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March 1974

Final Report

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16. Abstract

A study was conducted to develop techniques for the improvement of front and side vehicle crashworthiness. These techniques were applied to a production compact vehicle, the 1973 AMC Hornet. General vehicle configuration was maintained as was production feasibility. Total weight increase for all modifications was 104 lbs. Five baseline, three subsystem and fifteen system vehicle crash tests were conducted. Modified vehicles demonstrated substantial improvement over baseline vehicle performance.

Mathematical models for estimating dynamic response characteristics of vehicles involved in a wide variety of crash conditions including flat barrier, oblique barrier, pole and vehicle-to-vehicle impacts were developed. Computer simulations were conducted and results of simulations compared with crash test results.

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SUMMARY

INTRODUCTION

This document summarizes the work accomplished under DOT Contract DOT-HS-257-2-461 entitled, "Frontal and Side Impact Crashworthiness - Compact Cars." The contract, which was for an eighteen month period, had as its objective the improvement in crashworthiness of a production compact car. The DOT Contract Technical Monitor was Mr. S. Craig Keifer. The contract was performed at the Advanced Systems Laboratory of AMF Incorporated under the program management of Mr. William J. Wingenbach. The major subcontractor was American Motors Corporation, who supplied the production vehicles used in the project, performed vehicle design for the incorporation of energy absorption concepts, and studied the production feasibility of the various vehicle modifications. The AMC effort was managed by Mr. Kenneth Schang of the Vehicle Safety Department. Other subcontractors were Aero Spacelines Inc. who performed all modification to production vehicles; Dynamic Science who conducted a series of baseline and subsystem vehicle impact tests; and Calspan Corporation who conducted a series of system vehicle impact tests. All mathematical modeling, concept generation, analyses and component development testing were performed at the AMF/ASL facility.

The vehicle selected for use in the program was the 1973 AMC Hornet. The 2-door sedan with 6-cylinder engine and automatic transmission was specified because that model was most representative of 1973 Hornets in use. Constraints on modifications to the vehicle included retention of the engine in its current configuration. Increases in length, width, weight and cost were limited to levels which would not change the character and public acceptability of the vehicle. An additional constraint adopted during the project was control of the aggressivity of the modified vehicle front end. That is, the modified front end should not cause a great deal more damage to another vehicle than an unmodified vehicle under similar crash conditions.

Energy absorption concepts and the methods used for designing them were selected on the basis of their adaptability to a wide variety of production vehicles. Performance goals sought were derived from consideration of occupant acceleration and vehicle intrusion limits which had been specified on past DOT projects. These are summarized in Table 1. Maximum impact velocity at which these performance goals could be realized were estimated after consideration of vehicle geometry and crush space to be 40 mph for frontal barrier and pole impacts and 10 mph for side impacts.

Table 1
Performance Goals

Type of Impact	Maximum Acceleration	Maximum Intrusion
Frontal Barrier	40 g	5 inches
Frontal Pole	40 g	5 inches
Side Pole	20 g	3.5 inches

Actual test velocities selected were

50 mph - frontal barrier
40 mph - frontal pole
10 mph - side pole
75 mph - relative velocity, vehicle front to vehicle front
25 mph - relative velocity, vehicle front to vehicle side

PROGRAM LOGIC

The program logic for the Compact Car Front and Side Impact Crashworthiness program is outlined in Figure 1. The program involved both hardware and software development. Hardware development included the following studies

- Front end component level
- Side component level

PROGRAM LOGIC

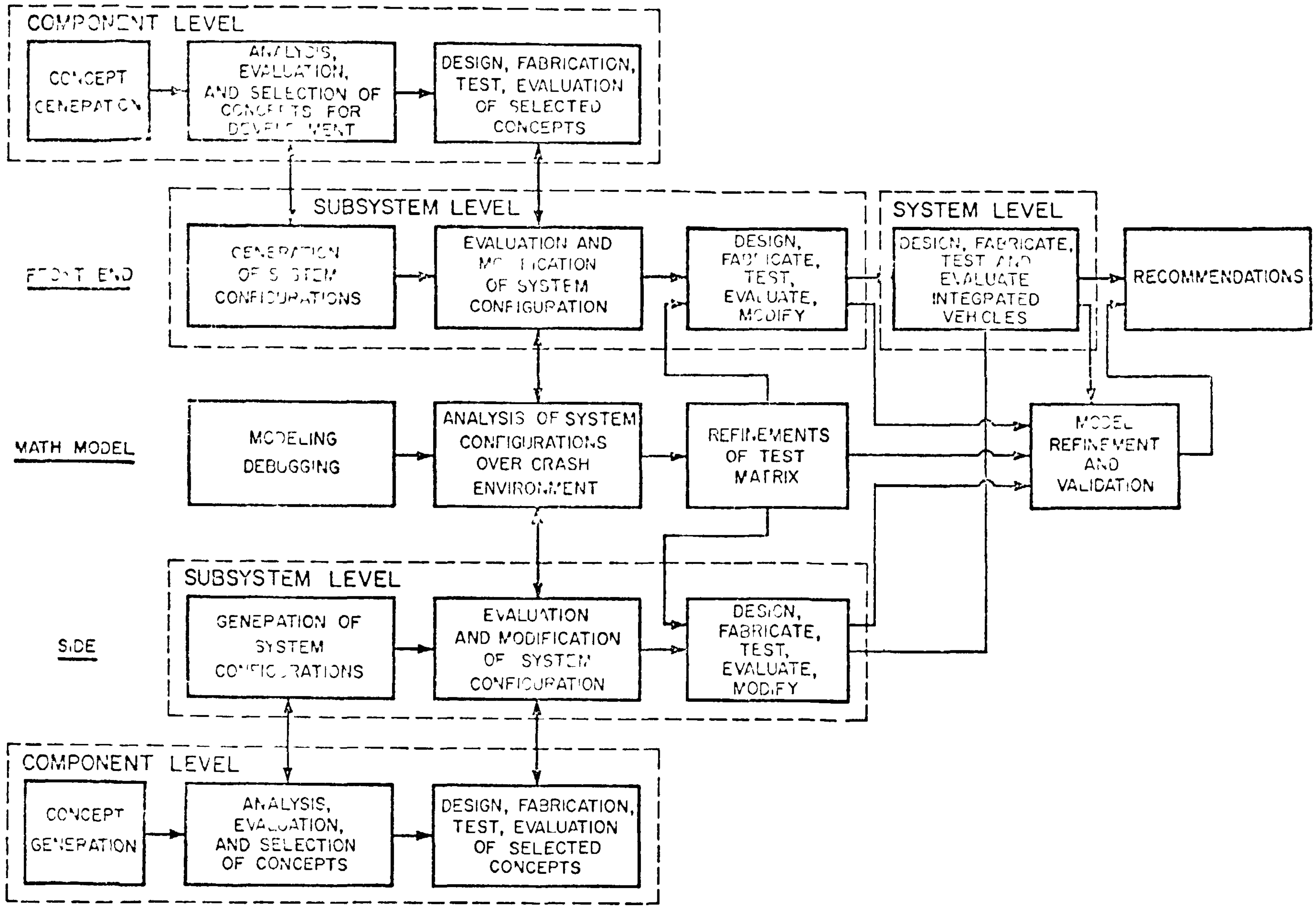


Figure 1

- Front end subsystem level
- Side subsystem level
- Integrated system level

Paralleling hardware development and interrelating with it was a continuing mathematical model development effort.

