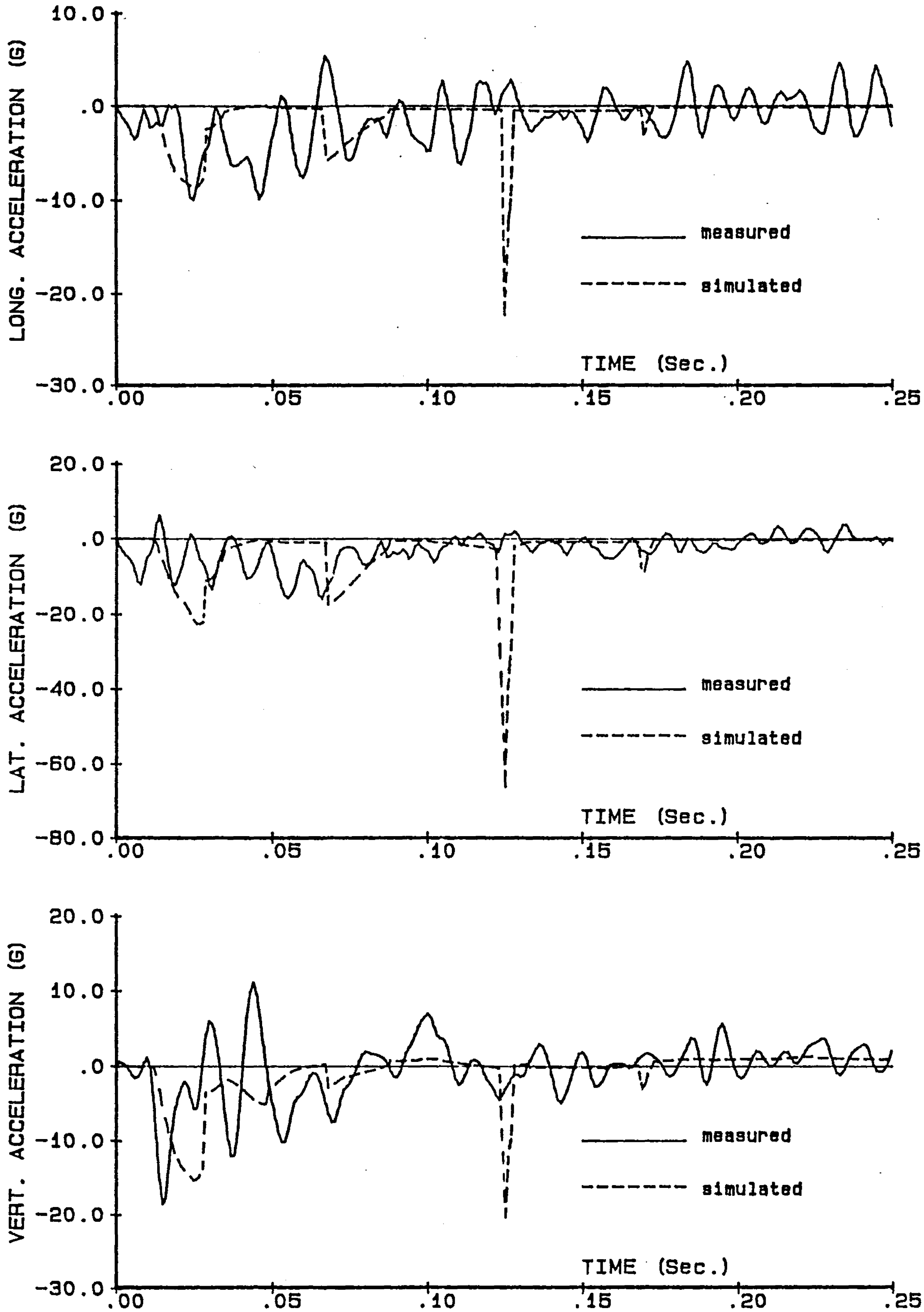


Figure 34. Measured and simulated vehicle angular displacements for test 7043-4 (1985 Ford Fiesta on a CSSB).

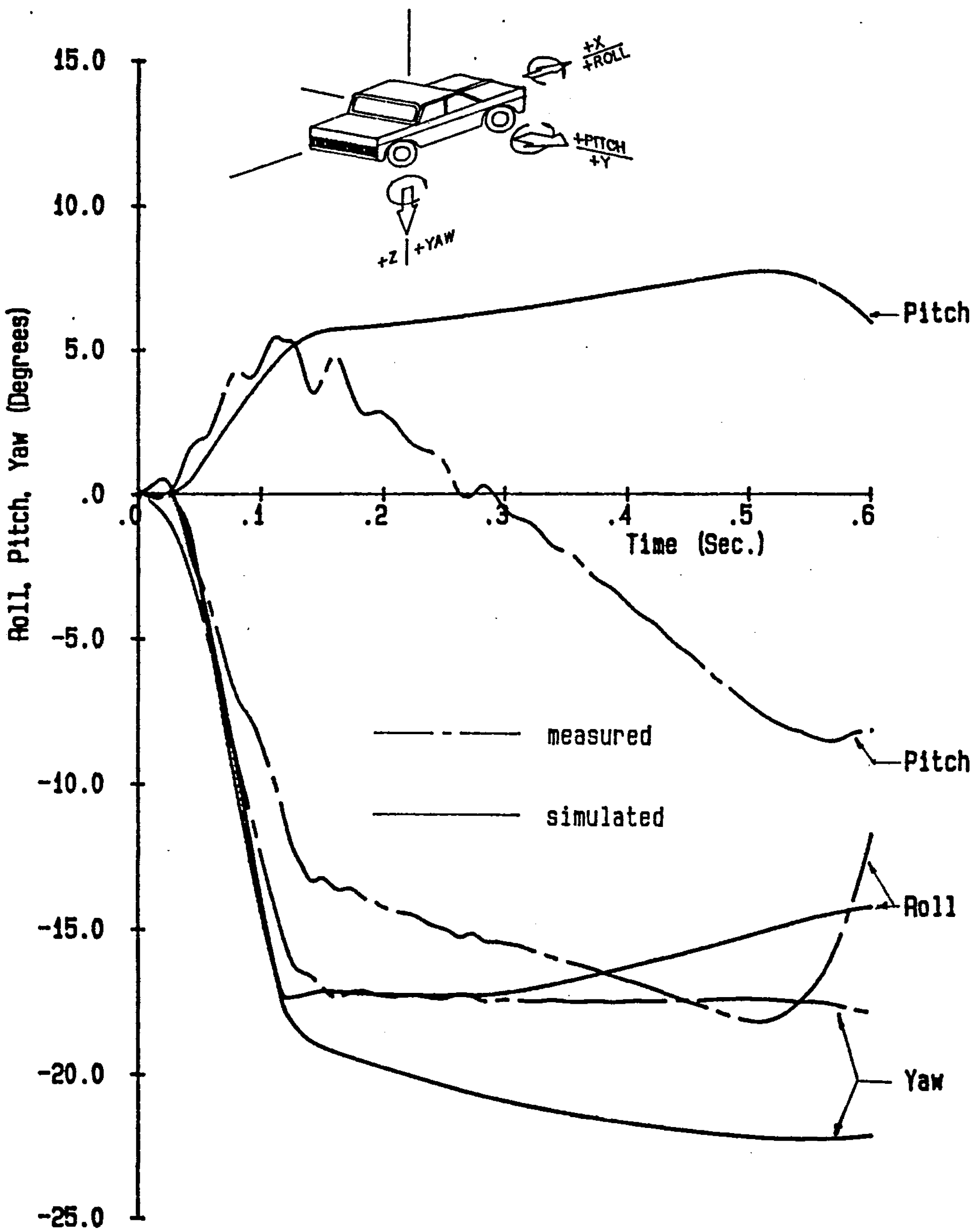


Figure 35. Measured and simulated vehicle angular displacements for test 7043-12 (1985 Chevrolet Sprint on a CSSB).

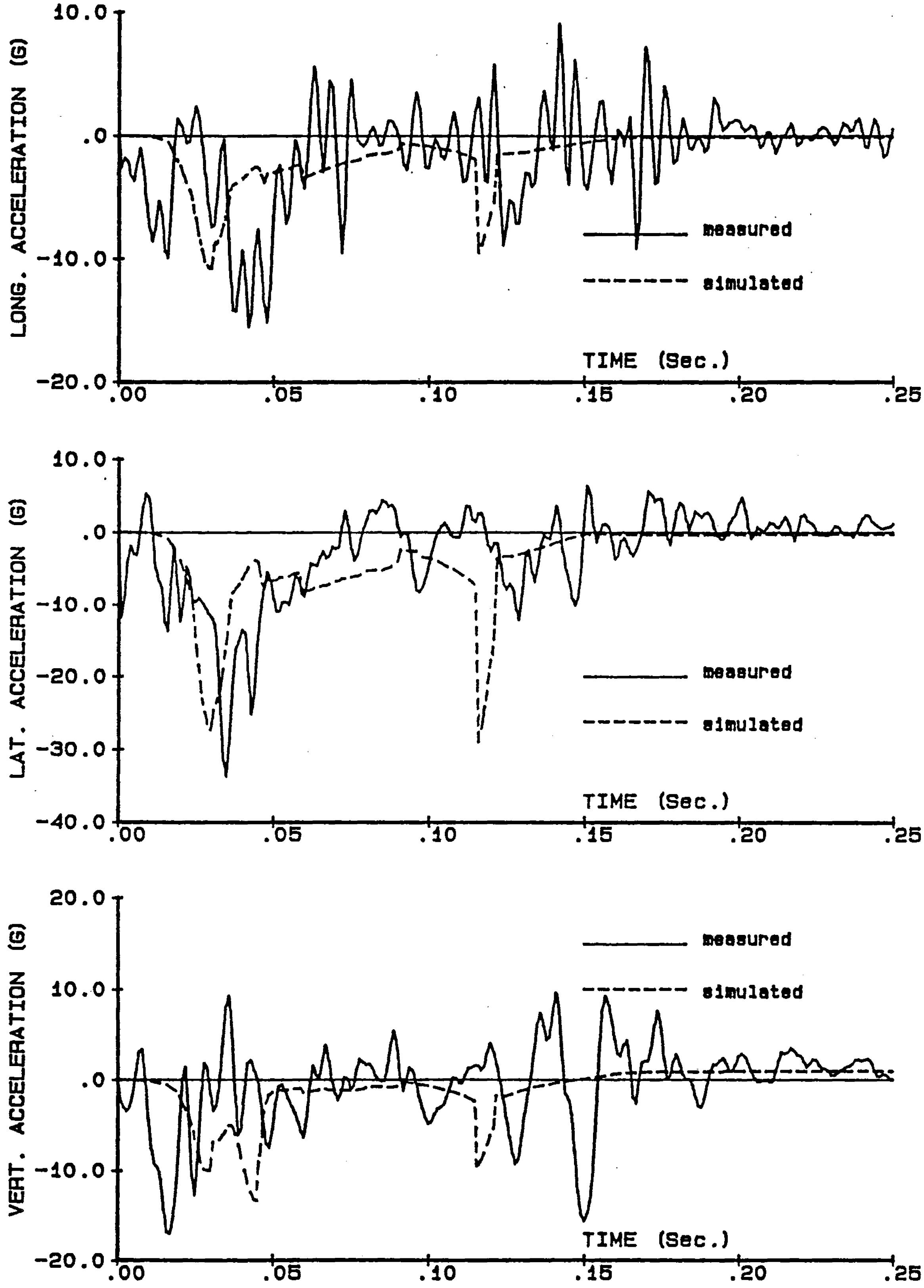


Figure 36. Measured and simulated longitudinal, lateral and vertical accelerations for test 7043-12 (1985 Chevrolet Sprint on a CSSB).

the barrier and predicted a yaw dispacement 11.5 degrees when the vehicle roll angle reached at 90 degrees.

Measured and predicted maximum 50-ms-average longitudinal, lateral, and vertical accelerations of the vehicle for all 8 tests with the CSSB are compared in table 21. The measured and predicted maximum values compare reasonably well. However, the simulations generally predicted lower accelerations than were observed in the vertical wall tests. Actual accelerations have perturbations due to the nonhomogeneous structure of the vehicle and high-frequency vibrations of vehicular structural elements. The assumption of a homogeneous crush model results in a smooth acceleration versus time curve. These differences in the idealized versus actual vehicle structure are believed to be the reason for differences in average accelerations compared over a relatively small time increment.

Calibration of the HVOSM program involved adjusting the vehicle/barrier friction coefficients to determine appropriate values for each tested barrier. This effort revealed that vehicle/barrier friction has a significant effect on longitudinal accelerations and consequently the vehicle's yaw trajectory is also effected significantly. However, barrier surface friction did not appear to have a significant effect on a vehicle's roll stability or hieght of climb. However, the aforementioned problems associated with HVOSM's thin disk tire model may mask some of the effects of high barrier friction on tire scrubbing forces. As a result, although the analysis described herein does not indicate that barrier surface friction affects vehicle roll stability, these findings cannot be considered to be conclusive.

As mentioned previously, the ranges of crush parameters k_v, c_v, and n_v estimated in frontal impact simulations were adjusted for angular impacts during the validation and calibration procedure described above. The values of these parameters used for each different vehicle were adjusted within the basic range to better simulate each test and are listed in table 21. The stiffness value used for the rear structural hard point was higher than that for the front to account for differences in front and rear suspension systems. These values are tabulated in table 22.

An attempt to develop a relationship between the crush parameters k_v, c_v, and n_v and the size or mass of the vehicle was unsuccessful due to extreme scatter in vehicle data. These findings are not surprising in light of extreme variations in measured frontal crush stiffness reported in references 4 and 15.

Table 21. Vehicle crush parameters used in vertical wall and CSSB simulations.

Vehicle	k_v (lb./in.^{3})	c_v	n_v
1974 Honda Civic	0.85	0.1	0.6
1975 Plymouth Fury	1.0	0.3	0.6
1985 Fiat Uno-45	0.7	0.15	0.6
1985 Daihatsu Domino	0.5	0.05	0.5
1985 Ford Fiesta	0.65	0.05	0.5
1985 Chevrolet Sprint	0.9	0.3	0.6

Table 22. Structural hard point parameters used in vertical wall and CSSB simulations.

Vehicle	Front			Rear		
	k_{sti} (lb/in)	c_{sti}	n_{sti}	k_{sti} (lb/in)	c_{sti}	n_{sti}
1974 Honda Civic	500	0.2	0.8	700	0.4	1.0
1975 Plymouth Fury	400	0.2	0.6	1000	0.35	0.75
1985 Fiat Uno-45	500	0.2	0.7	600	0.3	0.8
1985 Daihatsu Domino	500	0.3	0.9	600	0.45	1.0
1985 Ford Fiesta	600	0.3	0.8	700	0.4	0.9
1985 Chevrolet Sprint	400	0.2	0.6	500	0.3	0.8

Description of the Modified Portions HVOSM Input

The HVOSM program was originally written such that input could be supplied in the form of punched cards. According to this input format, all data cards must contain a three-digit number in columns 78-80. The first of these represent the card number within the data block. Data blocks are catagorized and numbered as follows:

Block Number	Data Content
1	Simulation Control data
2	Vehicle data
3	Tire data
4	Vehicle Control data
5	Terrain/Environmental data
6	Initial Conditions

Each data block may contain a title card with two digits of the card number being 00 (e.g., vehicle data title card would be numbered 200). Title cards may contain alphanumeric information which is printed on each output page.

Data is entered on individual data cards in 9 fields of 8 columns each (9F8.0 format). Any data not supplied defaults to 0.0. The last card in the input data deck must be numbered 9999 in columns 77-80. For more information on input card decks, the reader is referred to reference 8.

To accommodate the input to the modified portions of HVOSM, a number of changes were made to the input format described in reference 8. These changes are as follows:

1. Some input parameters in card nos. 102 and 103 of block no. 1 were changed.

2. Four cards were allocated to input suspension damping properties in place of card no. 206. In order to accomadate these four cards, every card following card no. 206 was moved down three positions (e.g. the card no. 207 was moved to card no. 210). (See figure 37.)

3. The last three cards numbered 212, 213, and 214 of block no. 2 of the original input format, that were moved to 215, 216 and 217 according to the change no. 2 above, were replaced with 5 cards to input the DT point and new structural hard point information.