The program began with an examination of the production vehicle which had been selected for modification. This included studies of various components of the vehicles as well as a comprehensive set of crash tests of the unmodified vehicle. These studies led to the identification of vehicle structures which would require modification.

Mathematical modeling of vehicles in various crash configurations was undertaken and the results of the baseline vehicle test program used to verify the validity of the modeling techniques.

In parallel efforts, various energy absorbing concepts were developed for front and side structures. The development effort involved component concept generation, analyses, and evaluation. Laboratory versions of promising concepts were fabricated, tested and further evaluated.

Since the selection of component concepts for fabrication and test was based on a performance evaluation in a system context, the second development cycle (subsystem level) overlapped the first cycle. Preliminary selection of front end and side structural configurations accompanied component selections.

At the completion of component testing, one front and one side structural configuration was selected for development. This started with a design program at the American Motors facility. Continuous manufacturing feasibility evaluation was performed as the designs emerged. The front end and side structural modifications were incorporated into a series of vehicles and a second cycle of testing performed. These tests were designed to explore the behavior of either the front end or side subsystem only, and not the entire vehicle. Therefore, the vehicle structure away from the subsystem under study was strongly reinforced so that deformation was concentrated in the area of interest. The subsystem test program consisting of a front barrier, a front pole and a side pole test provided a second opportunity for comparing math model simulations with crash test results.

The last cycle (system level) was directed toward improving the front end and side structure as indicated by subsystem tests and incorporating these refined structures into an integrated design with the basic vehicle structure. This was accompanied by a continuing effort to minimize weight and to maintain production feasibility.

A comprehensive series of tests was conducted with systems level modified vehicles. The series of fifteen tests explored the behavior of the modified vehicle in a wide variety of crash situations. It included a study of the effects of vehicle aggressiveness since the series involved both modified and unmodified vehicles in identical crash situations. Also studied was the behavior of the modified vehicle in encounters with full-sized 4200 lb vehicles.

The results of this test series were evaluated leading to a series of conclusions and recommendations. The system level test series results provided an additional opportunity for checking and verifying the results of the mathematical simulations of crash events.

VEHICLE MODIFICATIONS

In designing for frontal impacts, the approach taken was to collect concentrated loads and to distribute them to energy absorbing components. The primary energy absorbing components include the crushable forward sills, the plastic-hinge rear sills and the ripple panels. The second-stage bumper absorbs energy when large concentrated loads are applied to it. The energy absorbing components are backed up by non-deforming components that carry loads into the passenger compartment. The reinforced "A" post structure, door beam and "B" post provide a major path for longitudinal loads. The upper

"A" pillar and roof form a secondary load path, with hinging expected in the roof over the "B" pillar. The vehicle was lengthened 3.5 inches to provide front end crush space. The engine mounts were modified to simulate an interlocking type mount. The complete front end modification is shown in Figure 2.

In side impacts, the principal energy absorbing element was a crushable beam membrane door panel. This panel was supported by reinforced "A" and "B" posts and improved door retention hardware. The rocker panel was strengthened and lateral braces added to transmit side load from the rocker panel to the rear sill structure.

All of the vehicle modifications were accomplished with a net weight increase of 104.3 pounds. This does not include any secondary weight effects such as a possible need of a modified front suspension. A detailed breakdown of the weight changes is given in Table 2. With the exception of the door beam, all components were fabricated from carbon steel.

TEST RESULTS

Various energy absorption concepts and structural modifications were developed with the aid of a series of component and subsystem tests. The total system crashworthiness was demonstrated in a series of tests representing a wide variety of crash conditions. A summary of these tests is given in Table 3.

The results of tests which correspond to previously conducted baseline tests of unmodified vehicles are shown in Figures 3 through 7. The acceleration shown was recorded at the trunk floor for frontal impacts and at the floor on the side away from impact for side impacts. This acceleration is most representative of gross passenger compartment acceleration since it does not contain perturbation due to local floor crippling. All data has been filtered per SAE J211. A summary of results of the five tests and their comparisons with baseline tests is given in Table 4.

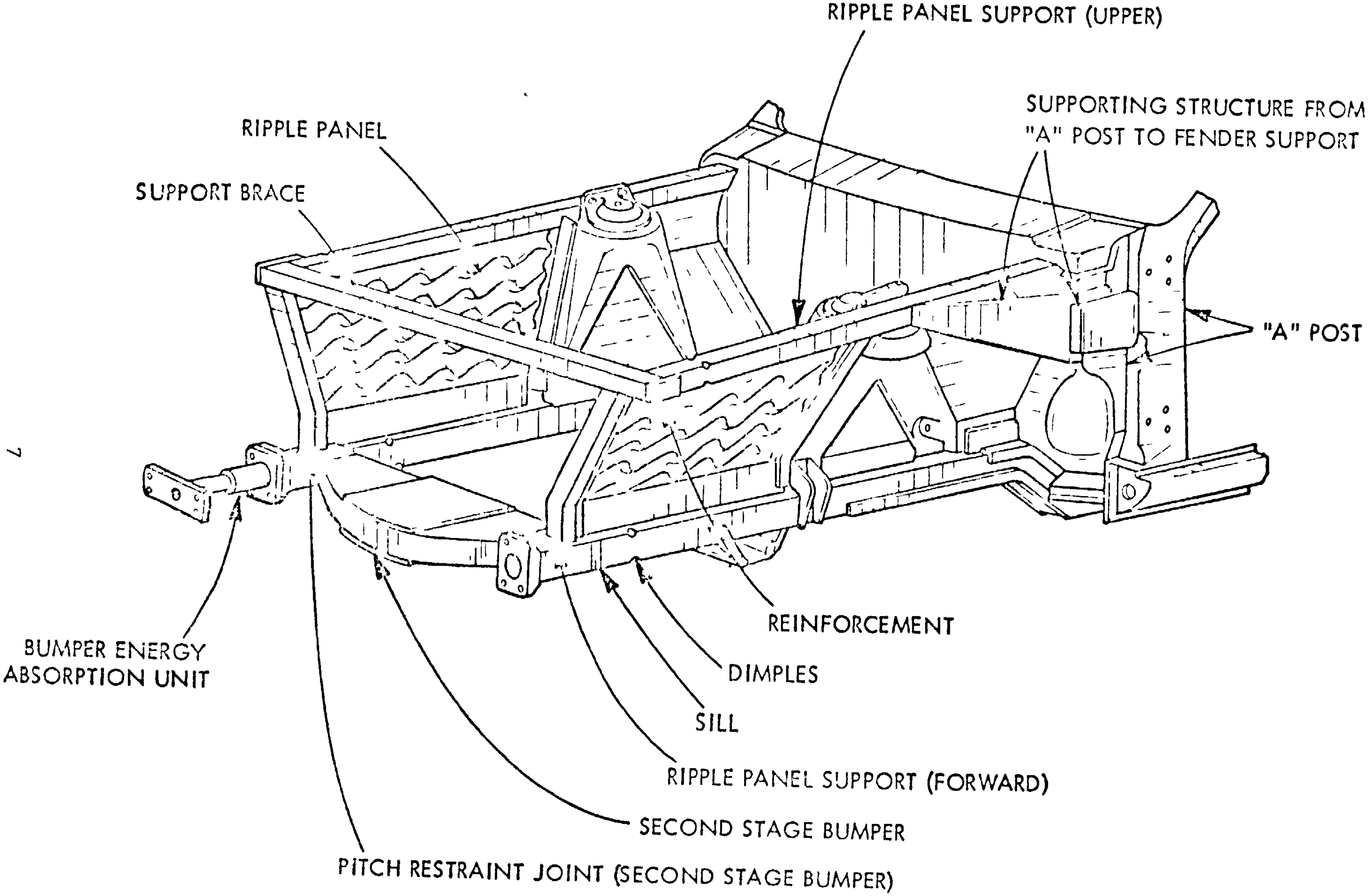


Figure 2. Front End Structure - System Test Vehicle

Table 2. Weight Evaluation System Test Vehicle

COMPONENT	WEIGHT ADDED lbs.	WEIGHT REMOVED lbs.	NET CHANGE lbs.
SILLS, GUTTERS, PANELS & MISC.	146.8	122.5	24.3
LATERAL BRACES	18.6		18.6
2nd STAGE BUMPER	26.0	8.0	18.0
"A" POST	28.6	5.0	23.6
"B" POST	31.0	4.0	27.0
DOOR BEAM ASSY.	26.4	33.6	-7.2
TOTAL	277.4	173.1	104.3

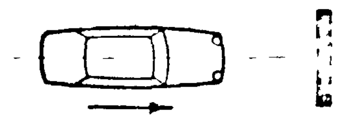
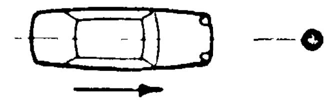
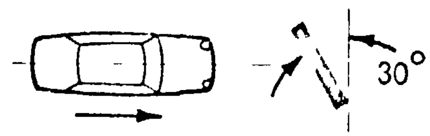
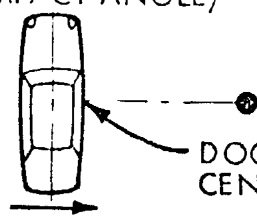
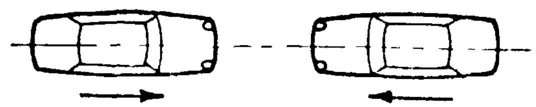
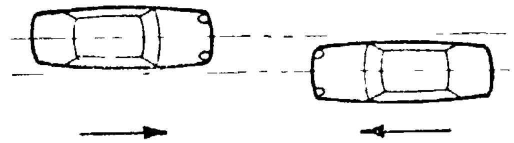
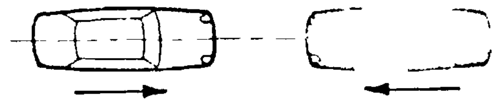
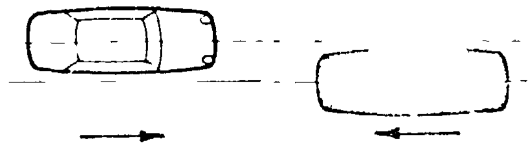
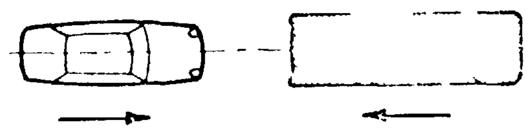
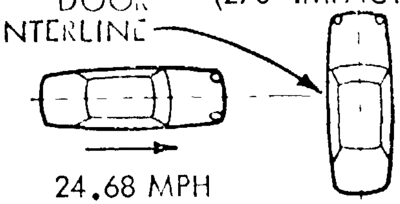
TEST #	IMPACTING VEHICLE	IMPACTED VEHICLE	IMPACT GEOMETRY
1.	#1 FRONT AND SIDE MODIFIED HORNET 2940 LB	FLAT BARRIER	 50.71 MPH (Comparable to [illegible] Test I)
2.	#5 FRONT MODIFIED HORNET 2940 LB	POLE	 40.23 MPH (Comparable to [illegible] Test [illegible])
3.	#2 FRONT AND SIDE MODIFIED HORNET 2930 LB	FLAT BARRIER	 50.0 MPH
4.	#12 SIDE MODIFIED HORNET 2930 LB	POLE	(90° IMPACT ANGLE) (Comparable to Baseline Test III)  9.71 MPH
5.	#10 FRONT MODIFIED HORNET 2930 LB	#11 FRONT MODIFIED HORNET 2910 LB	 36.60 MPH 36.60 MPH (Comparable to Baseline Test [illegible])

Table 3. System Test Program Summary

TEST	IMPACTING VEHICLE	IMPACTED VEHICLE	IMPACT GEOMETRY
6.	#3 FRONT AND SIDE MODIFIED HORNET 2930 LB	#4 FRONT AND SIDE MODIFIED HORNET 2930 LB	 36.25 MPH 36.25 MPH
7.	#6 FRONT MODIFIED HORNET 2920 LB	#14 UNMODIFIED HORNET 2830 LB	 37.73 MPH 37.73 MPH
8.	8 FRONT MODIFIED HORNET 2920 LB	#16 UNMODIFIED HORNET 2830 LB	 36.[illegible] MPH 36.93 MPH
9.	#7 FRONT MODIFIED HORNET 2930 LB	#17 UNMODIFIED FORD CUSTOM 4170 LB	 36.93 MPH 36.93 MPH
10.	#8 FRONT MODIFIED HORNET 2920 LB	#13 SIDE MODIFIED HORNET 2930 LB	(270° IMPACT ANGLE) DOOR CENTERLINE  STATIONARY VEHICLE 24.68 MPH (Co[illegible] to Baseline Test)

Note: Dashed line indicates unmodified vehicle.

Table 3. System Test Program Summary (Continued)