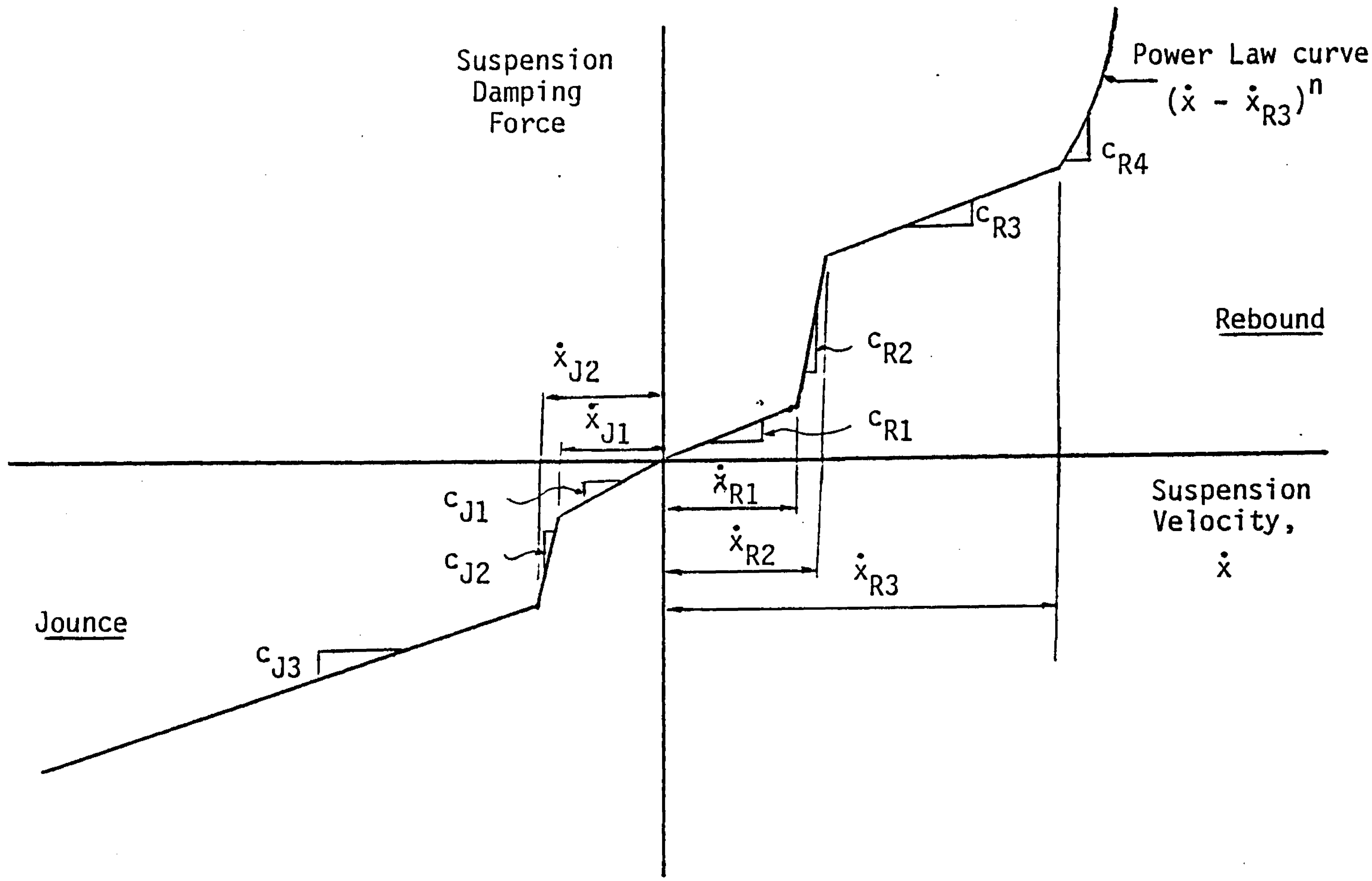


Figure 37. Suspension damping parameters.

4. Card nos. 510 and 511 of block no. 5 were changed to input the new barrier model.

A description of the data required on each of these changed and new input cards is given on following pages.

Listing of the Modified Portions of HVOSM

Modified portions of the existing subroutines and the new subroutines added to HVOSM are listed on the following pages. Each modified portion of existing subroutines starts on a new page and is listed along with a few unchanged statements at the beginning and at the end. The modified statements are given in boldface. All of the new subroutines are also given in boldface.

Card No. 102									
ISUS	INDCRB	NCRBSL	DELTC	INDB	DELTB	COLL	NUMT	ISKIP	102
1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64	65-72	78-80

Program Variable	Analyt. Variable	Description	Input Units
ISUS		SUSPENSION OPTION INDICATOR = 0, INDEPENDENT FRONT, SOLID REAR AXLE = 1, INDEPENDENT FRONT AND REAR = 2, SOLID FRONT AND REAR AXLES	-
INDCRB		CURB IMPACT INDICATOR = 0, NO CURB INPUT = 1, CURB INPUT SUPPLIED (PROVIDES STEER DEGREE OF FREEDOM AND RADIAL SPRING-DAMPER TIRE MODEL) = -1, NO CURB INPUT SUPPLIED (PROVIDES STEER DEGREE OF FREEDOM WITH POINT CONTACT TIRE MODEL)	-
NCRBSL		NUMBER OF CURB SLOPES SUPPLIED IF INDCRB = 1 ($2 \le$ NCRBSL ≤ 6)	-
DELTC	Δt_C	INTEGRATION TIME STEP FOR CURB IMPACTS	sec
INDB		BARRIER IMPACT INDICATER = 0, NO BARRIER INPUT = 1, VEHICLE IS GOING TO IMPACT A BARRIER AND THE BARRIER INPUT IS SUPPLIED	
DELTB	$(\Delta t)_B$	VEHICLE INTEGRATION TIME STEP FOR USE DURING BARRIER IMPACTS NOTE: If INDCRB = -1, initial conditions for the front steer angle (PSIFIO, PSIFD) must be supplied on card 601.	sec
COLL		SIGN IMPACT OPTION INDICATOR = 0, SIGN IMPACT OPTION IS NOT IN EFFECT = 1, SIGN IMPACT OPTION IS IN EFFECT	-

Card No. 102 (continued)			
Program Variable	**Analyt. Variable**	**Description**	**Input Units**
NUMT		NUMBER OF DATA POINTS IN THE SIGN IMPACT FORCE VS. TIME CURVE	-
ISKIP		INDICATOR FOR PRINTING HEADINGS ON TOP OF EACH PAGE OF OUTPUT FILES = 0, PRINTED ON TOP OF EACH PAGE = 1, PRINTED ONLY ON TOP OF OUTPUT FILES	-

Card No. 103									
MODE								IDR	103
1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64	65-72	78-80

Program Variable	**Analyt. Variable**	**Description**	**Input Units**
MODE		NUMERICAL INTEGRATION MODE INDICATOR Note: Fixed and variable Adams-Moulton integration modes were taken off, due to their rare use. Hence, only the Runge-Kutta integration mode can be used and MODE should always be equal to 1.	-
IDR		INDICATOR FOR ANGULAR ACCELERATION UNITS OPTION = 0, SPRUNG MASS ANGULAR ACCELERATIONS ARE PRINTED IN DEG/SEC^2 = 1, SPRUNG MASS ANGULAR ACCELERATIONS ARE PRINTED IN RAD/SEC^2	-

Card No. 206									
(CFJ(I),DLFJ(I),I=1,2)				CFJ(3)	CFP	EPSF	RATF		206
1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64	65-72	78-80

Program Variable	Analyt. Variable	Description	Input Units
CFJ(1) CFJ(2) CFJ(3)	c_{J1} c_{J2} c_{J3} (front)	FRONT VISCOUS DAMPING COEFFICIENTS NUMBERE 1,2, & 3 IN JOUNCE (see Figure F-33), PER SIDE	$\frac{\text{lb-sec}}{\text{in.}}$
DLFJ(1)	$\dot{x}_{J1}$ (front)	FRONT SUSPENSION VELOCITY AT THE CHANGE OF DAMP. COEF. NO. 1 IN JOUNCE TO DAMP. COEF. NO. 2 IN JOUNCE	in./sec
DLFJ(2)	$\dot{x}_{J2}$ (front)	FRONT SUSPENSION VELOCITY AT THE CHANGE OF DAMP. COEF. NO. 2 IN JOUNCE TO DAMP. COEF. NO. 3 IN JOUNCE	in./sec
CFP	C'_F	FRONT SUSPENSION COULOMB FRICTION PER SIDE	lb
EPSF	ϵ_F	FRONT SUSPENSION FRICTION NULL BAND	in./sec
		NOTE: For solid axle all suspension parameters are effective at the spring. For indep. susp. the parameters effective at the shockabsorber can be specified with a ratio converting them to the values effective at the wheel.	
RATF		RATIO CONVERTING THE FRONT SUSPENSION PARAMETERS TO THE VALUES EFFECTIVE AT THE WHEEL. RATF = (AT SHOCKAB.)/(AT WHEEL)	-

Card No. 207									
(CFR(I),DLFR(I),I=1,3)						CFR(4)	POWF		207
1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64	65-72	78-80

Program Variable	Analyt. Variable	Description	Input Units
CFR(1) CFR(2) CFR(3) CFR(4)	c_{R1} c_{R2} c_{R3} c_{R4} (front)	FRONT VISCOUS DAMPING COEFFICIENTS NUMBERE 1,2,3, & 4 IN REBOUND (see Figure F-33), PER SIDE	$\frac{\text{lb-sec}}{\text{in.}}$
DLFR(1)	$\dot{x}_{R1}$ (front)	FRONT SUSPENSION VELOCITY AT THE CHANGE OF DAMP. COEF. NO. 1 IN REBOUND TO DAMP. COEF. NO. 2 IN REBOUND	in./sec
DLFR(2)	$\dot{x}_{R2}$ (front)	FRONT SUSPENSION VELOCITY AT THE CHANGE OF DAMP. COEF. NO. 2 IN REBOUND TO DAMP. COEF. NO. 3 IN REBOUND	in./sec
DLFR(3)	$\dot{x}_{R3}$ (front)	FRONT SUSPENSION VELOCITY AT THE CHANGE OF DAMP. COEF. NO. 3 IN REBOUND TO DAMP. COEF. NO. 4 IN REBOUND	in./sec
POWF	n (front)	POWER TO WHICH THE FRONT SUSPENSION VELOCITY IS RAISED IN THE POWER LAW DAMPING TERM OF THE EXPRESSION FOR DAMP. FORCE IN REBOUND	

Card No. 208									
(CRJ(I),DLRJ(I),I=1,2)				CRJ(3)	CRP	EPSR	RATR		208
1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64	65-72	78-80

Program Variable	**Analyt. Variable**	**Description**	**Input Units**
CRJ(1) CRJ(2) CRJ(3)	c_{J1} c_{J2} c_{J3} (rear)	REAR VISCOUS DAMPING COEFFICIENTS NUMBERE 1,2, & 3 IN JOUNCE (see Figure F-33), PER SIDE	$\frac{\text{lb-sec}}{\text{in.}}$
DLRJ(1)	$\dot{x}_{J1}$ (rear)	REAR SUSPENSION VELOCITY AT THE CHANGE OF DAMP. COEF. NO. 1 IN JOUNCE TO DAMP. COEF. NO. 2 IN JOUNCE	in./sec
DLRJ(2)	$\dot{x}_{J2}$ (rear)	REAR SUSPENSION VELOCITY AT THE CHANGE OF DAMP. COEF. NO. 2 IN JOUNCE TO DAMP. COEF. NO. 3 IN JOUNCE	in./sec
CRP	C'_R	REAR SUSPENSION COULOMB FRICTION PER SIDE	lb
EPSR	ϵ_R	REAR SUSPENSION FRICTION NULL BAND	in./sec
		NOTE: For solid axle all suspension parameters are effective at the spring. For indep. susp. the parameters effective at the shockabsorber can be specified with a ratio converting them to the values effective at the wheel.	
RATR		RATIO CONVERTING THE REAR SUSPENSION PARAMETERS TO THE VALUES EFFECTIVE AT THE WHEEL. RATR = (AT SHOCKAB.)/(AT WHEEL)	-

Card No. 209									
(CRR(I),DLRR(I),I=1,3)						CRR(4)	POWR		209
1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64	65-72	78-80

Program Variable	**Analyt. Variable**	**Description**	**Input Units**
CRR(1) CRR(2) CRR(3) CRR(4)	c_{R1} c_{R2} c_{R3} c_{R4} (rear)	REAR VISCOUS DAMPING COEFFICIENTS NUMBERE 1,2,3, & 4 IN REBOUND (see Figure F-33), PER SIDE	$\frac{\text{lb-sec}}{\text{in.}}$
DLRR(1)	$\dot{x}_{R1}$ (rear)	REAR SUSPENSION VELOCITY AT THE CHANGE OF DAMP. COEF. NO. 1 IN REBOUND TO DAMP. COEF. NO. 2 IN REBOUND	in./sec
DLRR(2)	$\dot{x}_{R2}$ (rear)	REAR SUSPENSION VELOCITY AT THE CHANGE OF DAMP. COEF. NO. 2 IN REBOUND TO DAMP. COEF. NO. 3 IN REBOUND	in./sec
DLRR(3)	$\dot{x}_{R3}$ (rear)	REAR SUSPENSION VELOCITY AT THE CHANGE OF DAMP. COEF. NO. 3 IN REBOUND TO DAMP. COEF. NO. 4 IN REBOUND	in./sec
POWR	n (rear)	POWER TO WHICH THE REAR SUSPENSION VELOCITY IS RAISED IN THE POWER LAW DAMPING TERM OF THE EXPRESSION FOR DAMP. FORCE IN REBOUND	

Card No. 215									
XVF	XVR	YV	ZVT	ZVB	AKV	CV	PNV		215
1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64	65-72	78-80

Program Variable	Analyt. Variable	Description	Input Units
XVF	x_{VF}	X COORDINATE OF FRONT OF VEHICLE	in.
XVR	x_{VR}	X COORDINATE OF REAR OF VEHICLE	in.
YV	y_V	HALF-WIDTH OF VEHICLE	in.
ZVT	z_{VT}	Z COORDINATE OF PLANE DEFINING TOP OF VEHICLE	in.
ZVB	z_{VB}	Z COORDINATE OF PLANE DEFINING BOTTOM OF VEHICLE	in.
AKV	k_v	VOLUMETRIC CRUSHING STIFFNESS OF VEHICLE STRUCTURE	lb/in^3.
CV	c_v	COEFF. OF DEFORMATION RATE TERM IN THE EXPRESSION FOR DYN. PRESSURE IN CRUSHING	-
PNV	n_v	POWER OF DEFORMATION RATE TERM IN THE EXPRESSION FOR DYN. PRESSURE IN CRUSHING	-

Card No. 216									
NPTX	NPTY	NPTV	KBT	KRTN					216
1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64	65-72	78-80

Program Variable	Analyt. Variable	Description	Input Units
NPTX	n_{px}	NUMBER OF DEFORMATION TRACKING (DT) POINTS IN X-DIRECTION	-
NPTY	n_{py}	NUMBER OF DT POINTS IN Y-DIRECTION	-
NPTV		NUMBER OF DT POINTS IN VERTICAL DIRECTION (A MAXIMUM OF 10 INCLUDING POINTS ON TOP AND BOTTOM VEHICLE EDGES)	-
KBT	k_{bt}	INDICATOR FOR OPTION OF PLACING DT POINTS ON TOP VEHICLE SURFACE = 1, DT POINTS PLACED ON BOTTOM SURFACE ONLY = 2, DT POINTS PLACED ON BOTH TOP AND BOTTOM SURFACES	-
KRTN		INDICATOR FOR DIRECTION OF PRIMARY YAW ROTATION = 1, ANTICLOCKWISE AROUND Z AXIS = -1, CLOCKWISE AROUND Z AXIS	

Card No. 217									
(SPTV(I),I=1,NPTV-1)									217
1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64	65-72	78-80

Program Variable	Analyt. Variable	Description	Input Units
SPTV		VERTICAL SPACING BETWEEN DT POINTS ON SIDE SURFACES, STARTING FROM BOTTOM EDGE	in.

Card No. 218									
(XPT(I),I=1,3)			(YPT(I),I=1,3)			(ZPT(I),I=1,3)			218
1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64	65-72	78-80

Program Variable	Analyt. Variable	Description	Input Units
XPT YPT ZPT		INITIAL X, Y, AND Z POSITIONS OF THE VEHICLE STRUCTURAL HARD POINTS WITH RESPECT TO THE VEHICLE FIXED AXIS SYSTEM	in. in. in.

Card No. 219									
(AKST(I),I=1,3)			(CH(I),I=1,3)			(ZPT(I),I=1,3)			219
1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64	65-72	78-80

Program Variable	Analyt. Variable	Description	Input Units
AKST	k_{st}	CRUSHING STIFFNESSES OF VEHICLE STRUCTURAL HARD POINTS	lb/in.
CH	c_{st}	COEFFICIENTS OF DEFORMATION RATE TERM IN THE EXPRESSION FOR DYNAMIC FORCE AT VEHICLE STRUCTURAL HARD POINTS	-
PNH	n_{st}	POWERS OF DEFORMATION RATE TERM IN THE EXPRESSION FOR DYNAMIC FORCE AT VEHICLE STRUCTURAL HARD POINTS	-

Card No. 510									
AMUB	EPSV	NS	XSP(1)	YSP(1)	ZSP(1)				510
1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64	65-72	78-80

Program Variable	Analyt. Variable	Description	Input Units
AMUB	μ_B	COEFFICIENT OF FRICTION ACTING BETWEEN VEHICLE SPRUNG MASS AND BARRIER	-
EPSV	ϵ_v	FRICTION LAG FOR VEHICLE-BARRIER FRICTION FORCE	in./sec
NS	n_s	NUMBER OF SURFACES ON THE IMPACT SIDE OF THE BARRIER (SHOULD BE LESS THAN 5)	-
XSP(1)	x'_1	SPACE-FIXED COORDINATES (x′,y′,z′) OF THE ORIGIN OF THE FIRST BARRIER SURFACE-FIXED REFERENCE FRAME	in.
YSP(1)	y'_1		in.
ZSP(1)	z'_1		in.
THETB	θ_g	UPWARD GROUNG SLOPE IN THE LONGITUDINAL DIRECTION OF THE BARRIER	deg
		NOTE: See Figure F-35	

Card No. 511									
YL(1)	THS(1)	YL(2)	THS(2)	YL(3)	THS(3)	YL(4)	THS(4)		511
1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64	65-72	78-80

Program Variable	Analyt. Variable	Description	Input Units
YL(K)	y_{bk}	HALF-WIDTH OF k^{th} BARRIER SURFACE	in.
THS(K)	θ_k	INCLINATION OF k^{th} BARRIER SURFACE TO THE HORIZONTAL	deg
		NOTE : If the barrier has 5 faces the half-width and inclination of the fifth face should be supplied in the first two fields of a card numbered 512.	