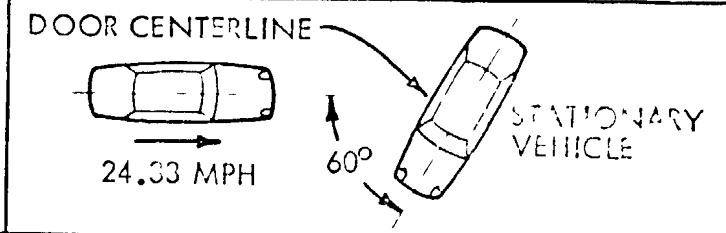
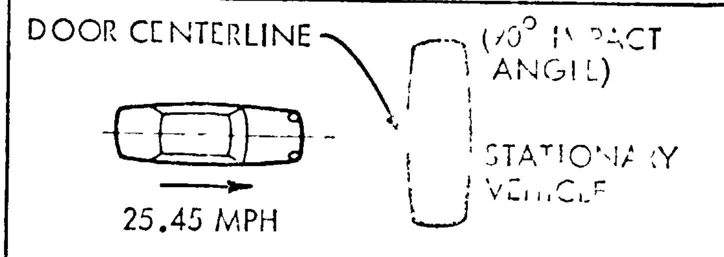
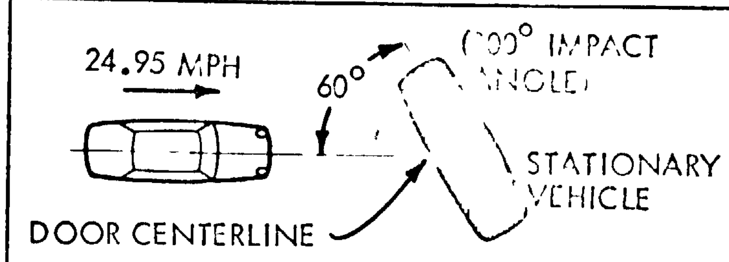
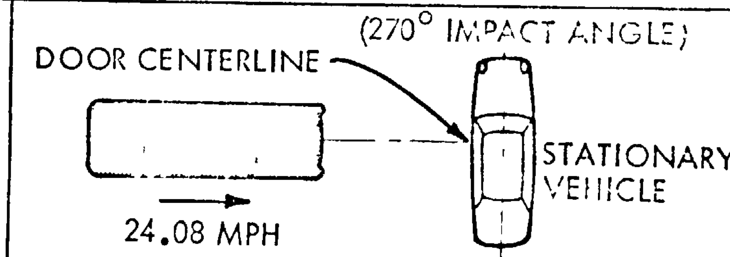
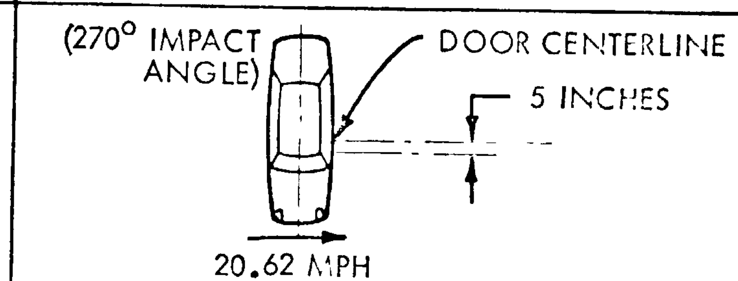
TEST #	IMPACTING VEHICLE	IMPACTED VEHICLE	IMPACT GEOMETRY
11.	9 FRONT MODIFIED HORNET 2920 LB	#13 SIDE MODIFIED HORNET 2930 LB	
12.	#8 FRONT MODIFIED HORNET 2920 LB	#15 UNMODIFIED HORNET 2920 LB	
13.	#9 FRONT MODIFIED HORNET 2920 LB	#16 UNMODIFIED HORNET 2830 LB	
14.	#10 UNMODIFIED FORD CUSTOM 4170 LB	#12 SIDE MODIFIED HORNET 2930 LB	
15.	#4 FRONT AND SIDE MODIFIED HORNET 2930 LB	POLE	

Table 3. System Test Program Summary (Continued)

Note: Shading indicates unmodified vehicle.

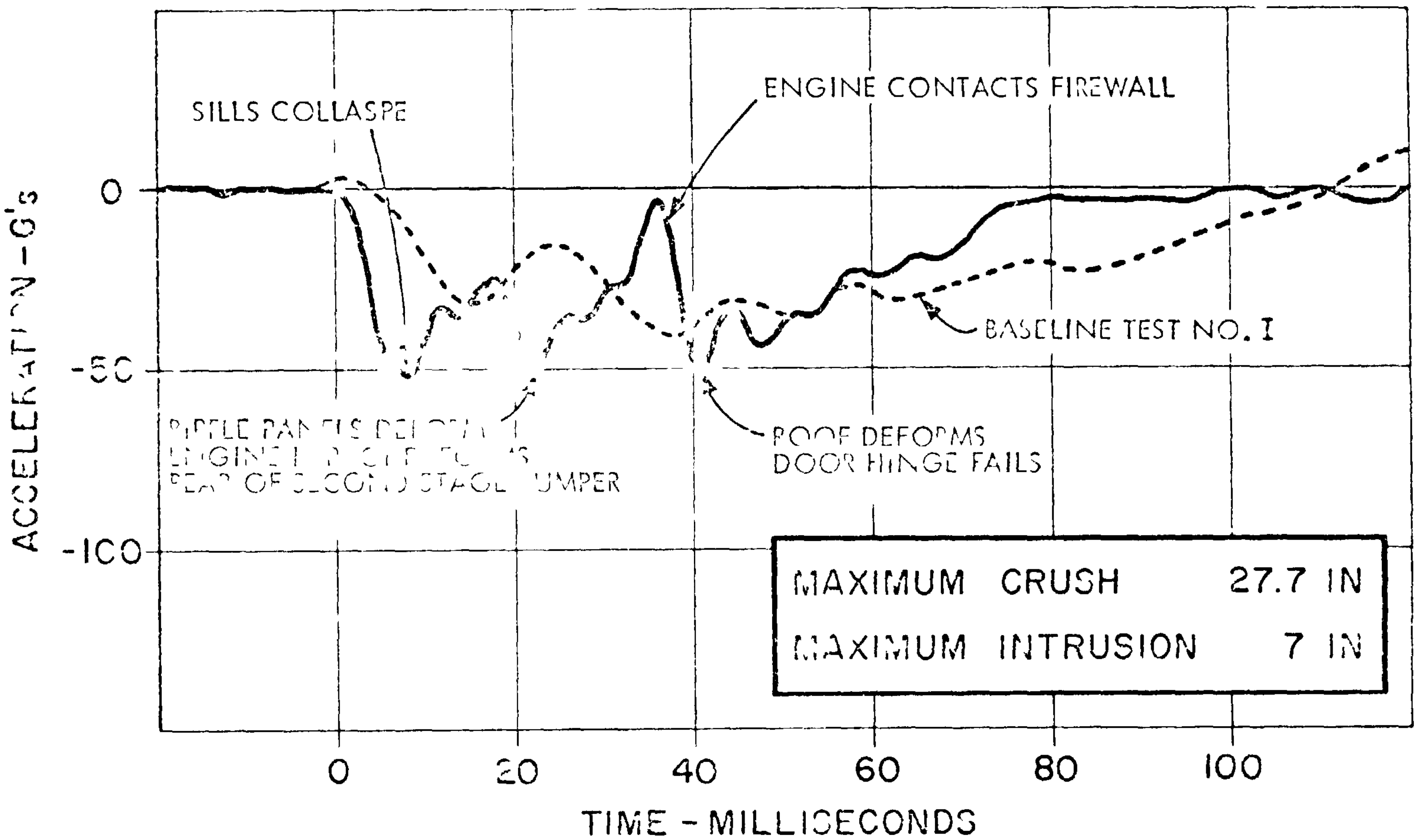


Figure 3. Tes' No. 1. 50.0 mph Flat Barrier Frontal 0° Front Modified Hornet
LONGITUDINAL CRASH PULSE - VEHICLE NO. 1

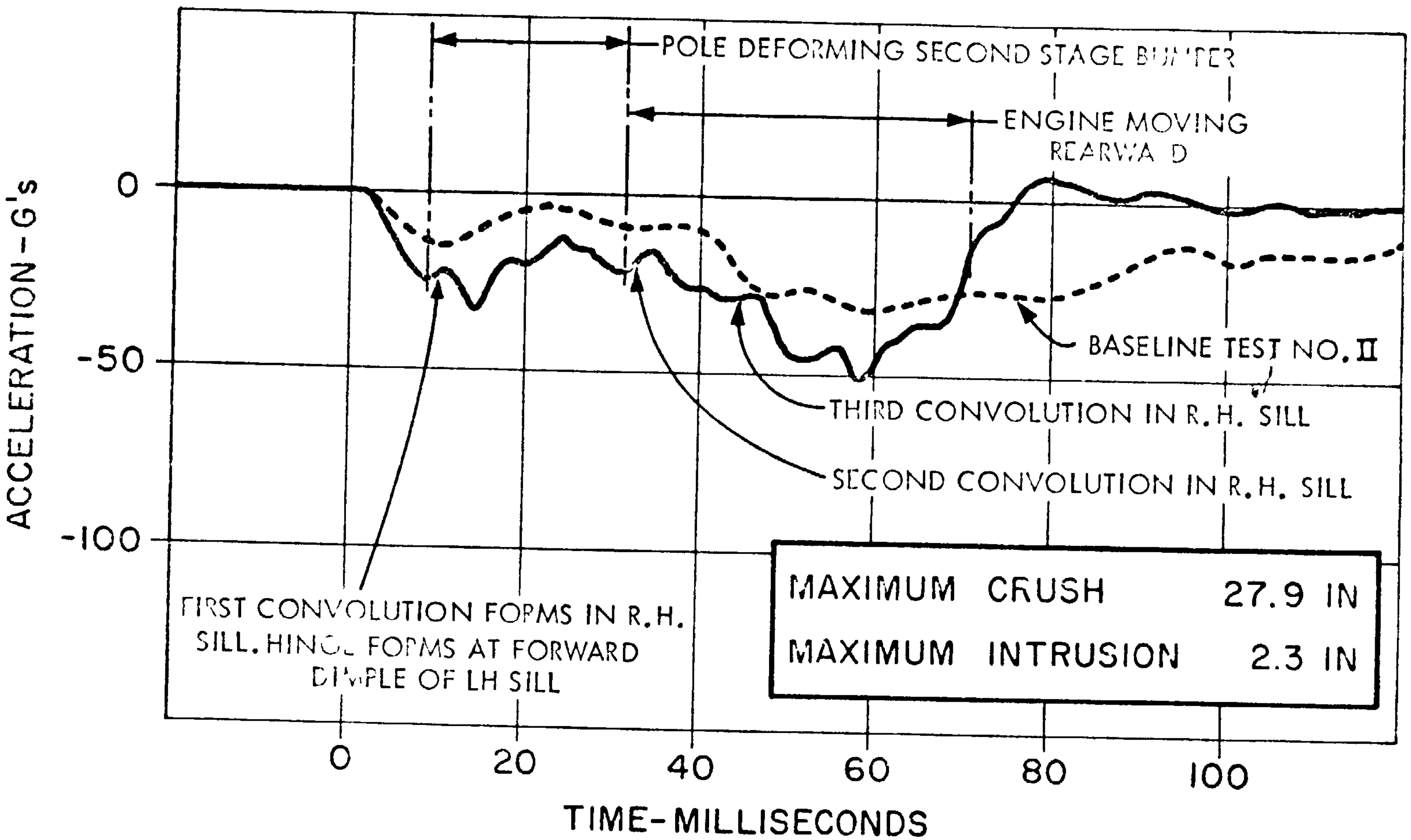


Figure 4. Test No. 2. 40.2 Frontal Pole - Centered. Front Modified Hornet LONGITUDINAL CRASH PULSE - VEHICLE NO. 5

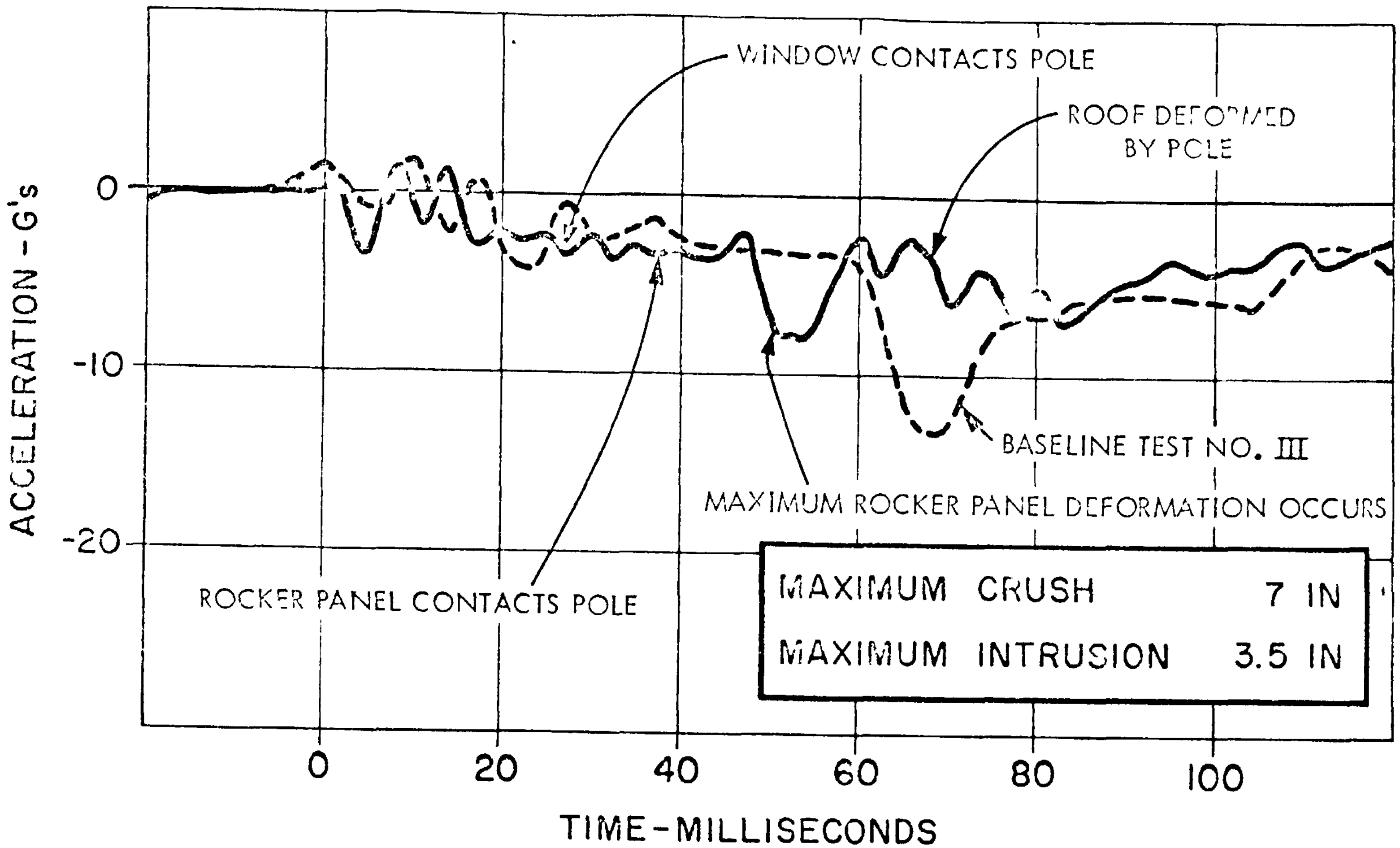


Figure 5. Test No. 4. 9.71 mph Side Pole Impact - 90° Side Modified Hornet
LATERAL CRASH PULSE - VEHICLE NO. 12