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APPENDIX G
FRICTION MEASUREMENTS OF CONCRETE BARRIER SURFACES
SUMMARY OF TEST RESULTS

Surface friction on concrete safety shaped barriers (CSSB) has been reported to have a significant influence on the stability of impacting vehicles.[1] While the conclusions were based on only a couple of crash tests and there were other extenuating circumstances that could also have affected the test results, it did raise the question of the effect of surface friction on the performance of CSSB.

The most important effect of high barrier surface friction is believed to be the increase in the lifting force imparted to an impacting vehicle through tire sidewall scrubbing. Another factor related to barrier surface friction is the longitudinal retarding or frictional forces acting on the sheet metal of the impacting vehicle as it slides along the barrier.

Other than the study mentioned above, there has been little effort to date to determine the importance of barrier surface friction to the performance of the CSSB. In fact, there is little information even on the extent of variation in friction from a smooth barrier surface to an extremely rough surface. In support of simulation efforts to examine the importance of barrier friction to its performance, limited laboratory testing was undertaken to estimate the degree of variation in the sliding coefficients of friction found on CSSB surfaces.

Two CSSB surfaces were selected for testing in this study. The first CSSB, believed to represent a very low friction surface, was a recently manufactured precast barrier segment with a very smoothly finished surface. The second CSSB, selected for its extremely rough surface, was a 20-yr old weathered concrete barrier.

Surface friction was measured using a block, which consisted of a 20-lb weight on either a rubber tire pad or a sheet metal pad, on a horizontal barrier surface. The block was dragged slowly across the surface and the force required to maintain a constant sliding speed was measured using a spring scale. Four sets of tests were conducted for combinations of smooth or rough barrier surface and rubber tire or sheet metal pad. Each set of test included three or more repetitions to ensure accurate and consistent results. The test results indicated that variations among tests were relatively small, in the range of 1 to 2 lb out of 10 to 18 lb total force. Given the purpose of the tests, such accuracy is considered adequate.

Table 23 summarizes the results of the friction tests conducted. There are a couple of surprising results. The first is that the measured sheet metal friction was higher on the smooth or apparently lower friction surface than on the rough or apparently higher friction surface. A review of the test procedure revealed that, for the rough surface, the sheet metal was actually sliding along on a few small contact surfaces, thereby limiting the force required to drag the block.

Table 23. CSSB sliding friction coefficients

Test Material	Friction Coefficient	
	Smooth Surface	Rough Surface
Rubber Tire	0.57	0.76
Sheet Metal	0.80	0.45

Another surprising result is that, for the smooth or apparently low friction surface, the coefficient of friction is found to be higher for the sheet metal surface than for the rubber surface. There is no apparent explanation for this unexpected result. It is possible to speculate for plausible explanations, but without additional data, it would not be able to substantiate any of the speculations. Also, it is believed that the coefficient of sheet metal friction found for the rough barrier surface is a better approximation of sheet metal friction at high speed than that of the smooth surface and that value will be used for the simulation effort.

REFERENCE

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APPENDIX H
TEST REPORT 7051-1 - PENNDOT

INTRODUCTION

This test was conducted to evaluate the rollover potential of an 1800-lb vehicle traveling at 60 mi/h and 15 degrees when impacting a 34-in high shaped barrier with a 5-in vertical face at the bottom. Procedures and standards set forth in reference 1 were used for conducting, evaluating, and reporting this test.

TEST INSTALLATION

The barrier design and assembly used in this test was in accordance with drawing RC-57, March 19, 1985, of the Pennsylvania Department of Transportation (see figure 38). As shown in figure 39 the barrier has a 34-in height above the roadway with a 5-in vertical face at the bottom; a base width of 24 in; and a top width of 6 in. The installation consisted of five 20-ft sections connected by slotted plates as shown in figure 40.

INSTRUMENTATION AND DATA ANALYSIS

The vehicle was equipped with triaxial accelerometers mounted near the center of gravity. In addition yaw, pitch, and roll rates were measured by on-board instruments. The electronic signals were telemetered to a base station for recording on magnetic tape and for display on a real-time strip chart. Provision was made for transmission of calibration signals before and after the test, and an accurate time reference signal was simultaneously recorded with the data.

Contact switches on the bumper were actuated just prior to impact by wooden dowels to indicate the elapsed time over a known distance to provide a measurement of impact velocity. The initial contact also produced an "event" mark on the data record to establish the instant of impact. Data from the electronic transducers were digitized, using a microcomputer, for analysis and evaluation of performance.

An uninstrumented special purpose 50th percentile anthropomorphic test dummy was placed in the driver's position of the test vehicle. The dummy was restrained with standard equipment seat belts.

Analog data obtained from the electronic transducers were digitized and then analyzed on a microcomputer using three computer programs: CRASHE, VEHICLE, and PLOTANGLE.

The CRASHE program uses digitized data from vehicle-mounted linear accelerometers to compute occupant/compartment impact velocities, time of occupant/compartment impact after vehicle impact, final occupant displacement, highest 0.010-s average of vehicle acceleration after occupant/compartment impact, and time of highest 0.010-s average. The CRASHE program also calculates a vehicle impact velocity and the change in vehicle velocity at the end of a given impulse period.

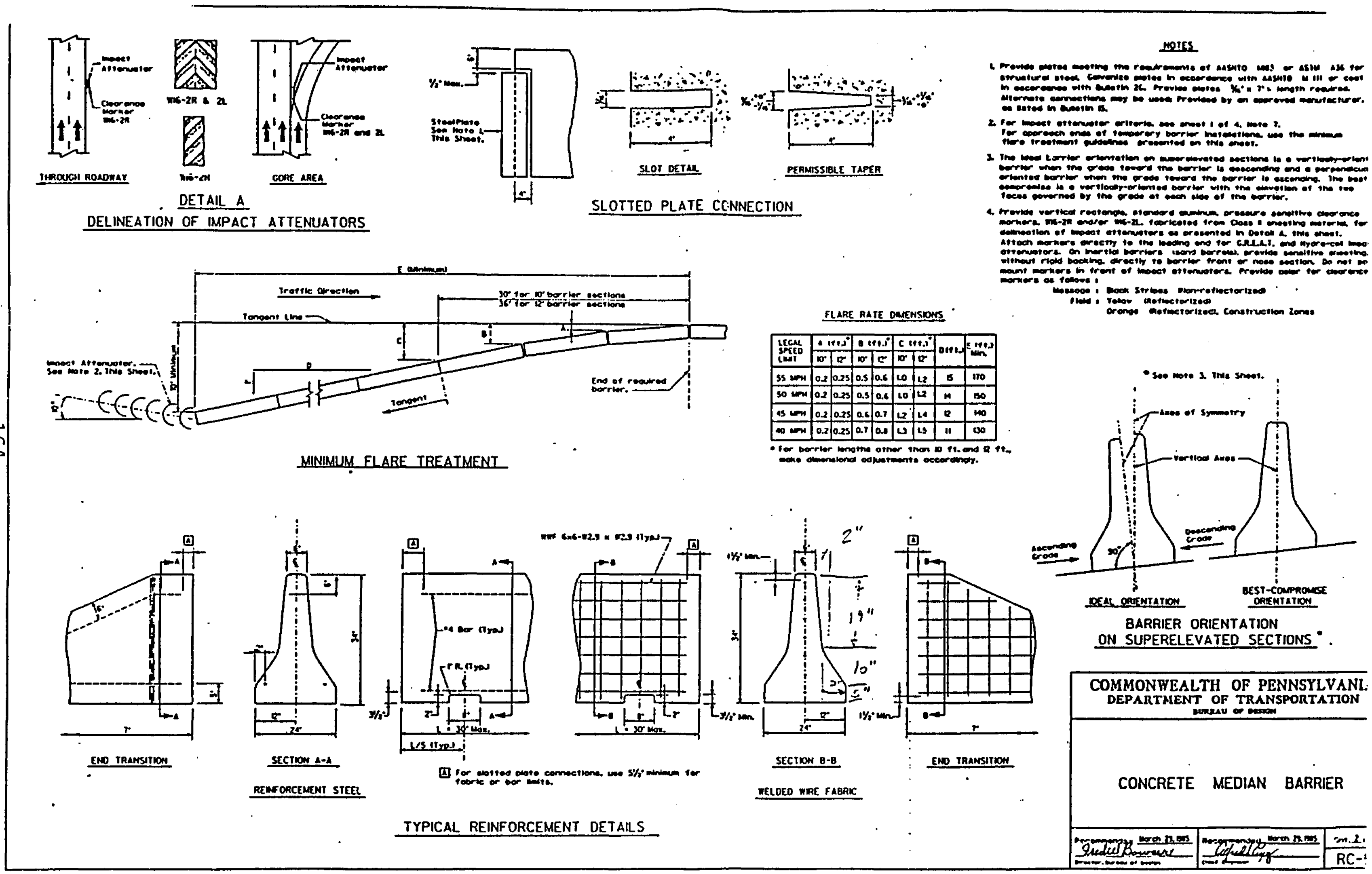


Figure 38. Details of barrier used in test 7051-1.

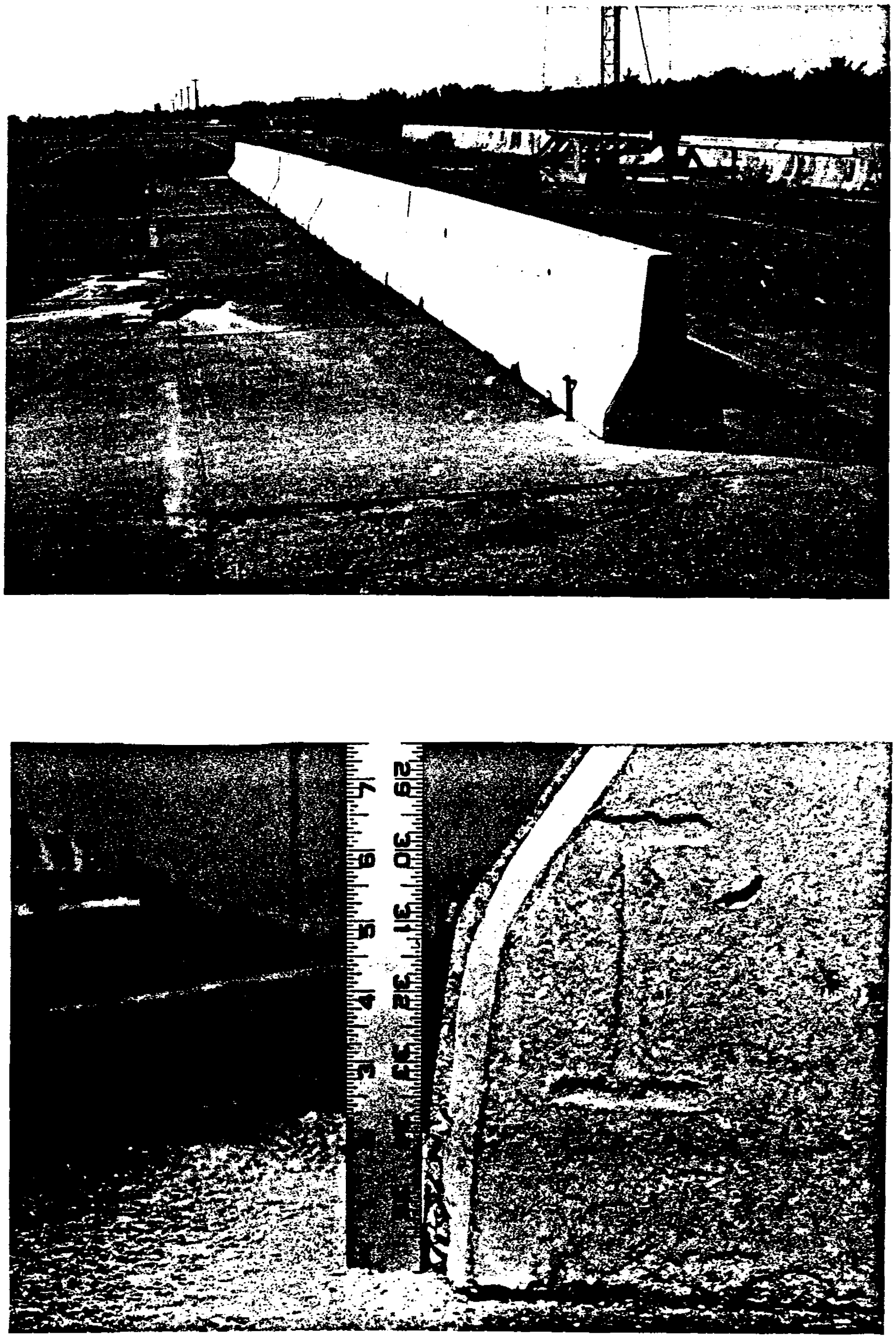


Figure 39. Test barrier before test 7051-1.

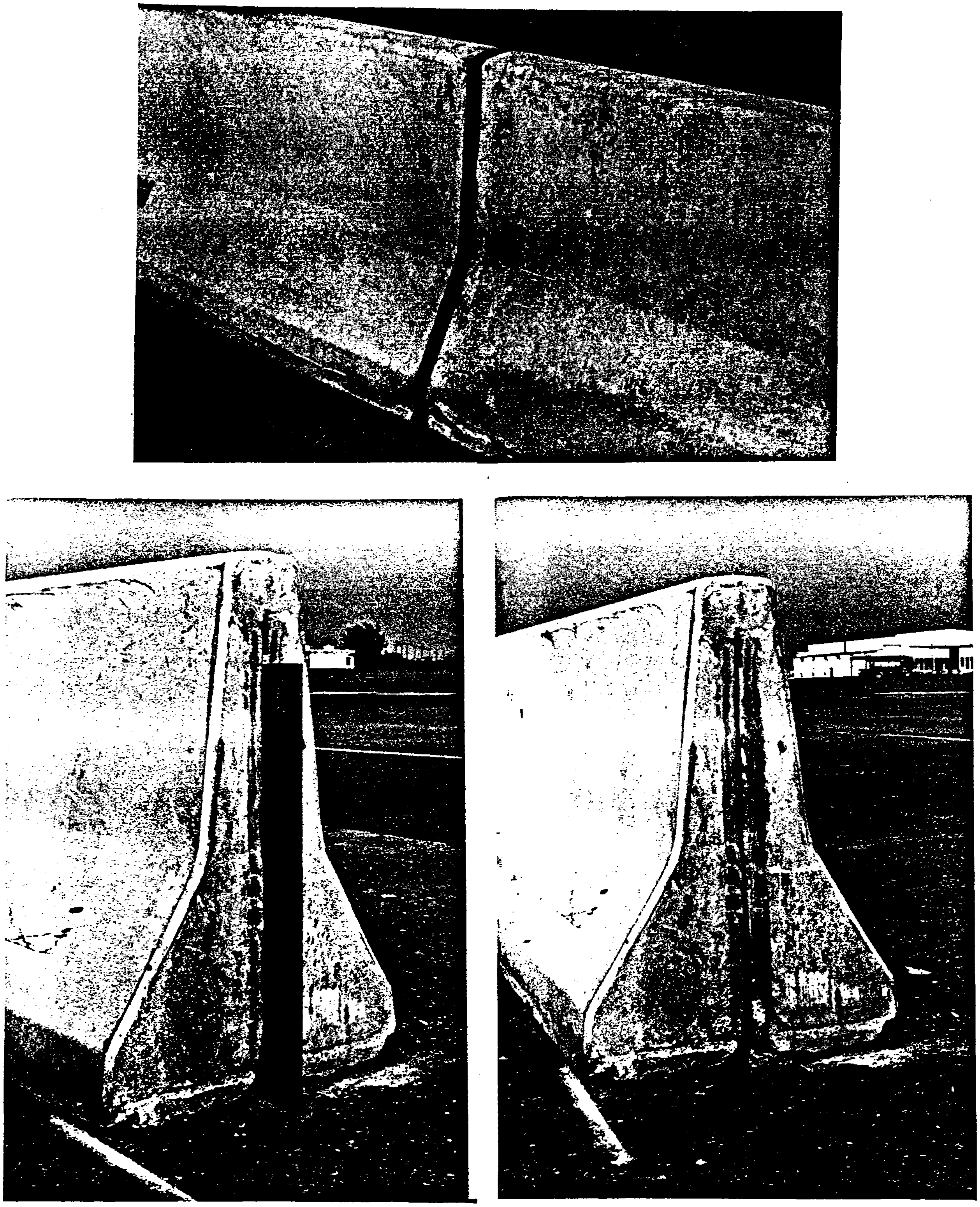


Figure 40. Barrier connections.

The VEHICLE program also uses digitized data from vehicle-mounted linear accelerometers to compute vehicle accelerations, areas enclosed by acceleration-time curves, changes in velocity, changes in momentum, instantaneous forces, average forces, and maximum average accelerations over 0.050-s intervals in each of three directions. The VEHICLE program also plots acceleration versus time curves for the longitudinal, lateral, and vertical directions.

The PLOTANGLE program uses the digitized data from the yaw, pitch, and roll rate charts to compute angular displacement in degrees at 0.001-s intervals and then instructs a plotter to draw a reproducible plot: yaw, pitch, and roll versus time. It should be noted that these angular displacements are sequence dependent with the sequence being yaw-pitch-roll for the data presented herein. These displacements are in reference to the vehicle-fixed coordinate system with the initial position and orientation of the vehicle-fixed coordinate system being that which existed at initial impact.