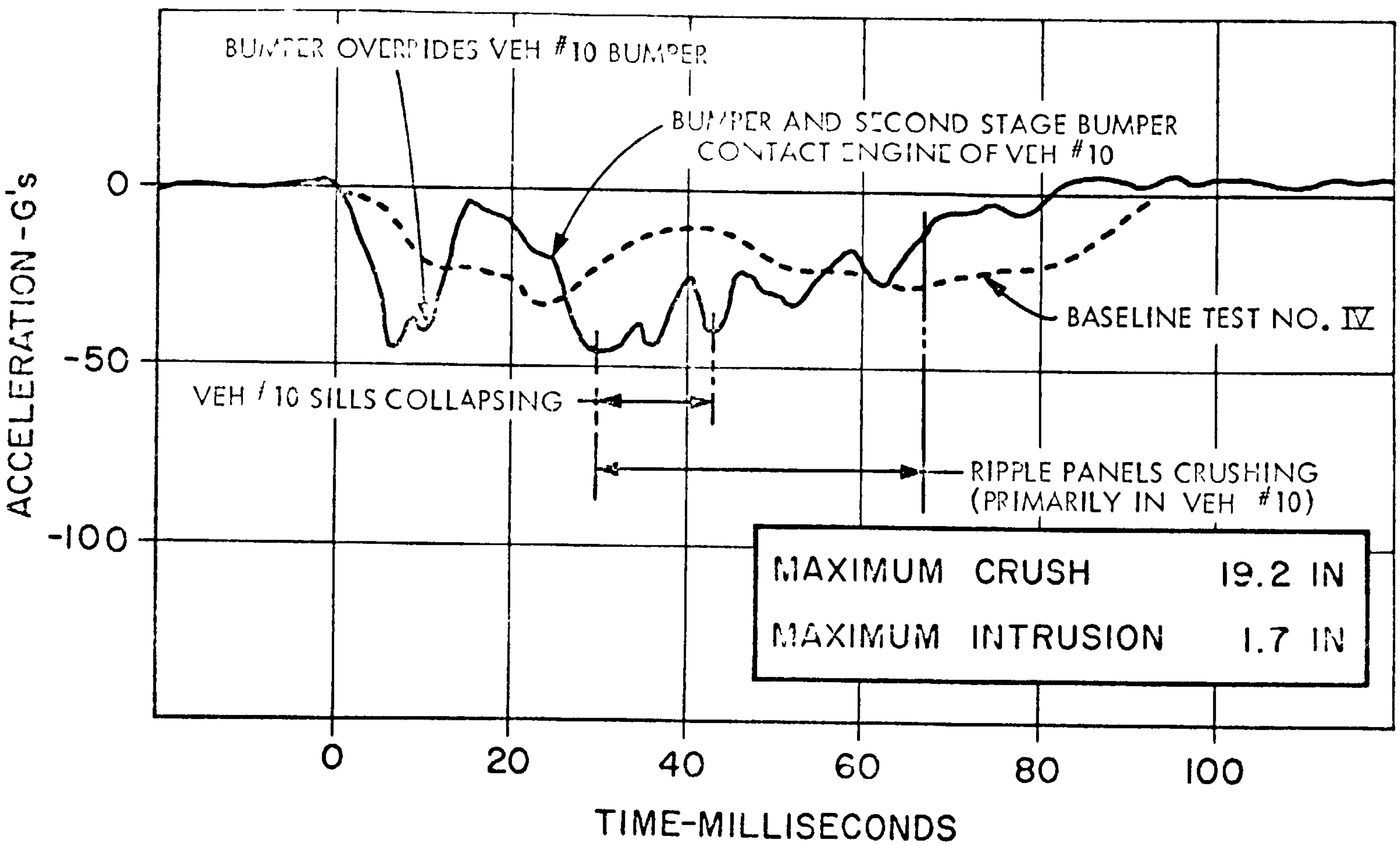


Figure 6. Test No. 5. 36.6 mph Vehicle-to-Vehicle (73.2 mph Relative Velocity) Frontal 0° Aligned. Vehicle No. 10 Front-Modified Hornet and Vehicle No. 11 Front-Modified Hornet
LONGITUDINAL CRASH PULSE - VEHICLE NO. 11 (Modified)

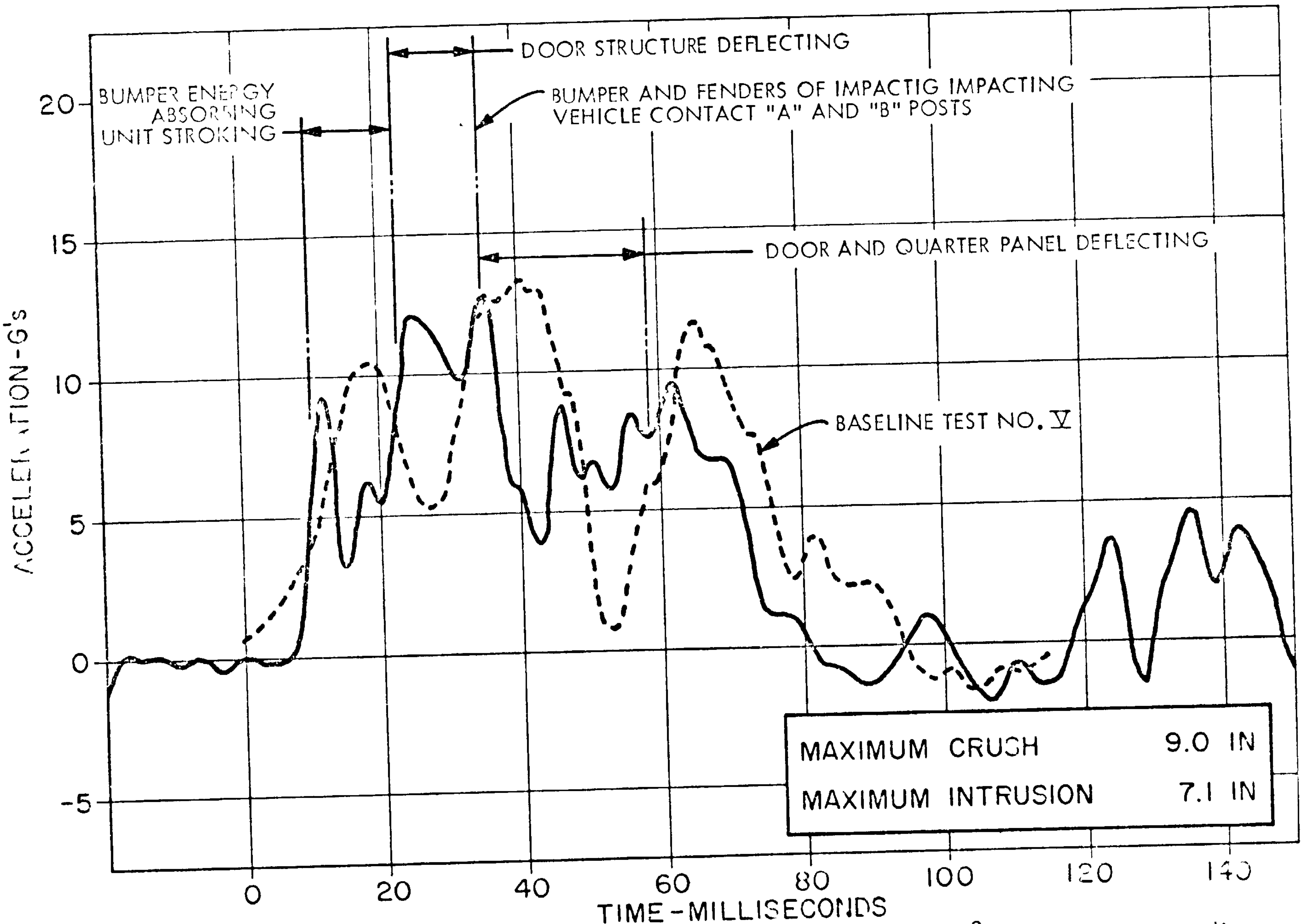


Figure 7. Test No. 10. 24.68 mph Vehicle-to-Vehicle Front/Side 270° Impact at Door Centerline. Impacting Vehicle No. 8 Front Modified Hornet. Impacted Vehicle No. 13 - Side Modified Hornet
LATERAL CRASH PULSE VEHICLE NO. 13 (Modified)