Still photography, real-time cine, and video were used to records conditions of the test vehicle and barrier before and after the test. Video and real-time and high-speed cine were used to document the test. One high-speed camera was placed to have a field of view parallel to and aligned with the barrier at the downstream end. Another high-speed camera was placed over the barrier to have a field of view perpendicular to the ground. The films from this cameras were used to observe phenomena occurring during collision and obtain time-event, displacement and angular data.

TEST DESCRIPTION

A 1980 Honda Civic (shown in figure 41) was directed into the barrier using a cable reverse tow and guidance system. Test inertia mass of the vehicle was 1,800 lb (817 kg) and its gross static mass was 1,965 lb (892 kg). The height to the lower edge of the vehicle bumper was 14.0 in (35.6 cm) and 19.5 in (49.5 cm) to the top of the bumper. Other dimensions and information on the test vehicle are given in figure 42. The vehicle was free-wheeling and unrestrained just prior to impact.

The speed of the vehicle at impact was 60.0 mi/h (94.0 km/h) and the angle of impact was 16.6 degrees. Shortly after impact the vehicle began to ride up the front face of the barrier. At approximately 0.048 s after impact the vehicle began to redirect. The rear of the vehicle came into contact with the barrier at 0.163 s and by 0.200 s the vehicle was totally airborne. The vehicle lost contact with the barrier at 0.290 s while still airborne. The vehicle contacted the ground at 0.436 s, 32.8 ft (10.0 m) from impact. Sequential photographs of the test are shown in figure 43.

The barrier received cosmetic damage as well as some spalling on the lower corner of joint 2-3 (shown in figure 44). The top of the barrier moved approximately 3.5 in (8.9 cm) laterally during the test. Maximum residual movement of the barrier was 0.5 in (1.3 cm) at the base of joint 2-3. The vehicle was in contact with the barrier a total of 15.3 ft (4.7 m). While in

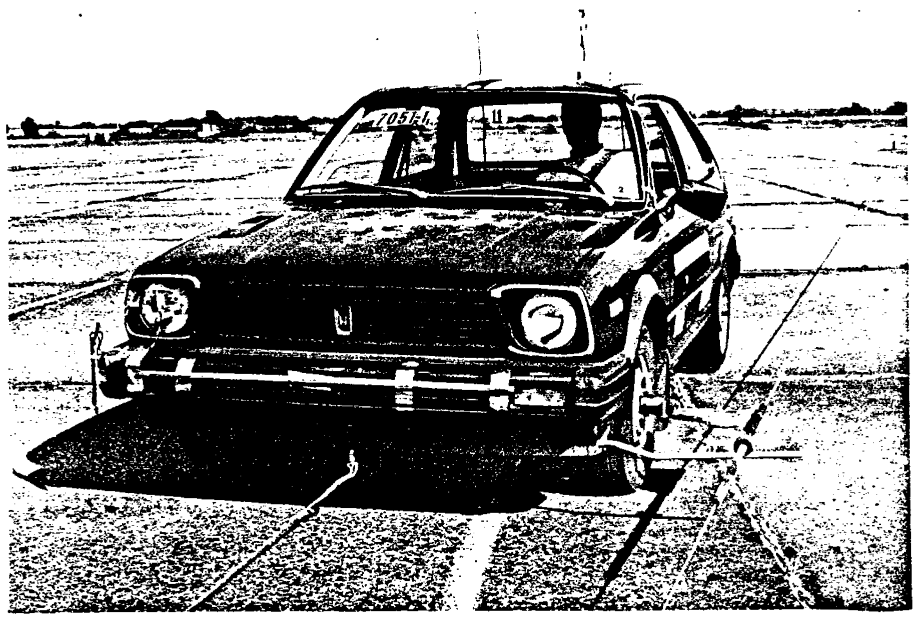


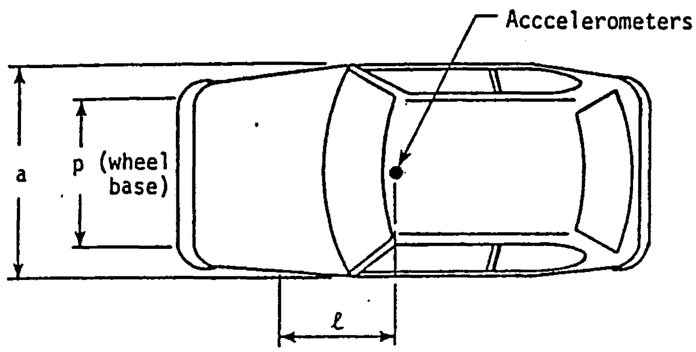
Figure 41. Test vehicle before test 7051-1.

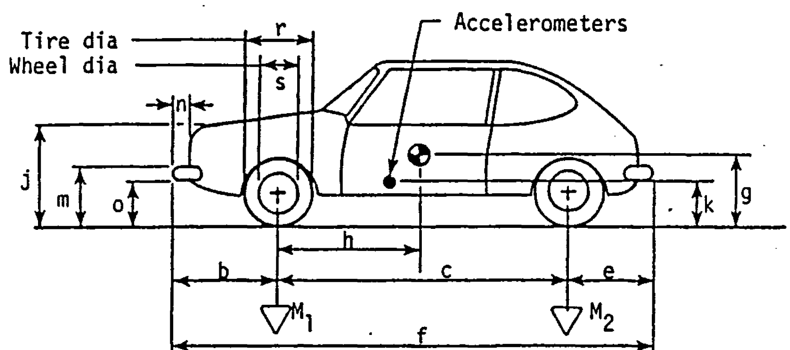
Date: 10-28-86 Test No.: 7051-1 VIN No.: SL-A1041057

Make: Honda Model: Civic Year: 1980 Odometer: 62161

Tire Size: KM 78 Ply Rating: 4 Bias Ply: X Belted: ___ Radial: ___

Tire Condition: good ___
fair X
badly worn ___





4-wheel weight for c.g. det. ℓf 548 rf 598 ℓr 307 rr 347

Mass - pounds	Curb	Test Inertial	Gross Static
M_1		1146	1227
M_2		654	738
M_T		1800	1965

Note any damage to vehicle prior to test:

___

___

*d = overall height of vehicle

Vehicle Geometry - inches

a	60 1/2	b	29 1/2
c	88	d*	52 1/2
e	28 1/4	f	146
g		h	31.97
i	---	j	29 1/2
k	15	ℓ	27
m	19 1/2	n	3
o	14	p	53 3/4
r	22 1/4	s	13 3/4

Engine Type: 4 cyl

Engine CID: 81

Transmission Type:
Automatic or (Manual)

(FWD) or RWD or 4WD

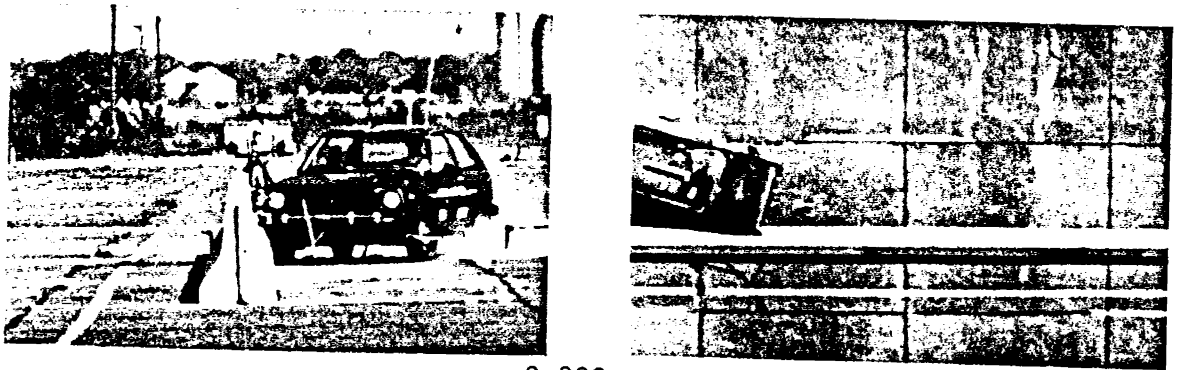
Body Type: Hatch Back

Steering Column Collapse Mechanism:

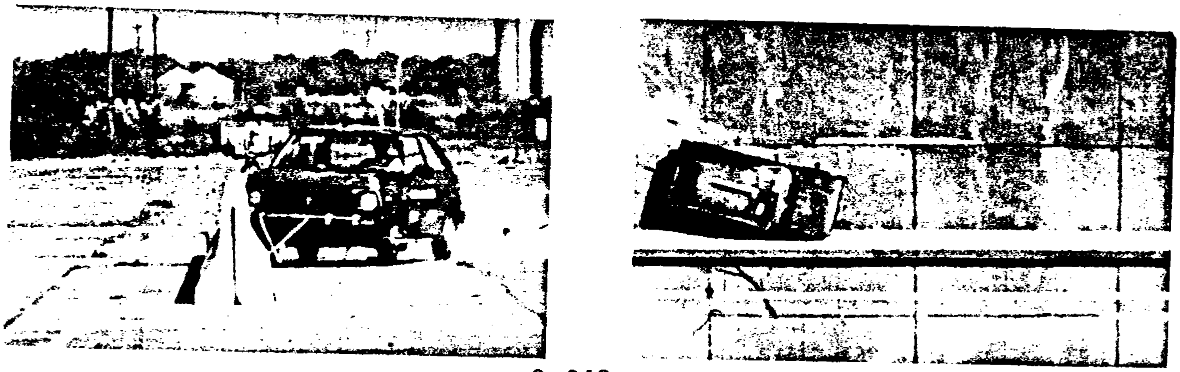
___Behind wheel units
___Convoluted tube
___Cylindrical mesh units
___Embedded ball
___NOT collapsible
___Other energy absorption
___Unknown

Brakes:
Front: disc X drum ___
Rear: disc ___ drum X

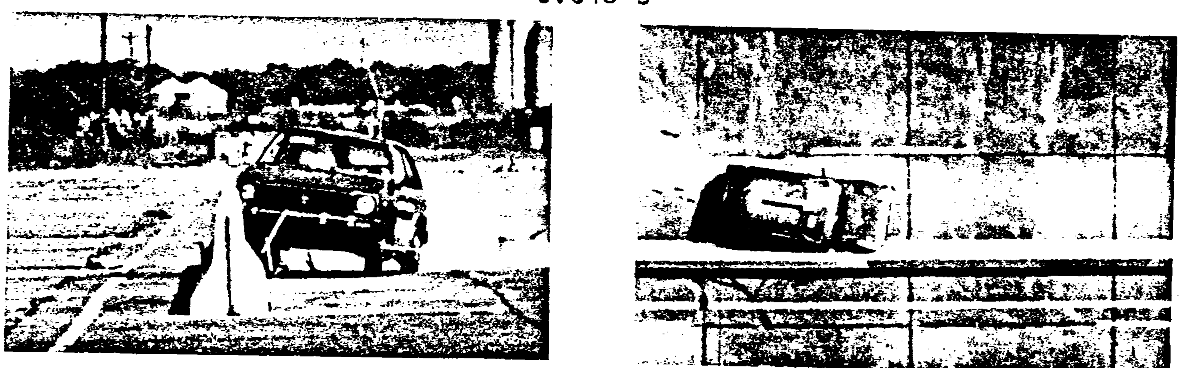
Figure 42. Test vehicle properties (7051-1).



0.000 s



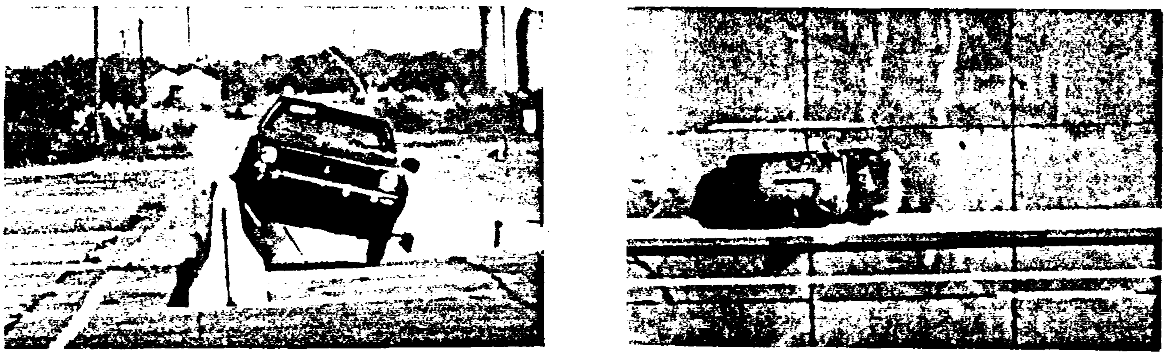
0.048 s



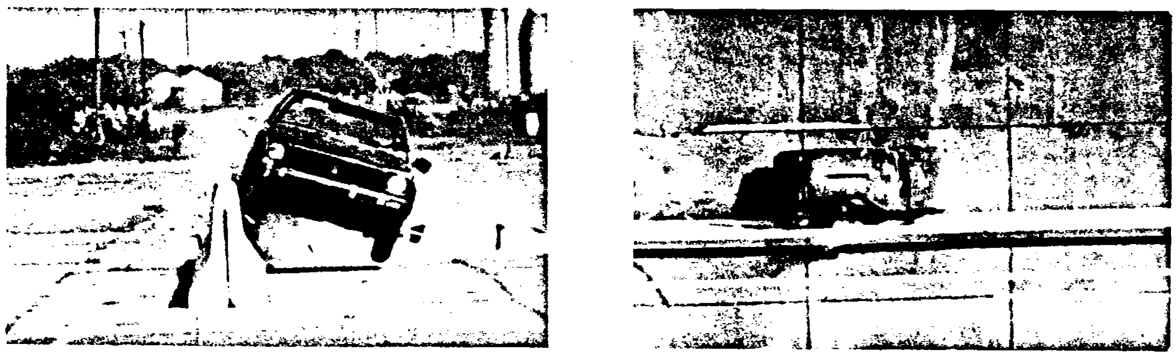
0.097 s

0.145 s

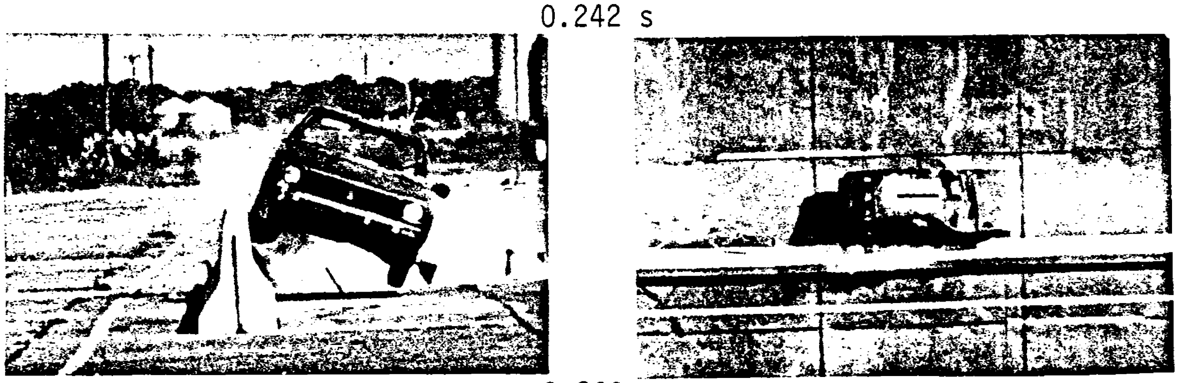
Figure 43. Sequential photographs for test 7051-1.



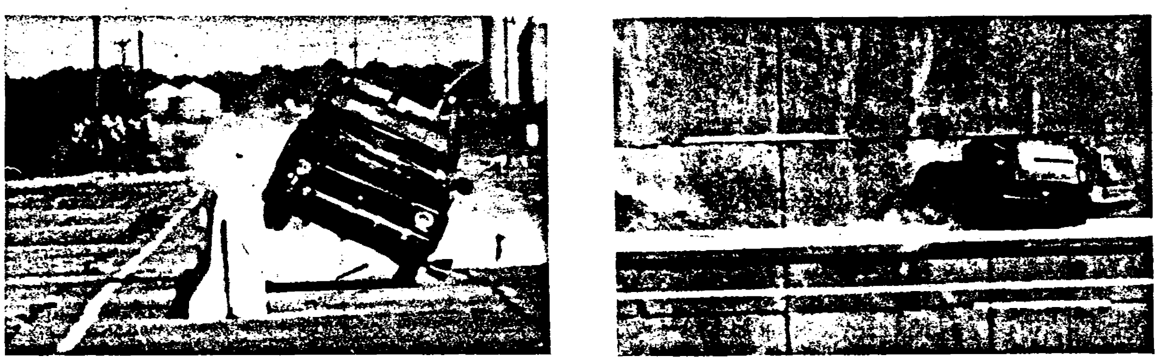
0.194 s



0.242 s



0.290 s



0.436 s

Figure 43. Sequential photographs for test 7051-1. (Continued)

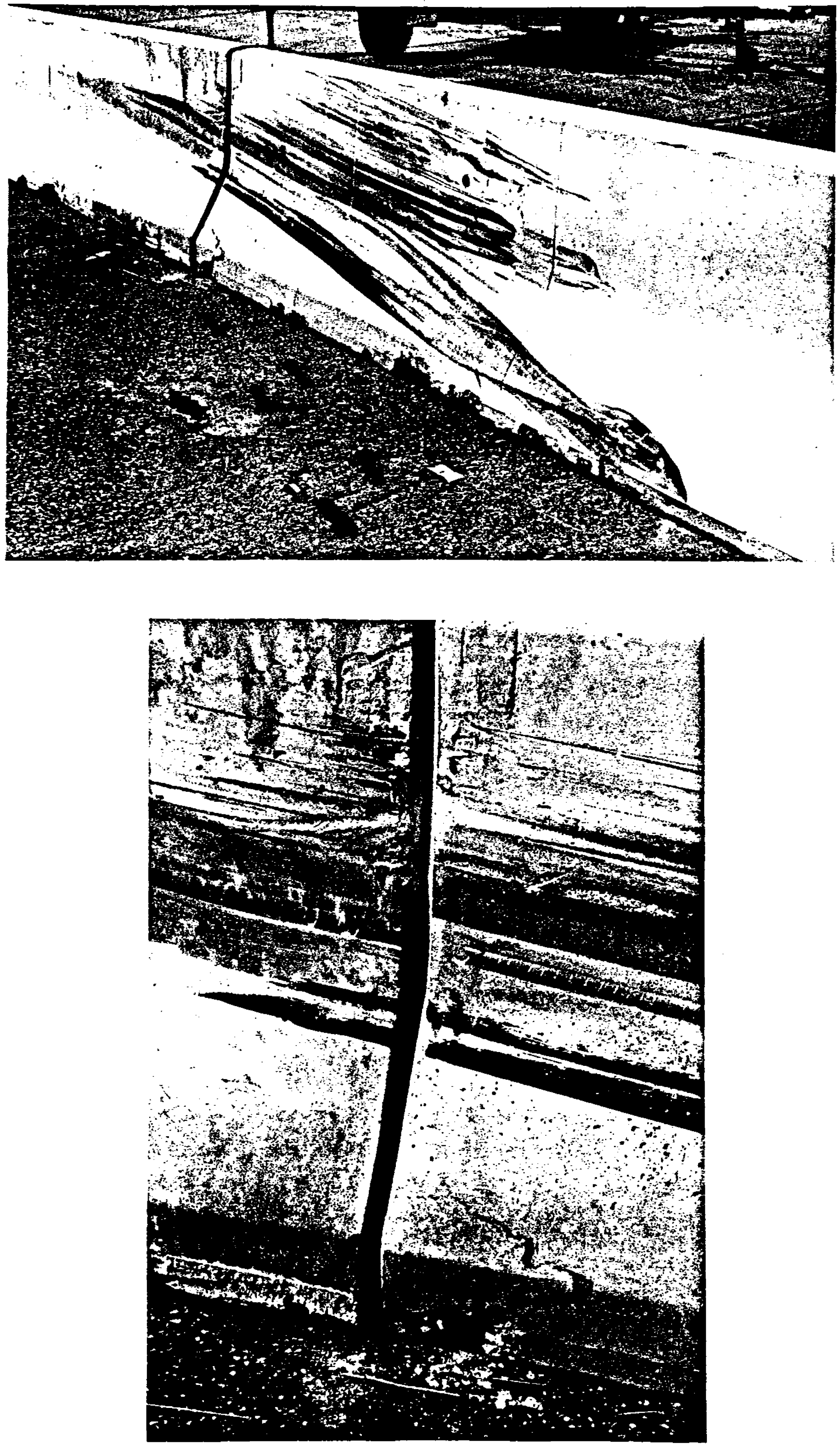


Figure 44. Barrier after test 7051-1.

contact with the barrier the vehicle rose 16.0 in (40.6 cm) above the ground. During time of contact with the barrier (0.000 - 0.290 s) the vehicle achieved a maximum roll angle of 15.4 degrees toward the barrier. As the vehicle's left front tire touched down (after being airborne) the vehicle had rolled 23 degrees away from the barrier. At 0.565 s the vehicle reached a maximum roll of 30.3 degrees. The vehicle subsequently came to rest upright. The vehicle received damage to the right front quarter as shown in figure 45. The hood, the right front fender and the right-side door were dented and scraped. The right front wheel rim was bent but the tire was not aired-out. There was damage to the right front and right rear strut. Maximum crush at bumper height was 7.0 in (17.8 cm).

TEST RESULTS

Impact speed was 60.0 mi/h (96.5 km/h) and angle of impact was 16.6 degrees. The exit speed at time of contact (0.290 s) was 52.3 mi/h (84.2 km/h) and exit angle was 3.5 degrees. Occupant impact velocity in the longitudinal direction was 11.5 ft/s (3.5 m/s) and 18.3 ft/s (5.6 m/s) in the lateral. The highest 0.010-s occupant ridedown accelerations were -0.7 g (longitudinal) and 3.9 g (lateral). These data and other pertinent information from the test are summarized in figure 46. Vehicle accelerometer traces are displayed in figures 47 through 49 and vehicular angular displacements are shown in figure 50.

The barrier contained and smoothly redirected the vehicle with little lateral movement of the barrier. No debris or detached elements were evident to present undue hazard to other traffic. The vehicle remained upright and stable although it was airborne for a brief period. There was no deformation or intrusion into the occupant compartment. The vehicle trajectory at loss of contact indicates minimum intrusion into adjacent traffic lanes.

Based on these results, this test meets all the criteria recommended for NCHRP Report 230 Test 12.

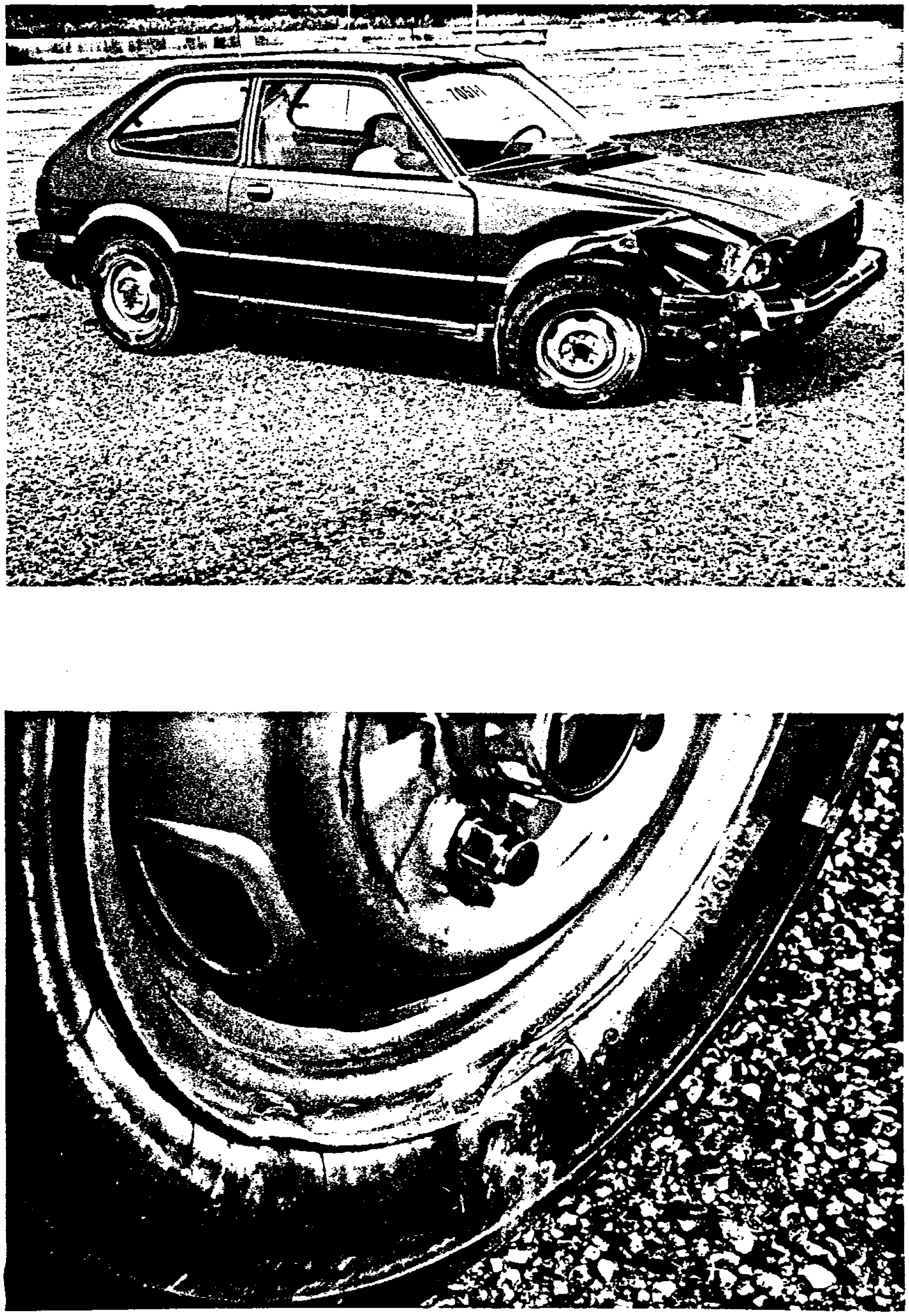
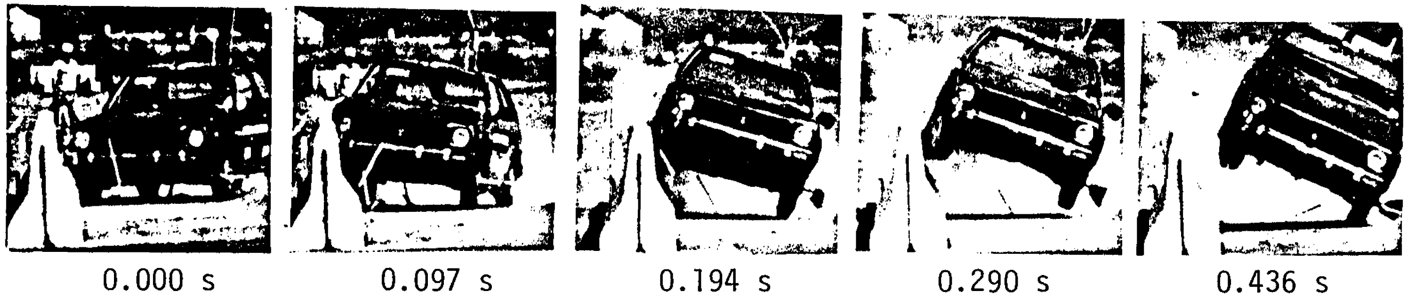
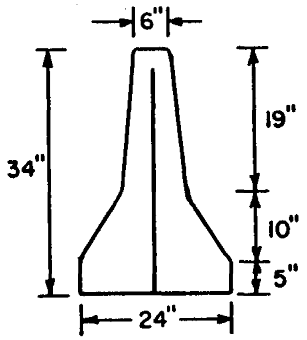
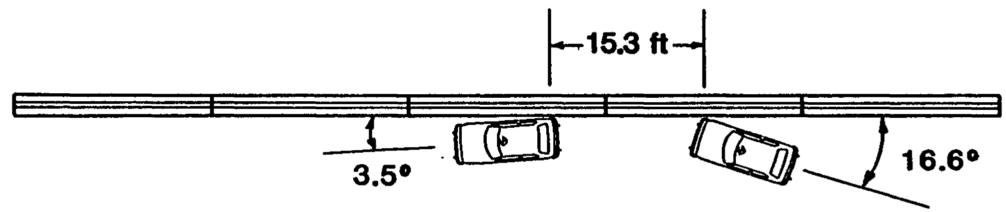


Figure 45. Test vehicle after test 7051-1.







Test No. 7051-1
Date 10/29/86
Test Installation. . . . . . . Pennsylvania CMB
Length of Installation . . . 100 ft (30.5 m)
Vehicle. . . . . 1980 Honda Civic
Vehicle Weight
    Test Inertia. . . . . . 1800 lbs (817 kg)
    Gross Static. . . . . . 1965 lbs (892 kg)
Vehicle Damage Classification
    TAD 1RFQ4
    CDC 01RFES5
Vehicle Crush. . . . . 7.0 in (17.8 cm)

Impact Speed. . . . . 60.0 mi/h (96.5 km/h)
Impact Angle. . . . . 16.6 degrees
Exit Speed. . . . . 52.3 mi/h (84.2 km/h)
Exit Angle. . . . . 3.5 degrees
Vehicle Accelerations
    (Max. 0.050-sec Avg)
    Longitudinal . . . . -3.4 g
    Lateral. . . . . 8.6 g
Occupant Impact Velocity
    Longitudinal . . . . 11.5 ft/s (3.5 m/s)
    Lateral. . . . . 18.3 ft/s (5.6 m/s)
Occupant Ridedown Accelerations
    Longitudinal . . . . -0.7 g
    Lateral. . . . . 3.9 g

Figure 46. Summary of results for test 7051-1.

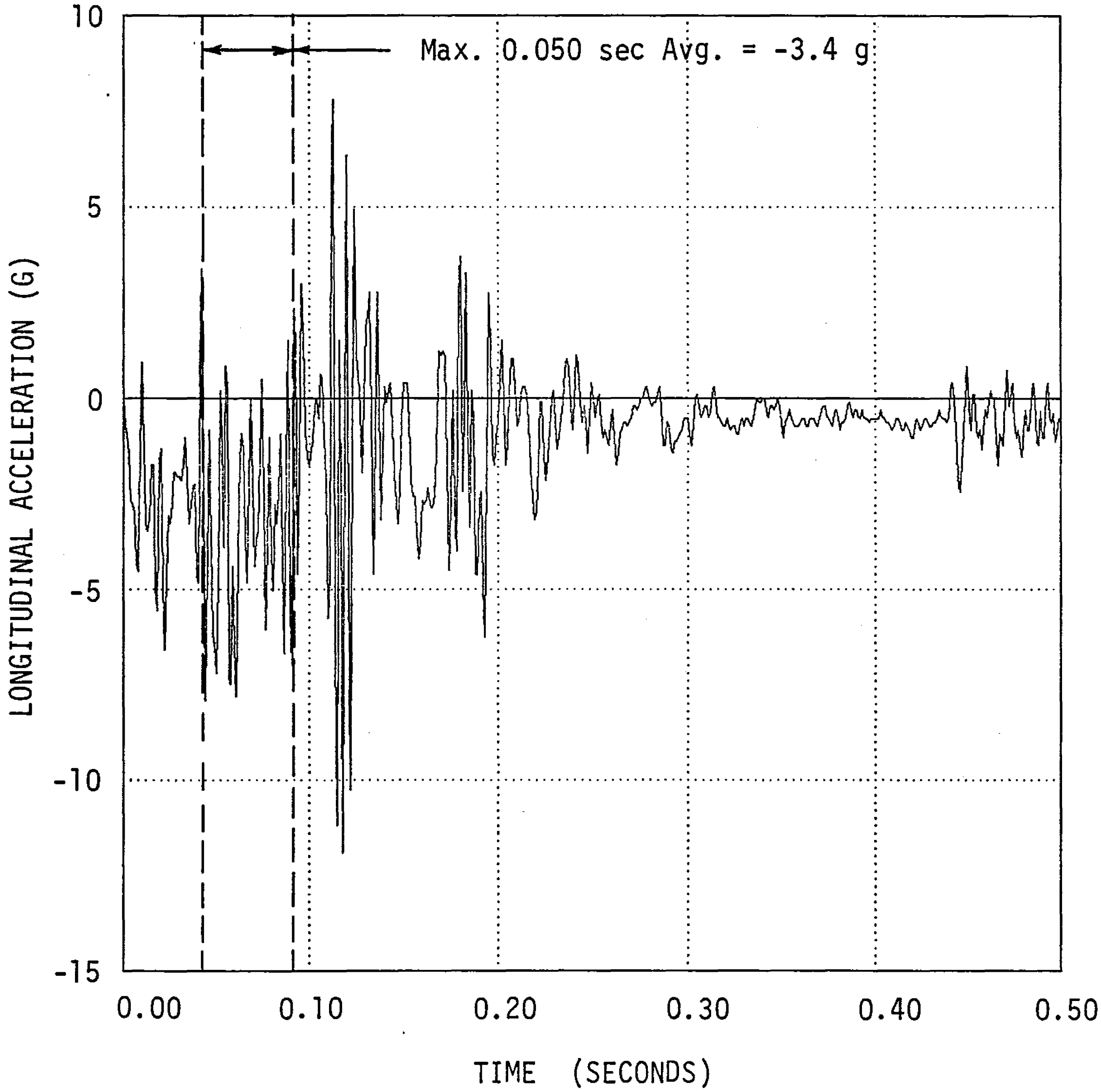


Figure 47. Vehicle longitudinal accelerometer trace for test 7051-1.