Table 4. Summary of Test Results

50 mph, Frontal Flat Barrier, 0°				
	System Test 1		Baseline Test I	
Maximum vehicle crush	27.7"		33"	
Maximum intrusion at dash center	9.6"		17.4"	
Occupant area intrusion:				
Left side	5"		10.5"	
Right side	7"		10.8"	
Maximum compartment acceleration	50 g		40 g	
40 mph, Frontal Pole				
	System Test 2		Baseline Test II	
Maximum vehicle crush	27.9"		39.5"	
Maximum intrusion at dash center	5.6"		12.1"	
Occupant area intrusion:				
Left side	1.7"		6.0"	
Right side	2.3"		7.8"	
Maximum compartment intrusion	50 g		30 g	
10 mph, Side Pole				
	System Test 4		Baseline Test III	
Maximum vehicle crush	7"		10"	
Maximum intrusion at rocker panel	5.1"			
Occupant area intrusion	3.5"		6"	
Maximum compartment acceleration	8 g		13 g	
75 mph, Front to Front, Aligned				
	System Test 5		Baseline Test IV	
	Car 10	Car 11	Car A	Car B
Maximum vehicle crush	25.7"	19.2"	25"	27"
Dash center intrusion	3.9"	.6"	5.6"	
Maximum occupant area intrusion	2.3"	1.7"	5.0"	
Maximum acceleration	46 g	48 g	33 g	
25 mph, Front to Side				
	System Test 10		Baseline Test V	
Maximum crush	9"		13.5"	
Maximum intrusion	7.1"		9.5"	
Maximum acceleration	13 g		14 g	

MATHEMATICAL MODEL

Mathematical models of automobiles in various crash situations were developed during the investigation. The purpose was to permit a study of dynamic response characteristics of vehicle configurations in crash situations through computer simulation. The models were used to determine desirable load deflection characteristics of structural elements during the design phase prior to fabrication and crash testing. They have been verified by comparing simulation results with crash test results.

The set of crash conditions modeled is as follows:

Single vehicle impacts

- Frontal flat barrier - normal impact
- Frontal flat barrier - angular impact
- Frontal pole
- Side pole

Two vehicle impacts

- Front to front vehicles aligned
- Front to front vehicles offset
- Front to side

The approach taken in the development of each of the models was to define the vehicle(s) in terms of a set of springs and lumped masses. Equations of motion for the system were then developed. Time-dependent solutions for the equations were then obtained by numerical integration. The particular tool chosen to perform the numerical integrations was a general purpose dynamic system simulation called DYSIM available on the G.E. Timeshare System.

A typical organization of masses and structural elements is shown in Figure 8. The results of a simulation are compared with test results in Figure 9.