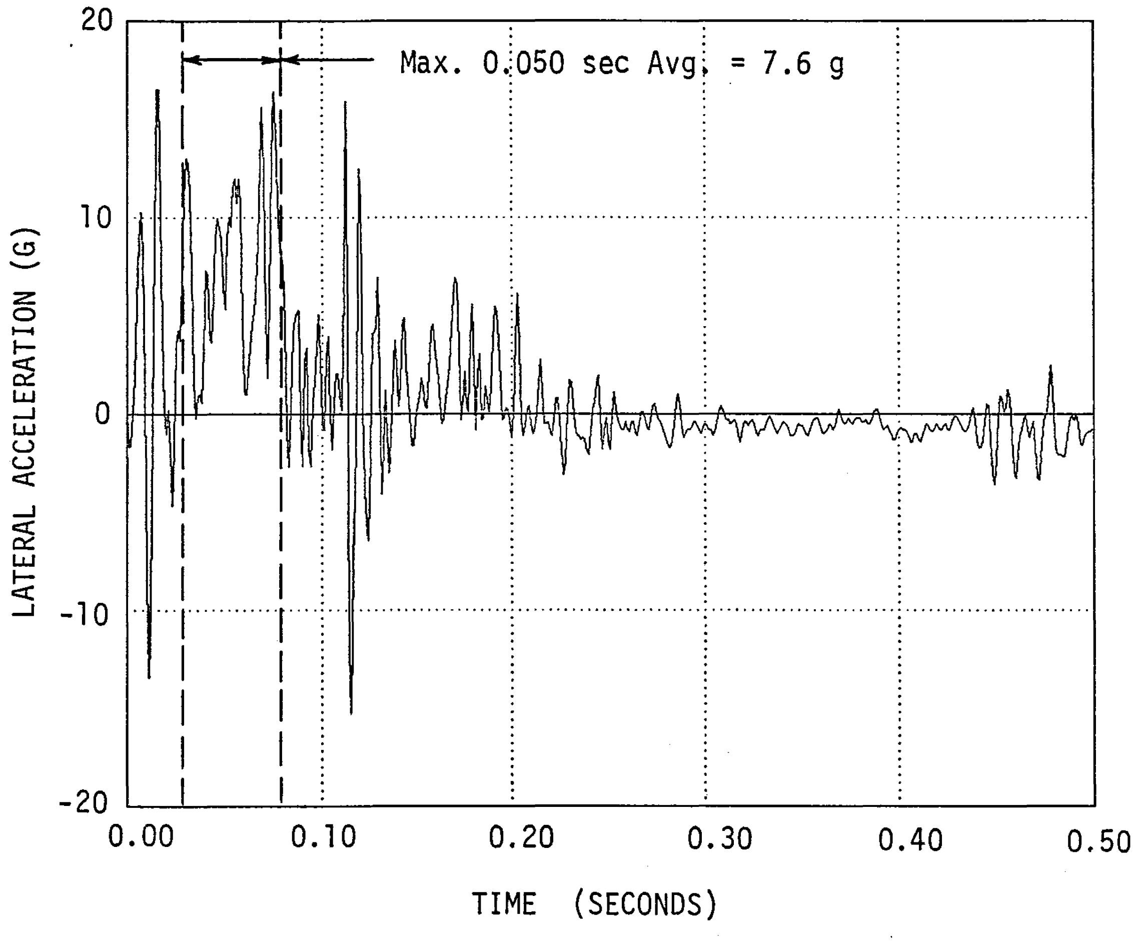


Figure 48. Vehicle lateral accelerometer trace for test 7051-1.

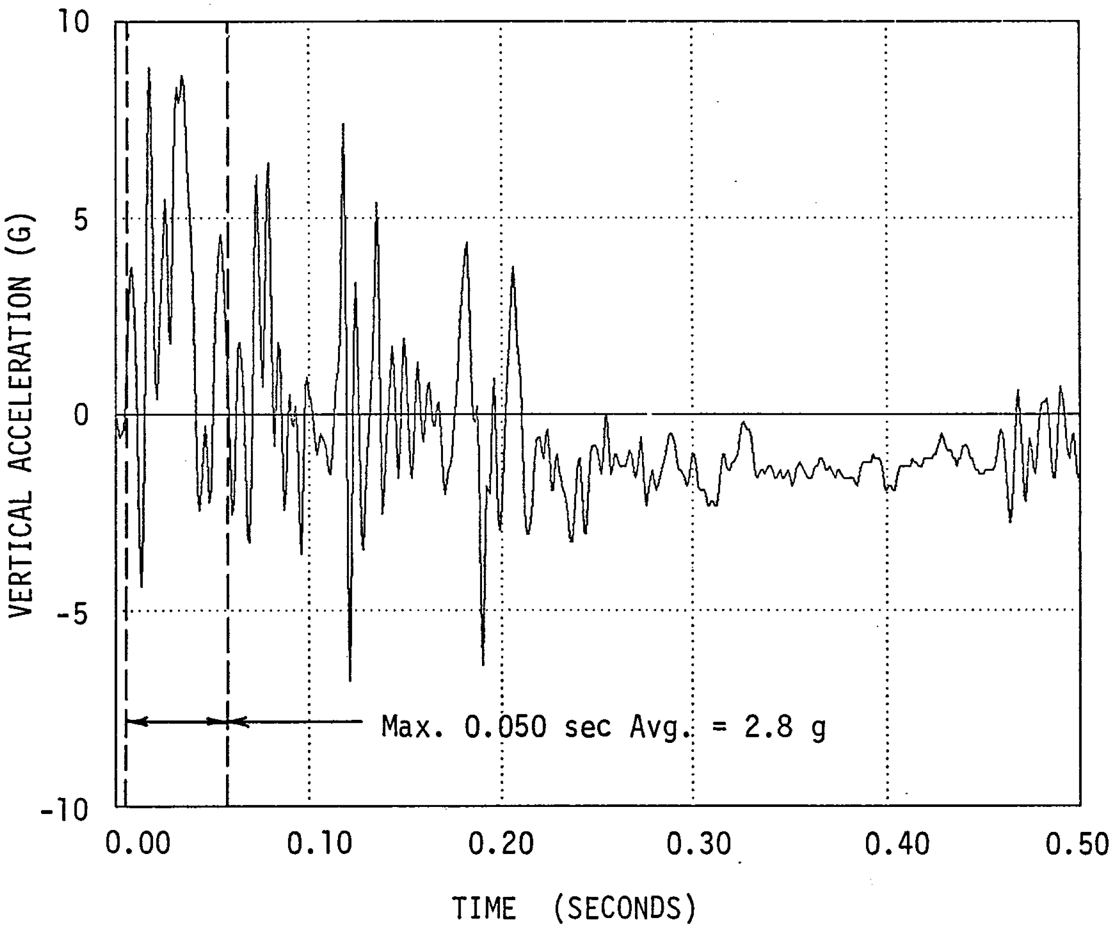


Figure 49. Vehicle vertical accelerometer trace for test 7051-1.

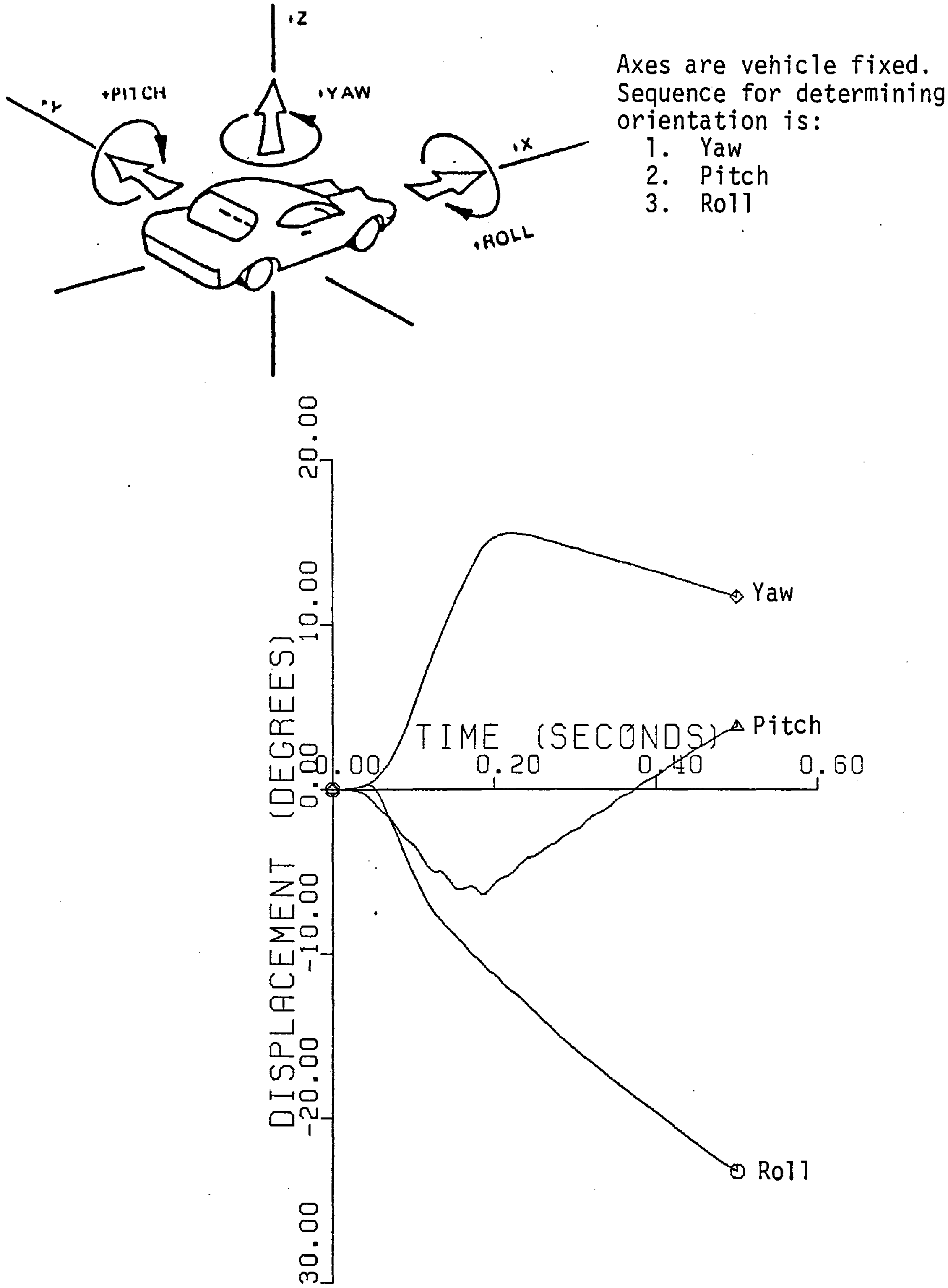


Figure 50. Vehicle angular displacements for test 7051-1.

APPENDIX I
CLINICAL ANALYSIS OF NASS LBSS CMB ROLLOVER ACCIDENTS

The emphasis in the analysis of the NASS LBSS data file was to identify factors that are causative or contributory to rollovers subsequent to impacts with concrete safety shaped barriers. The analysis was strictly clinical in nature, using hard copies of the accident cases, including the various field data collection forms, scaled collision diagram, and slides. The accidents were first reconstructed, if possible, using a simplified reconstruction procedure, details of which are presented in Appendix D of this report.

The accident cases, especially those resulting in rollovers, were reviewed and analyzed clinically by the project staff in efforts to identify factors that are causative or contributory to the propensity for rollover subsequent to impact with the concrete safety shaped barrier. For the accidents resulting in rollovers, each accident was analyzed in detail and a summary of the key data elements and an assessment of how the rollover occurred were prepared. These summary descriptions of the rollover accidents are attached to the end of this appendix. The nonrollover accidents, especially those with impact conditions similar to rollover accidents, were also analyzed to determine why rollovers did not occur in those accidents. However, no case summaries were prepared for the nonrollover accidents.

Of the total of 130 CMB accidents analyzed, 31 cases involved rollovers. However, only 22 of the rollover accidents were considered applicable for the purpose of identifying factors that are causative or contributory to rollovers. The remaining nine rollover accidents were of little use for this purpose for a variety of reasons, including involvement of tractor-trailers (3 cases), rollover prior to impact with barrier (1 case), rollover resulting from impact with the end of the barrier (1 case), or rollover caused by factors other than and subsequent to the barrier impact, such as impact with curb (1 case), utility pole (1 case) and steep embankment (1 case) or severe driver steering input (1 case). A summary of the case numbers and the reasons for the cases being considered not applicable are shown in table 24.

Although the number of rollover accidents in the data file was too small for any firm conclusions to be drawn, a number of potential causative or contributory factors for rollovers involving safety shaped barriers were identified through the clinical analysis. Discussions on these identified potential factors will be presented later in the appendix. First, definitions of some of the standard terms used in the discussions are presented as follows:

Tracking - A vehicle is tracking when the heading angle and the velocity vector of the vehicle are the same.

Yawing - A vehicle is yawing when the heading angle of the vehicle is different from that of the velocity vector.

Table 24. Summary of rollover accidents considered as not applicable

Case Number	Circumstances of Rollover
82 02 514 S	Vehicle left barrier tracking at very high speed. The vehicle struck a utility pole and tripped in the soil as it rotated post-impact.
82 36 151 T	Ford bronco rolled over prior to impacting the CMB.
82 82 535 K	Vehicle was a White tractor-trailer.
82 82 537 K	Vehicle was an International tractor-trailer.
83 03 523 W	Driver made hard right steer input after very light contact with barrier. Vehicle rotated and tripped.
83 08 509 T	Honda Civic struck a 6-inch curb face after separation.
83 28 043 R	Vehicle was a Dodge van that struck the sloped down end of a CMB section on a city street.
83 82 521 L	Vehicle was a Kenworth tractor-trailer.
84 80 503 P	Vehicle rolled down steep embankment on opposite side of road after being redirected.

Slip Angle - The angle between the heading angle and the velocity vector, expressed in degrees.

Yaw Angle - The angle between the heading angle and the barrier, expressed in degrees.

Yaw Rate - The rate at which the yawing angle is changing, expressed as degrees per second.

Impact Angle - The angle between the velocity vector of the vehicle and the barrier at the point of initial contact with the barrier.

Impact Speed - The velocity of the vehicle at the point of initial contact with the barrier.

Table 25 lists the key factors pertaining to impact conditions for each of the 22 LBSS accident cases analyzed. The actual yaw rates were not available from the data and are subjectively categorized as: low (< 20 degrees per second), moderate (20 - 40 degrees per second), and high (> 40 degrees per second). Also, for cases that were not reconstructed and the

Table 25. List of key data elements pertaining to impact conditions for applicable LBSS rollover accidents

Case Number	Impact Angle (Deg)	Slip Angle (Deg)	Yaw Angle (Deg)	Yaw Rate	Impact Speed (mi/h)	Curb Weight (Lbs)
82 30 131 V	14	86	100	high	27	2,000
82 30 228 V	07	00	07	none	high	2,200
82 79 514 W	02	00	02	none	65	3,200
82 80 516 R	29	00	29	none	high	2,500
82 82 534 V	38	12	50	low	high	4,000
82 82 559 W	04	00	04	none	40-55	2,700
82 82 561 R	41	09	50	low	high	2,700
82 82 574 T	12	01	13	none	58	2,100
83 03 040 V	18	00	18	low	high	2,100
83 03 066 V	54	27	81	moderate	high	2,000
83 11 508 W	06	00	06	none	high	3,300
83 30 164 V	19	00	19	none	39	2,200
83 36 099 W	02	00	02	none	high	2,100
83 76 066 W	25	01	26	none	high	3,400
83 79 509 W	10	00	10	none	high	2,600
83 82 503 T	28	07	35	low	moderate	1,900
83 82 515 N	20	220	240	high	high	3,300
83 82 530 V	41	00	41	low	high	2,000
83 82 532 V	06	41	47	high	44	3,500
83 82 539 T	17	44	61	high	41	2,500
84 39 099 R	40	15	55	moderate	high	3,500
84 59 512 V	30	60	90	high	57	2,800

impact speeds were unknown, a subjective judgement was made by the project staff to categorize the impact speed into three levels: low (< 25 mi/h), moderate (25 - 50 mi/h), and high (> 50 mi/h). These categorizations are arbitrary in nature and are determined subjectively by the project staff.

Discussions on a number of potential causative or contributory factors identified from the clinical analysis are presented as follows.

One common condition observed for the rollover accidents studied involved vehicles impacting the barriers in a tracking mode at high impact angles (greater than 25 degrees) and moderate to high impact speeds. The impacting vehicle would typically climb up the lower sloped face of the barrier and continue to climb up the upper sloped face of the safety shape without any significant redirection. This would cause the vehicle to attain a high roll angle away from the barrier as the vehicle began to redirect and separate from the barrier, leading to subsequent rollover.

Another common condition observed for rollovers involved vehicles skidding sideways into the barriers with high yaw angles (greater than 45 degrees) and low yaw rates at high speed. The impacting vehicle would already be leaning toward the side of the vehicle leading the skid as the vehicle impacted the barrier. The roll angle would continue to increase as the vehicle crushed into the barrier, leading to subsequent rollover.

On the other hand, review of nonrollover accidents indicated that most skidding vehicles with high yaw rates did not result in rollovers, especially on lower friction surfaces. The impacting vehicle would typically continue to rotate after the initial impact with the barrier and then impact with the barrier a second time with the rear corner. The roll angle of the vehicle was usually fairly small and the second impact would generally stabilize the trajectory of the vehicle as it separated from the barrier, thus not resulting in rollovers.

Another common condition observed in the rollover accidents involved vehicles impacting the barriers at very high impact speeds (above 60 mi/h) and very low impact angles (less than 10 degrees). The impacting vehicle would typically climb up quickly over the lower sloped face of the safety shape and continue climbing onto the upper sloped face. The vehicle would climb higher and stay on the barrier longer than normal and eventually roll on the side away from the barrier as the vehicle separated from the barrier, sometimes even prior to separating from the barrier.

The presence of 18-in high concrete glare screens on top of the concrete safety shaped barrier was found in a couple of the high speed, low angle rollover accidents. It appeared that the glare screen would act as an extension to the top of the safety shaped barrier, thereby causing the impacting vehicle to climb higher on the barrier than without the glare screen. This allowed the roll angle on the vehicle to go higher than normal, leading to subsequent rollover.

In some of the rollover accidents, the vehicles actually separated from the barriers in a relatively stable fashion and then began to rotate after separation and subsequently rolled over. The rotation to the vehicle is probably the result of braking and steering inputs from the drivers and damages to the front suspension from impact with the barrier. It is arguable whether the subsequent rollover is actually related to the shape of the barrier or independent of the barrier type.

Lateral displacement of the barrier segments was found in one rollover accident. Crash tests have shown that lateral displacement of the barrier during impact allowed the barrier to rotate in the direction of the impact, thus allowing the vehicle to climb higher on the barrier which could lead to subsequent rollover. Lateral displacement of the barrier is usually not a problem for permanent barrier installations, but certainly an area of concern for temporary installations, such as in construction zones.

The majority of the rollover accidents occurred under dry surface conditions. This is consistent with accident analysis results which indicate that the propensity for rollover after impact with a concrete safety shaped barrier is actually lower under wet or snowy/icy surface condition than under dry surface condition. The reduced coefficient of friction under wet or snowy/icy surface condition prevents critical side forces from building up and tripping the vehicle.

Smaller and lighter vehicles were found to be disproportionally involved in rollovers under all of the abovementioned impact conditions except for high angle impacts. This is probably due to the narrower track width and lower roll moment of inertia inherent in the smaller and lighter vehicles. For the high angle impacts, the size and weight of the vehicle do not appear to have a significant effect on rollover. In fact, the majority of the vehicles involved were either intermediate or larger vehicles.

It should be noted that some of the characteristics identified in previous studies as affecting the propensity of rollover, e.g., height of reveal and lower curb face, slope and offset of upper sloped face, barrier surface friction, and approach terrain, did not appear to play any part in any of the rollover accident cases studied. There was very little variation in the barrier shape and dimensions among the barriers involved in the accidents for their effects to be assessed. As to the effect of the approach terrain, all except one of the barriers involved in the rollover accidents had paved shoulders and none with nonlevel terrain in the approach.

CASE NUMBER:	83 79 509 W
VEHICLE:	1979 Ford Mustang
CURB WEIGHT:	2,600 pounds
ENVIRONMENT:	Two travel lanes in each direction on controlled access roadway. CMB section divided the opposing lanes. Road was straight and level at this site.
NARRATIVE:	Vehicle traveling in the left lane at highway speeds drove at a low angle to the left into the CMB. The vehicle climbed the lower surface of the CMB and continued to climb until contacting chain link glare screen mounted on top. The vehicle then separated from the CMB rotating ccw at low rate. Right side struck pavement and vehicle rolled 180 degrees.
IMPACT CONDITIONS:	High speed, low angle, tracking
IMPACT ANGLE:	10 degrees
SLIP ANGLE:	0 degrees
YAW ANGLE:	10 degrees
YAW RATE:	None
ROTATION DIRECTION:	None
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	12 degrees
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Right side lateral sliding after separation from top of CMB. No rim gouges but heavy tire tracks visible in slides.
BARRIER ASSOCIATION:	Vehicle climbed lower face. Barrier has extremely rough texture surface. Chain link style glare screen mounted on top.

CASE NUMBER:	82 02 514 S
VEHICLE:	1973 Dodge Charger
CURB WEIGHT:	3,600 pounds
ENVIRONMENT:	Two travel lanes in each direction and a left shoulder. CMB section divided the opposing lanes. Road was curved right and level at this site.
NARRATIVE:	Vehicle traveling in the left lane at approximately 90+ miles per hour sideswiped the CMB with the left side tires as it sloped vertically downward at its end. The vehicle continued to travel down and across the road where it impacted a utility pole, rotated 90 degrees and tripped in the soil.
IMPACT CONDITIONS:	Low angle, very high speed
IMPACT HEADING ANGLE:	5 degrees
SLIP ANGLE:	4 degrees
YAW ANGLE:	9 degrees
YAW RATE:	Low
ROTATION DIRECTION:	None
IMPACT SPEED:	90+ mi/h
SEPARATION ANGLE:	4 degrees
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Right side tires dug in soil as vehicle slid at 90 degree yaw.
BARRIER ASSOCIATION:	Vehicle just brushed CMB before impacting utility pole and rolling

CASE NUMBER:	82 80 516 R
VEHICLE:	1982 Chevrolet S-10 Pickup
CURB WEIGHT:	2,500 pounds
ENVIRONMENT:	Two travel lanes in each direction and a left shoulder. CMB section divided the opposing lanes. Road was straight and level at this site.
NARRATIVE:	Vehicle traveling in the right lane at highway speeds made a steer input to the left. The front left corner and left side wheels climbed to the top of the barrier. The vehicle separated from the barrier in the air rotating ccw. The vehicle rolled right side first after yawing 90 degrees. The vehicle rolled 180 degrees.
IMPACT CONDITIONS:	High speed, high impact angle
IMPACT HEADING ANGLE:	29 degrees
SLIP ANGLE:	00 degrees
YAW ANGLE:	29 degrees
YAW RATE:	None
ROTATION DIRECTION:	None
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	24 degrees
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Fell on ground from position on top of CMB. The vehicle landed and began a ccw rotation. The vehicle tripped on the pavement without a subsequent impact. The wrong scene was documented for this case.
BARRIER ASSOCIATION:	Vehicle climbed lower face of CMB with front-left corner then continued up barrier. Vehicle rolled after separation from barrier.

CASE NUMBER:	82 30 131 V
VEHICLE:	1977 Subaru DL
CURB WEIGHT:	2,000 pounds
ENVIRONMENT:	Two lanes in each direction and a left and right shoulder. CMB section is located on the edge of the right shoulder. Road was straight and level at this site.
NARRATIVE:	Vehicle traveling in the left lane at highway speeds steered to the right, began rotating cw, and struck the CMB with the right rear. The vehicle continued to rotate and impacted the barrier with the right front and then the full front end. The vehicle climbed the barrier with the front end and rolled left side first 180 degrees to final rest on its roof.
IMPACT CONDITIONS:	Moderate speed, moderate impact angle, high slip angle and rate
IMPACT HEADING ANGLE:	14 degrees
SLIP ANGLE:	86 degrees
YAW ANGLE:	100 degrees
YAW RATE:	High
ROTATION DIRECTION:	CW
IMPACT SPEED:	27 mi/h
SEPARATION ANGLE:	5 degrees
DIRECTION OF ROLL:	Left side first
TRIP DEVICE:	Fell to ground from position with front end on top of CMB. The vehicle was rotating cw as it left the barrier.
BARRIER ASSOCIATION:	Vehicle climbed lower face of CMB with the entire front end then continued up barrier. Vehicle rolled during separation from barrier.

CASE NUMBER:	83 28 043 R
VEHICLE:	1980 Dodge 300 Van
CURB WEIGHT:	4,100 pounds
ENVIRONMENT:	City street intersection.
NARRATIVE:	Vehicle struck a sloped down end section of a CMB section along the section's longitudinal axis with the front center of the van. This case is not in scope.
IMPACT CONDITIONS:	Tracking centerline to centerline.
IMPACT HEADING ANGLE:	00 degrees
YAW ANGLE:	00 degrees
YAW RATE:	None
ROTATION DIRECTION:	None
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	N/A
DIRECTION OF ROLL:	N/A
TRIP DEVICE:	N/A
BARRIER ASSOCIATION:	N/A

CASE NUMBER:	82 82 534 V
VEHICLE:	1977 Chevrolet Monte Carlo
CURB WEIGHT:	4,000 pounds
ENVIRONMENT:	Three travel lanes in each direction. CMB section divided the opposing lanes. Road was straight and level at this site.
NARRATIVE:	Vehicle traveling in the center lane at highway speeds made an hard steer input to the left. The vehicle rotated CCW into a yaw and struck the CMB at a high angle with little to no yaw rate. The impact produced a large nonhorizontal upward force on the front-left corner. The right front tire deflated and the rim dug into the pavement, tripping the vehicle upon separation.
IMPACT CONDITIONS:	High speed, moderate slip w/right side leading.
IMPACT HEADING ANGLE:	38 degrees
SLIP ANGLE:	12 degrees
YAW ANGLE:	50 degrees
YAW RATE:	Low
ROTATION DIRECTION:	CCW
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	0 degrees
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Right front rim dug into pavement after separation.
BARRIER ASSOCIATION:	Vehicle climbed lower face of CMB with left front corner then continued to the top of barrier.

CASE NUMBER:	82 82 535 K
VEHICLE:	1980 White COE with trailer
CURB WEIGHT:	13,600 pounds plus trailer and cargo
ENVIRONMENT:	Three travel lanes in each direction. CMB section divided the opposing lanes. Road was straight and level at this site.
NARRATIVE:	18 wheel vehicle jackknife and struck barrier.
IMPACT CONDITIONS:	N/A
IMPACT HEADING ANGLE:	N/A
YAW ANGLE:	N/A
YAW RATE:	N/A
ROTATION DIRECTION:	N/A
IMPACT SPEED:	N/A
SEPARATION ANGLE:	N/A
DIRECTION OF ROLL:	N/A
TRIP DEVICE:	N/A
BARRIER ASSOCIATION:	N/A - broke concrete

CASE NUMBER:	82 82 537 K
VEHICLE:	1982 International
CURB WEIGHT:	13,100 pounds
ENVIRONMENT:	Three travel lanes in each direction. CMB section divided the opposing lanes. Road was straight and level at this site.
NARRATIVE:	Bobtail tractor rotated ccw and struck CMB.
IMPACT CONDITIONS:	N/A
IMPACT HEADING ANGLE:	N/A
YAW ANGLE:	N/A
YAW RATE:	N/A
ROTATION DIRECTION:	N/A
IMPACT SPEED:	N/A
SEPARATION ANGLE:	N/A
DIRECTION OF ROLL:	N/A
TRIP DEVICE:	N/A
BARRIER ASSOCIATION:	N/A

CASE NUMBER:	83 82 530 V
VEHICLE:	1981 Datsun 210
CURB WEIGHT:	2,000 pounds
ENVIRONMENT:	Four travel lanes in each direction and a left shoulder. CMB section divided the opposing lanes. Road was curved to right and level at this site.
NARRATIVE:	Vehicle traveling in the second lane from the left swerved to left to avoid a truck. Vehicle began slight ccw rotation and struck CMB with front left at a high impact angle with little to no yaw angle or yaw rate. Front left of vehicle climbed to top of barrier, and began a roll left side leading upon separation. Vehicle slid to final rest on roof.
IMPACT CONDITIONS:	High speed, high impact angle, tracking
IMPACT HEADING ANGLE:	41 degrees
SLIP ANGLE:	0 degrees
YAW ANGLE:	41 degrees
YAW RATE:	Low
ROTATION DIRECTION:	CCW
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	Unknown
DIRECTION OF ROLL:	Left side first
TRIP DEVICE:	Fell to ground from position on top of CMB. The vehicle landed on roof and slid to final rest.
BARRIER ASSOCIATION:	Vehicle climbed lower face of CMB with front-left corner then continued up barrier. Vehicle rolled during separation from barrier.

CASE NUMBER:	83 82 503 T
VEHICLE:	1972 Volkswagen Beetle
CURB WEIGHT:	1,900 pounds
ENVIRONMENT:	One lane ramp curved to left with CMB on outside of travel lane.
NARRATIVE:	Vehicle traveling on the ramp lane started a cw rotation into barrier. Impacted CMB with high impact angle and low yaw angle and yaw rate. Right front corner impacted CMB. Front end climbed to top of CMB as vehicle continued cw rotation. Vehicle separated from CMB traveling 90 degrees yaw, rolling left side first.
IMPACT CONDITIONS:	High angle, moderate speed
IMPACT HEADING ANGLE:	28 degrees
SLIP ANGLE:	7 degrees
YAW ANGLE:	35 degrees
YAW RATE:	Low
ROTATION DIRECTION:	CW
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	3 degrees
DIRECTION OF ROLL:	Left side first
TRIP DEVICE:	Fell on ground from position on top of CMB while rotating cw. Rolled upon separation with CMB.
BARRIER ASSOCIATION:	Vehicle climbed entire face of CMB with the right front end. Vehicle rolled during separation from barrier.

CASE NUMBER:	84 39 099 R
VEHICLE:	1969 Mercury Cougar
CURB WEIGHT:	3,500 pounds
ENVIRONMENT:	One and a half lane road due to construction. Temporary CMB sections 10 feet long did not move at impact points.
NARRATIVE:	Vehicle traveling in the open lane was impacted on the right side by vehicle two. Vehicle impacted barrier and separated tracking back into travel lane. The vehicle was again impacted in the right side by vehicle two. Vehicle started ccw rotation and impacted the CMB at high angle. The vehicle climbed directly to the top of the CMB in less than 10 feet, and separated rolling right side first, and came to final rest on roof.
IMPACT CONDITIONS:	High speed, high impact angle
IMPACT HEADING ANGLE:	40 degrees
SLIP ANGLE:	15 degrees
YAW ANGLE:	55 degrees
YAW RATE:	Moderate
ROTATION DIRECTION:	CCW
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	Unknown
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Fell to ground from position on top of CMB, rolling before impacting ground.
BARRIER ASSOCIATION:	Vehicle climbed entire face of CMB with the front end. Vehicle rolled during separation from barrier.

CASE NUMBER:	84 59 512 V
VEHICLE:	1982 Nissan 280 ZX
CURB WEIGHT:	2,800 pounds
ENVIRONMENT:	Three lanes each direction. Left paved shoulder area with CMB separating the opposing traffic lanes.
NARRATIVE:	Vehicle traveling in the left lane started a ccw rotation into barrier. Impacted CMB with high angle and high yaw angle and rate. Right front corner impacted CMB. Front end climbed to top of CMB as vehicle continued ccw rotation. Right rear corner impacted CMB and vehicle continued to rotate. Vehicle separated from CMB sliding 90 degrees yaw on pavement with left side leading. Vehicle tripped and rolled 360 degrees left side first.
IMPACT CONDITIONS:	High speed, high impact angle, high slip angle
IMPACT HEADING ANGLE:	30 degrees
SLIP ANGLE:	60 degrees
YAW ANGLE:	90 degrees
YAW RATE:	High
ROTATION DIRECTION:	CCW
IMPACT SPEED:	57 mi/h
SEPARATION ANGLE:	32 degrees
DIRECTION OF ROLL:	Left side first
TRIP DEVICE:	Fell to ground from position on top of CMB while rotating ccw. Vehicle slid at 90 degrees yaw, tripped on ground and rolled 360 degrees.
BARRIER ASSOCIATION:	Vehicle climbed entire face of CMB with the front end. Vehicle rolled after separation from barrier.

CASE NUMBER:	82 82 561 R
VEHICLE:	1964 Ford Econoline Van
CURB WEIGHT:	2,700 pounds
ENVIRONMENT:	Three travel lanes in each direction and a ramp exiting to the left. CMB section divided the opposing lanes. Road was straight and level at this site.
NARRATIVE:	Vehicle traveling in the left lane at highway speeds made hard steer input to the left, crossed gore area and exit ramp travel lane. The vehicle struck CMB at a high angle and rotated ccw approximately 90 degrees. The front-left climbed the CMB and the vehicle rolled right side first. After rolling the van was struck in the left-rear by vehicle number two. The van rolled over right side first due to the vehicle to barrier.
IMPACT CONDITIONS:	High speed, high impact angle, low slip angle
IMPACT HEADING ANGLE:	41 degrees
SLIP ANGLE:	9 degrees
YAW ANGLE:	50 degrees
YAW RATE:	Low
ROTATION DIRECTION:	CCW
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	1 degree
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Fell on right side from position on top of CMB.
BARRIER ASSOCIATION:	Vehicle climbed lower face of CMB with front-left corner then continued up barrier. Vehicle rolled when vehicle slid at 90 degree slip angle

CASE NUMBER:	83 08 509 T
VEHICLE:	1979 Honda Civic
CURB WEIGHT:	1,800 pounds
ENVIRONMENT:	Two travel lanes in each direction and a 6 inch curb on the right edge of road. CMB section divided the opposing lanes. Road was straight and level at this site.
NARRATIVE:	Vehicle traveling in the second lane from the left swerved to left and impacted CMB with the front left corner at low angle while tracking. The vehicle separated in a tracking attitude, traveled across the two travel lanes as it began a ccw rotation back to a heading along the travel lane. The right side of tires impacted the 6 inch curb tripping the vehicle. The vehicle rolled to 180 degrees to final rest.
IMPACT CONDITIONS:	High speed, moderate angle, tracking
IMPACT HEADING ANGLE:	15 degrees
SLIP ANGLE:	00 degrees
YAW ANGLE:	15 degrees
YAW RATE:	None
ROTATION DIRECTION:	None
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	02 degrees
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Struck curb face with right side tires after separation.
BARRIER ASSOCIATION:	Vehicle was redirected across road. Vehicle rolled during after from barrier.

CASE NUMBER:	83 82 521 L
VEHICLE:	1981 Kenworth with van trailer
CURB WEIGHT:	80,000 pounds
ENVIRONMENT:	One lane ramp curved to the left with CMB on outside of curve.
NARRATIVE:	Vehicle traveling in the ramp lane struck CMB with right front and rolled over top of barrier.
IMPACT CONDITIONS:	Low angle, high speed
IMPACT HEADING ANGLE:	N/A
YAW ANGLE:	N/A
YAW RATE:	N/A
ROTATION DIRECTION:	N/A
IMPACT SPEED:	N/A
SEPARATION ANGLE:	N/A
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	CMB
BARRIER ASSOCIATION:	Vehicle rolled over CMB.