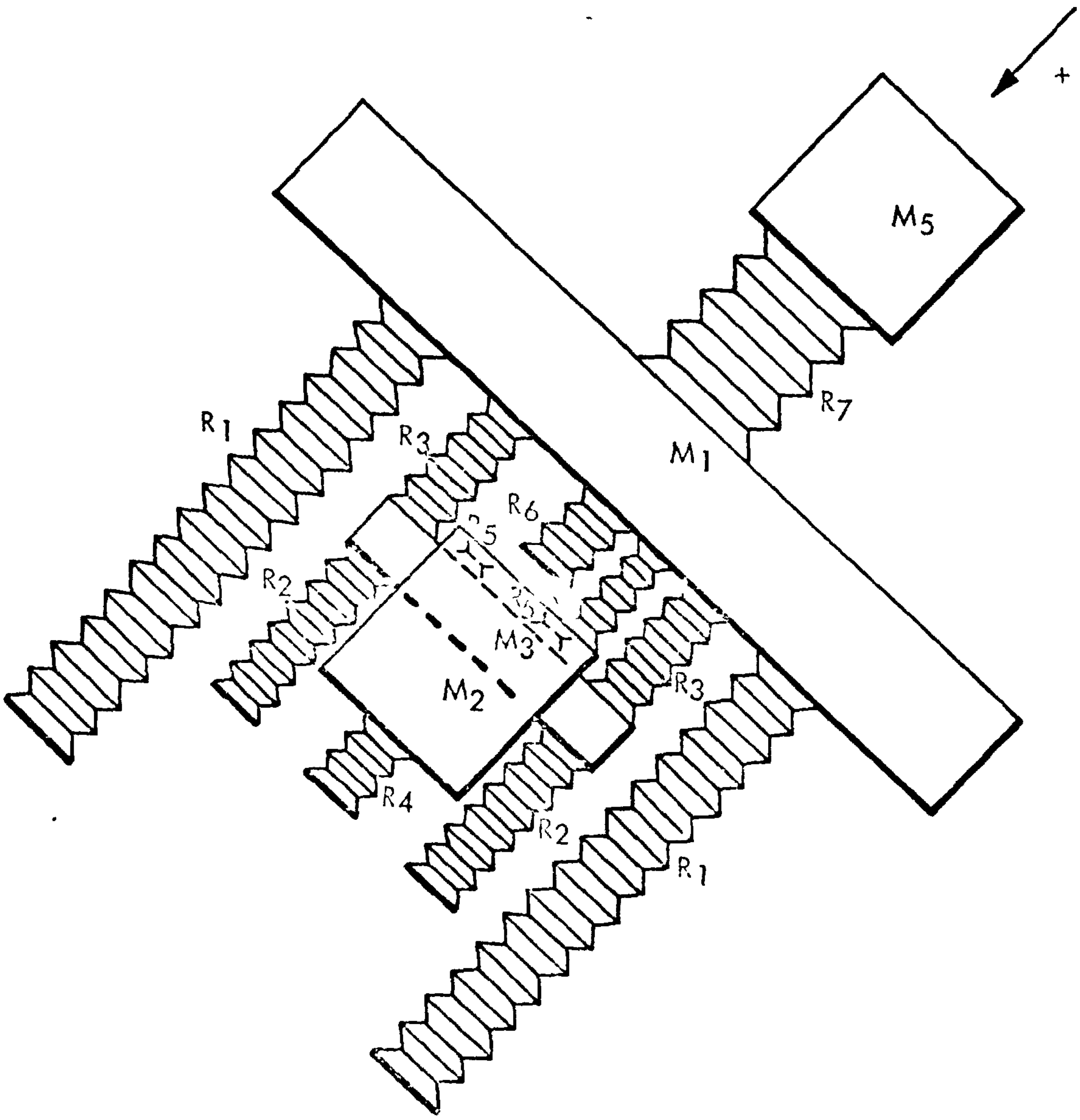


Figure 8. Frontal Normal Barrier Impact Model

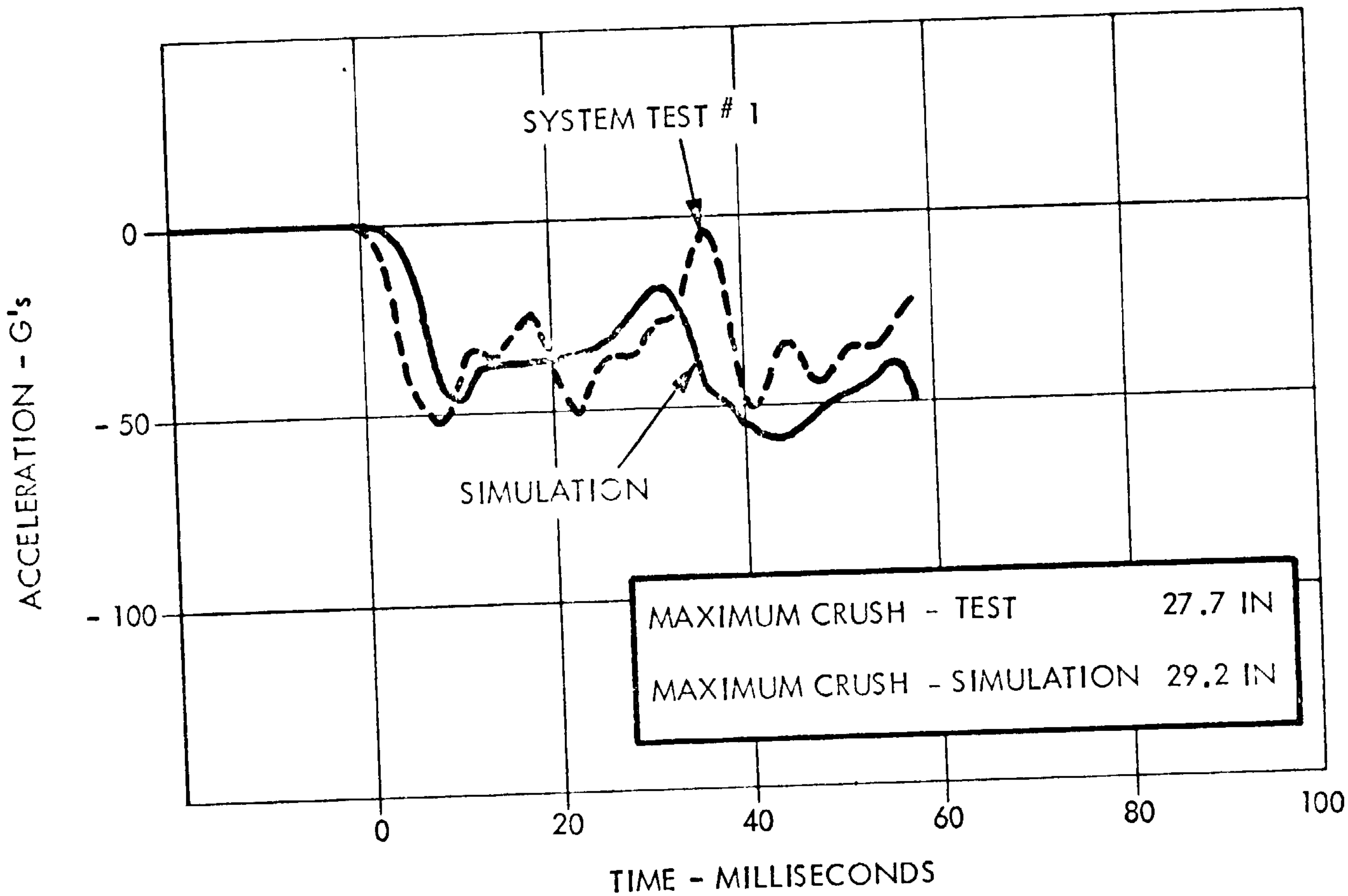


Figure 9. Front Normal Barrier Simulation (50 MPH)

CONCLUSIONS

The compact car modification program produced substantial improvements over baseline vehicle performance. In all cases, modified vehicle intrusion was less than baseline vehicle intrusion under identical crash conditions. This improvement was accomplished by a faster rising crash pulse.

In front impacts, the modified vehicle had a higher level of acceleration than the baseline. Performance goals were met with the exception that acceleration levels in front crashes reached 50 g for short durations and exceeded the target of 40 g. Intrusion in the region of passenger occupancy reached 7 inches in the front barrier impact and exceeded the goal of 5 inches. This was expected, as the available crush distance does not permit achieving a 40 g acceleration limit with a 5 inch intrusion limit for a 50 mph front barrier crash.

Since the modified vehicle is stiffer than the baseline vehicle, it is also somewhat more aggressive. This is as expected, but the increased aggressivity is relatively mild. The total weight increase for vehicle modifications was 104 pounds. This does not include any secondary weight effects such as might develop from a need for a larger suspension system or larger tires, etc.

Modifications to the bumper energy absorbing units prevented them from bursting during high-speed impacts and permitted them to stroke at a significant force level. This modification would require additional engineering for application to production vehicles.

The ripple panel replacing the fender inner panel has proven to be an effective energy absorbing element. It is considered to be currently production feasible and can be incorporated with a net reduction in weight.

The collapsing front sills in conjunction with the ripple panel provided a preditable well-controlled energy absorber which became effective early in the crash pulse. As designed, the sills adapt well to incorporation in front end designs. The sills as employed in crash tests were made from square tubing and welded to the rear sill. Typical mass production manufacturing technique is to fabricate the entire sill structure in two full-length pieces. These are then welded together. Further studies would be required to assure that the same predictable well-controlled collapse mode could be obtained with two-piece welded sills as was obtained with the square tubing.

The secondary high-strength bumper proved to be highly effective in front pole impacts and oblique impacts involving the front end. In pole impacts the bumper crushed at a high load, absorbing substantial energy and transmitting load outward and rearward to the front sills which also collapsed, absorbing energy. In oblique impacts, the bumper provided a load transfer path between both sides of the front end so that the entire frontal structure collapsed in a parallelogram mode. This was effective in absorbing energy and in directing the vehicle away from the impact point. The bumper employed in the test series was drawn and fabricated from 1/8-inch thick mild steel. The adaptation of drawing such thick material and the welding of it to thinner sections is outside of normal automotive experience. Additional study would be required before this component design could be considered to be production feasible.

The rear sills, containing a pair of plastic hinges, were not required to deform at the impact speeds tested. That is, all of the available crush space was expended by involving only only the front sills. However, the technique of design of effective plastic hinges which was developed in this program may be appropriate for other vehicles since the geometry which forms a plastic hinge is typical of automotive front ends. The fabrication technique developed includes the injection of plastic foam in the region where the hinge will form. This is necessary to stabilize the hinge against collapse of the section during bending. The production feasibility of the foam injection process has not been established and will require a development program.

The crushable beam membrane door panel which is aluminum honeycomb sandwich construction was effective in side impacts. The panel acted initially as a beam and under large deformations, acted as a stretching membrane absorbing a substantial amount of energy. The fabrication technique involved is typical of aircraft construction, but is not typical of automotive construction. This energy absorbing technique has proven to be highly effective, but may require some compromise in the design approach and a substantial development effort before it would be considered for adoption in mass production.

The "A" and "B" post structure and accessories were drawn from up to 1/8-inch thick material and welded to other thinner sections. This presents the same problem as discussed for the secondary bumper and will require some advances in normal production technique.

The mathematical modeling effort to simulate the dynamic response of automobiles in a wide variety of crash conditions is considered to be successful. Seven separate models were developed to simulate various front and side barrier and vehicle-to-vehicle crash situations. Peak accelerations and maximum crush results obtained from various simulations agree with crash test results generally within 10 to 15 percent which is within the range of expected deviations between tests. The shape of the crash pulse is in good agreement in most instances. In a few of the simulations, the timing of events differed somewhat. This can be attributed to random occurrences in the crash tests or in selection of structural deformation characteristics for the simulation which differ from the actual structural crash behavior. The models are simple to use and are appropriate for use on any production vehicle.