CASE NUMBER:	83 76 066 W
VEHICLE:	1977 Chevrolet Nova
CURB WEIGHT:	3,400 pounds
ENVIRONMENT:	Two travel lanes in each direction. CMB section divided the opposing lanes. Road was curved right and level at this site.
NARRATIVE:	Vehicle traveling in the right lane at highway speeds. The vehicle drove onto the left paved shoulder and struck the CMB at a moderate angle while tracking. The barrier moved approximately 2 ft as the vehicle climbed to the top and began to roll right side first. Vehicle came to rest on roof.
IMPACT CONDITIONS:	High speed, moderate impact angle, tracking
IMPACT HEADING ANGLE:	25 degrees
SLIP ANGLE:	1 degree
YAW ANGLE:	26 degrees
YAW RATE:	None
ROTATION DIRECTION:	None
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	16 degrees
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Left side of vehicle mounted CMB. CMB deflected during impact. Vehicle rolled right side first upon separation.
BARRIER ASSOCIATION:	Vehicle mounted barrier as barrier deflected.

CASE NUMBER:	83 82 532 V
VEHICLE:	1972 Chevrolet Malibu
CURB WEIGHT:	3,500 pounds
ENVIRONMENT:	Three travel lanes in each direction. Straight and level roadway with CMB along left edge of left shoulder.
NARRATIVE:	Vehicle traveling in the left lane struck CMB at low angle with left front. The left front climbed to the top of the barrier and the vehicle began to rotate ccw and slide at 90 degree slip angle with right side leading. The left rear tire deflated and pulled off the rim causing the rim it dig into the pavement, tripping the vehicle. Vehicle rolled right side first and came to final rest on its roof.
IMPACT CONDITIONS:	Moderate speed, low angle, high slip
IMPACT HEADING ANGLE:	6 degrees
SLIP ANGLE:	41 degrees
YAW ANGLE:	47 degrees
YAW RATE:	High
ROTATION DIRECTION:	CCW
IMPACT SPEED:	44 mi/h
SEPARATION ANGLE:	2 degrees
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Tire came off rim and rim dug into pavement
BARRIER ASSOCIATION:	Vehicle climbed lower face of CMB with front corner then continued up barrier. Vehicle rolled during separation from barrier.

CASE NUMBER:	83 82 515 N
VEHICLE:	1959 Chevrolet pickup
CURB WEIGHT:	3,300 pounds
ENVIRONMENT:	Three travel lanes in each direction and a left shoulder. CMB with chain link glare screen divided the opposing lanes. Road was straight and level at this site.
NARRATIVE:	Vehicle traveling in the center lane at highway speeds struck the rear of vehicle number two, which went off the right side of the road and rolled over. The striking truck rotated cw and impacted the CMB with the right rear corner. The truck mounted the barrier with the right side and began to roll one-quarter turn as it separated. Vehicle came to rest on its left side.
IMPACT CONDITIONS:	High speed, moderate impact angle
IMPACT HEADING ANGLE:	Approximately 20 degrees
SLIP ANGLE:	220 degrees
YAW ANGLE:	240 degrees
YAW RATE:	High
ROTATION DIRECTION:	CW
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	8 degrees
DIRECTION OF ROLL:	Left side first
TRIP DEVICE:	Fell to ground from position on top of CMB. The vehicle landed on its left side.
BARRIER ASSOCIATION:	Vehicle climbed lower face of CMB with the right rear end and right side then continued up barrier. Vehicle rolled during separation from barrier.

CASE NUMBER:	83 03 040 V
VEHICLE:	1980 Chevrolet Chevette
CURB WEIGHT:	2,100 pounds
ENVIRONMENT:	Four lanes each direction. Slight curve to the right. Left paved shoulder area with CMB separating the opposing traffic lanes.
NARRATIVE:	Vehicle traveling in the left lane impacted CMB with low angle and tracking. Left front corner impacted CMB hard. Front end climbed to top of CMB as vehicle began cw rotation. Vehicle separated from CMB rotating with left side leading. Vehicle rolled 360 degrees left side first.
IMPACT CONDITIONS:	High speed, moderate impact angle
IMPACT HEADING ANGLE:	18 degrees
SLIP ANGLE:	0 degrees
YAW ANGLE:	18 degrees
YAW RATE:	Low
ROTATION DIRECTION:	None
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	27 degrees
DIRECTION OF ROLL:	Left side first
TRIP DEVICE:	Fell to ground from position on top of CMB while rotating cw and rolling.
BARRIER ASSOCIATION:	Vehicle climbed face of CMB with the front end. Vehicle rolled during separation from barrier.

CASE NUMBER:	82 36 151 T
VEHICLE:	1970 Ford Bronco
CURB WEIGHT:	3,200 pounds
ENVIRONMENT:	Three travel lanes in each direction. CMB section divided the opposing lanes. Road was straight and level at this site. A bridge rail was mounted on the right next to the right lane.
NARRATIVE:	Vehicle traveling in the right lane at highway speeds made an evasive type steer input to the left. The vehicle rotated CCW into a yaw and tripped in the center lane. The vehicle then slid into the barrier on its right side causing damage to the roof and hood. The vehicle was redirected by the barrier and slid to final rest on its right side.
IMPACT CONDITIONS:	Sliding on right side.
IMPACT HEADING ANGLE:	18 degrees
SLIP ANGLE:	50 degrees
YAW ANGLE:	68 degrees
YAW RATE:	None
ROTATION DIRECTION:	CCW
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	6 degrees
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Steer input from driver caused high yaw rate and angles. Dynamic instability of vehicle allowed trip without significant contact with any object.
BARRIER ASSOCIATION:	Vehicle was already on right side at impact with CMB. CMB redirected sliding vehicle.

CASE NUMBER:	83 30 164 V
VEHICLE:	1982 Nissan Stanza
CURB WEIGHT:	2,200 pounds
ENVIRONMENT:	Two lanes, straight and level, in each direction. Left paved shoulder area with CMB separating the opposing traffic lanes.
NARRATIVE:	Vehicle traveling in the left lane steered toward the CMB. The vehicle impacted the CMB with high angle and no slip angle or rate. The left front corner impacted CMB. Front end climbed to top of CMB as vehicle began ccw rotation at separation. Vehicle separated from top of the CMB rotating and rolling right side first. Vehicle rolled 360 degrees.
IMPACT CONDITIONS:	Moderate speed and impact angle
IMPACT HEADING ANGLE:	19 degrees
SLIP ANGLE:	0 degrees
YAW ANGLE:	19 degrees
YAW RATE:	None
ROTATION DIRECTION:	None
IMPACT SPEED:	39 mi/h
SEPARATION ANGLE:	3 degrees
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Fell to ground from position on top of CMB while rotating ccw.
BARRIER ASSOCIATION:	Vehicle climbed entire face of CMB with the left side. Vehicle rolled during separation from barrier.

CASE NUMBER:	82 82 574 T
VEHICLE:	1967 Toyota Corona
CURB WEIGHT:	2,100 pounds
ENVIRONMENT:	Three travel lanes in each direction and a wide left shoulder.e left. CMB section divided the opposing lanes. Road was curved slightly right and level at this site.
NARRATIVE:	Vehicle traveling in the left lane at highway speeds and made a slight steer input to the left. The front left corner and left side wheels climbed to the top of the barrier. The vehicle separated from the barrier and struck the ground hard on the right front corner, collapsing the suspension. The vehicle rolled right side first after yawing 90 degrees. The vehicle rolled 360 degrees.
IMPACT CONDITIONS:	High speed, high angle, slight slip
IMPACT HEADING ANGLE:	12 degrees
SLIP ANGLE:	1 degree
YAW ANGLE:	13 degrees
YAW RATE:	None
ROTATION DIRECTION:	None
IMPACT SPEED:	58 mi/h
SEPARATION ANGLE:	9 degrees
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Fell on ground from position on top of CMB. The right side front suspension collapsed as the vehicle landed and began a ccw rotation. The vehicle tripped on folded suspension.
BARRIER ASSOCIATION:	Vehicle climbed lower face of CMB with front-left corner then continued up barrier. Vehicle rolled after separation from barrier.

CASE NUMBER:	83 03 523 W
VEHICLE:	1974 Audi Fox
CURB WEIGHT:	2,100 pounds
ENVIRONMENT:	Three travel lanes in each direction. CMB section divided the opposing lanes. Road was straight and level at this site.
NARRATIVE:	Vehicle traveling in the left lane at highway speeds. The vehicle drove onto the left paved shoulder and struck the CMB at a low angle. Very light contact with CMB. Driver made an evasive type steer input to the right. The vehicle rotated CW into a yaw and tripped in the center lane while sliding at 90 degree slip angle. The vehicle then slid to final rest on its roof.
IMPACT CONDITIONS:	High speed, low impact angle
IMPACT HEADING ANGLE:	6 degrees
SLIP ANGLE:	3 degrees
YAW ANGLE:	9 degrees
YAW RATE:	None
ROTATION DIRECTION:	None
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	4 degrees
DIRECTION OF ROLL:	Left side first
TRIP DEVICE:	Steer input from driver caused high yaw rate and angle. Dynamic instability of vehicle allowed trip without significant contact with any object other than ground.
BARRIER ASSOCIATION:	Vehicle was redirected in stable attitude.

CASE NUMBER:	83 36 099 W
VEHICLE:	1980 Chevrolet Chevette
CURB WEIGHT:	2,100 pounds
ENVIRONMENT:	Two lanes each direction. Left paved shoulder area with CMB separating the opposing traffic lanes.
NARRATIVE:	Vehicle traveling in the left lane was struck on right side by a larger vehicle. The larger vehicle stayed in contact as it pushed the Chevette into the CMB at a low impact angle. The Chevette climbed the face of the CMB with the left side climbing over the top of the barrier. The right side dropped down and the vehicle separated rolling right side first along the barrier. Final rest was on the right side.
IMPACT CONDITIONS:	Low angle, high speed
IMPACT HEADING ANGLE:	2 degrees
SLIP ANGLE:	0 degrees
YAW ANGLE:	2 degrees
YAW RATE:	None
ROTATION DIRECTION:	None
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	6 degrees
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Fell to ground from position on top of CMB while sliding along top of barrier.
BARRIER ASSOCIATION:	Vehicle climbed entire face of CMB with the left side. Vehicle rolled during separation from barrier.

CASE NUMBER:	83 03 066 V
VEHICLE:	1983 Toyota Tercel
CURB WEIGHT:	2,000 pounds
ENVIRONMENT:	Four travel lanes in each direction and a left shoulder. CMB section divided the opposing lanes. Road was straight and level at this site.
NARRATIVE:	Vehicle traveling in the second lane from the left at highway speeds struck the rear of vehicle number two and started rotating ccw. The vehicle then struck the CMB, rotated ccw, separated and rolled right side first. The vehicle rolled 180 degrees.
IMPACT CONDITIONS:	High speed, high angle
IMPACT HEADING ANGLE:	54 degrees
SLIP ANGLE:	27 degrees
YAW ANGLE:	87 degrees
YAW RATE:	Moderate
ROTATION DIRECTION:	CCW
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	8 degrees
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Fell to ground from position on top of CMB. The vehicle landed and began a ccw rotation. The vehicle tripped on the pavement without a subsequent impact.
BARRIER ASSOCIATION:	Vehicle climbed lower face of CMB with the entire front end then continued up barrier. Vehicle rolled after separation from barrier.

CASE NUMBER:	83 82 539 T
VEHICLE:	1977 Fiat 131
CURB WEIGHT:	2,500 pounds
ENVIRONMENT:	Three lanes each direction. Left paved shoulder area with CMB separating the opposing traffic lanes.
NARRATIVE:	Vehicle traveling in the center lane started a ccw rotation into barrier. Impacted CMB with high angle and high yaw angle and rate. Full frontal impact with CMB. Vehicle climbed CMB face and continued to yaw 90 degrees with right side leading as right front suspension collapsed and dug into pavement. Vehicle rolled right side first due to suspension failure.
IMPACT CONDITIONS:	Moderate speed, moderate angle, high yaw rate
IMPACT HEADING ANGLE:	17 degrees
SLIP ANGLE:	44 degrees
YAW ANGLE:	61 degrees
YAW RATE:	High
ROTATION DIRECTION:	CCW
IMPACT SPEED:	41 mi/h
SEPARATION ANGLE:	1 degree
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Right front suspension collapse while sliding at 90 degree slip angle.
BARRIER ASSOCIATION:	Vehicle climbed CMB with full frontal impact

CASE NUMBER:	84 80 503 P
VEHICLE:	1983 Chevrolet S-10 Pickup
CURB WEIGHT:	3,000 pounds
ENVIRONMENT:	Two lanes in each direction. Slight down-grade. CMB separating the opposing travel lanes.
NARRATIVE:	Vehicle traveling in the left lane made a slight steer input to the left and struck CMB at low impact and yaw angle. The vehicle was redirected at a low angle back to the travel lanes where it ran off the right side of the road and travelled down a steep embankment. The vehicle began rolled as it travelled down the side of the embankment.
IMPACT CONDITIONS:	Low angle, high speed
IMPACT HEADING ANGLE:	5 degrees
SLIP ANGLE:	7 degrees
YAW ANGLE:	11 degrees
YAW RATE:	Low
ROTATION DIRECTION:	CCW
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	10 degrees
DIRECTION OF ROLL:	Left side first
TRIP DEVICE:	Traveled sideways down embankment
BARRIER ASSOCIATION:	Vehicle was redirected tracking - no association.

CASE NUMBER:	82 30 228 V
VEHICLE:	1980 Plymouth Horizon
CURB WEIGHT:	2,200 pounds
ENVIRONMENT:	One lane with right shoulder, slight curve to left and CMB along left edge of travel lane.
NARRATIVE:	Vehicle traveling in the lane struck CMB at low angle with left front. The left front and left rear tires climbed to the top of the barrier and the vehicle began to roll and rotate ccw. Vehicle rolled right side first and came to final rest on roof after impacting W-beam on right side of road.
IMPACT CONDITIONS:	High speed, low angle, tracking
IMPACT HEADING ANGLE:	7 degrees
SlIP ANGLE:	0 degrees
YAW ANGLE:	7 degrees
YAW RATE:	None
ROTATION DIRECTION:	None
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	12 degrees
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Fell to ground from position on top of CMB. The vehicle landed on roof and slid to rest.
BARRIER ASSOCIATION:	Vehicle climbed lower face of CMB with front-left corner then continued up barrier. Vehicle rolled during separation from barrier.

CASE NUMBER:	82 82 559 W
VEHICLE:	1978 Ford Mustang
CURB WEIGHT:	2,700 pounds
ENVIRONMENT:	Three travel lanes in each direction. CMB section divided the opposing lanes. Road was straight and level at this site.
NARRATIVE:	Vehicle traveling in the left lane at highway speeds made slight steer input to the left. The vehicle struck CMB at very low angle, climbed the lower face and continued to the top of the CMB. The left side wheels mounted the barrier and the car traveled 214 feet along top of the barrier. The right side dropped down and contacted the ground for a final rest roll of 90 degrees.
IMPACT CONDITIONS:	High speed, low angle, tracking
IMPACT HEADING ANGLE:	4 degrees
SLIP ANGLE:	0 degrees
YAW ANGLE:	4 degrees
YAW RATE:	None
ROTATION DIRECTION:	None
IMPACT SPEED:	40-55 mi/h
SEPARATION ANGLE:	5 degrees
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Fell on right side from position on top of CMB.
BARRIER ASSOCIATION:	Vehicle climbed lower face of CMB with left side then continued to the top of barrier.

CASE NUMBER:	82 79 514 W
VEHICLE:	1970 Dodge Challenger
CURB WEIGHT:	3,200 pounds
ENVIRONMENT:	Four travel lanes in each direction. CMB section divided the opposing lanes. Road was straight and level at this site.
NARRATIVE:	Vehicle traveling in the left lane at highway speeds made a steer input to the left. The vehicle tracked into the CMB and impacted with the front left corner and left front wheel. The left front wheel climbed over the top of the barrier. The right side moved close to the base of the barrier and the vehicle rolled right side first 180 degrees.
IMPACT CONDITIONS:	High speed, low angle, tracking
IMPACT HEADING ANGLE:	2 degrees
SLIP ANGLE:	0 degrees
YAW ANGLE:	2 degrees
YAW RATE:	None
ROTATION DIRECTION:	None
IMPACT SPEED:	65 mi/h
SEPARATION ANGLE:	2 degrees
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Left side mounted top of CMB. Vehicle rolled right side first at separation.
BARRIER ASSOCIATION:	Vehicle rolled due to left side mounting CMB.

CASE NUMBER:	83 11 508 W
VEHICLE:	1981 Oldsmobile Cutlass
CURB WEIGHT:	3,300 pounds
ENVIRONMENT:	Two lanes in each direction and left shoulder. CMB with concrete glare screen separates the opposing traffic lanes. Slight curve to right.
NARRATIVE:	Vehicle traveling in the left lane steered into barrier at a low angle and high speed. Vehicle impacted CMB with right front corner and left side tires. The left side climbed the CMB to the top of the glare screen where the vehicle continued along the barrier for approximately 380 feet. The glare screen ended and the vehicle dropped off onto its right side. The vehicle slid to a stop on its right side.
IMPACT CONDITIONS:	High speed , low angle
IMPACT HEADING ANGLE:	6 degrees
SLIP ANGLE:	0 degrees
YAW ANGLE:	6 degrees
YAW RATE:	None
ROTATION DIRECTION:	None
IMPACT SPEED:	Unknown
SEPARATION ANGLE:	01 degrees
DIRECTION OF ROLL:	Right side first
TRIP DEVICE:	Fell to ground from position on top of CMB where glare screen ended.
BARRIER ASSOCIATION:	Vehicle climbed entire face and concrete glare screen of CMB with the entire left side. Vehicle rolled during separation from barrier.