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Final Report

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The Minicars Research Safety Vehicle Program Phase III

Volume I—Technical Final Report

V. K. Ausherman
A. V. Khadilkar
S. R. Syson
C. E. Strother
D. E. Struble

Minicars, Inc.
55 Depot Road
Goleta, California 93117

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16. Abstract

The objective of the RSV Program was to provide research and test data applicable to the automobile safety performance requirements for the mid-1980s, and to evaluate the compatibility of these requirements with environmental policies, efficient energy utilization, and consumer economic considerations. The program was designed to answer the question, "Can small fuel-efficient cars be made safe?," and to address such topics as: How safe should cars in general, and small cars in particular, be? What technologies will be required to make them this safe? Are these technologies feasible? Can they be, or have they been, sufficiently developed to justify the promulgation of more stringent safety standards?

The RSV Program has demonstrated that it is possible to make cars much safer than they are presently. It has produced automobile designs that are consistent, at affordable cost, with the national objectives for fuel economy and environmental protection. It has indicated, at least to a limited degree, that the technological findings are applicable, at varying levels, to a variety of car designs. And it has provided evidence that these findings can be wrapped in a package of considerable appeal to the public.

This Final Report is a comprehensive compilation of the findings of the Phase III efforts of Minicars, Inc. It describes the design and testing of the RSV systems, and the performance levels achieved. Specific topics include a vehicle description and performance specification, the structure, occupant restraints, braking and handling, propulsion, the vehicle exterior, driver controls, the radar and electronics, the Large Research Safety Vehicle, and the accident environment analysis.

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Unclassified	Unclassified	349	

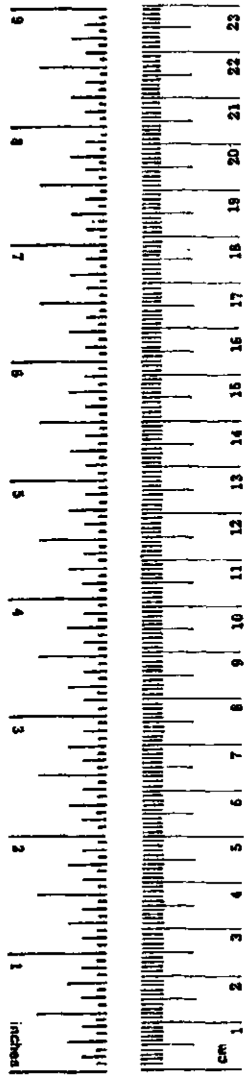
Form DOT F 1700.7 (8-72)

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

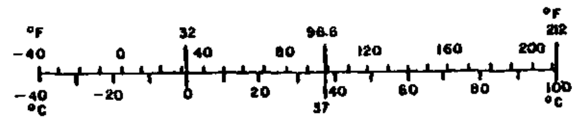
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	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

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



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	35	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



NOTICE

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ACKNOWLEDGEMENTS

The RSV Program touched on nearly all areas of automotive safety. As an integrated vehicle program should, it provided badly needed coordination between these areas, and it has advanced the state of the art on a number of fronts. It was a very involved program. The Contract Technical Manager, Mr. Jerome Kossar, was involved with the program from the outset and is largely responsible for its broad, yet integrated, purview. The success of this project in dealing with such diversified topics will be a lasting tribute to Mr. Kossar's technical breadth.

Special thanks go to Mr. David Hunter, who rendered this document into readable English, and to Mrs. Terri Hille, who with great patience converted thousands of proofreader's marks into neat, legible text.

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SECTION 1
INTRODUCTION

In the early 1970s the National Highway Traffic Safety Administration (NHTSA) of the Department of Transportation (DOT) began the Research Safety Vehicle Program. The objective of the program was to conduct automotive safety research to assist in formulating government regulations. The NHTSA proposed to design, build and test Research Safety Vehicles (RSVs), prototype automobiles that would exhibit advanced safety performance without unduly compromising their other attributes. By conspicuously demonstrating and publicizing these vehicles, the NHTSA also intended to increase the public's awareness of safety, and thus to increase the demand for safety in the marketplace.

Prototype safety vehicles have limited value if they do not conform to the constraints imposed on other automobiles in the real world. These constraints govern both vehicle characteristics that are readily quantifiable (such as fuel economy, emissions levels and interior volume) and those that are difficult to quantify (such as practicality, marketability and styling). Likewise, research prototypes would probably have little value today if they had been designed according to the market constraints that existed in 1974, when the program's first phase began. Therefore, the NHTSA decided that the RSVs would be designed for the 1985 automotive environment (both regulatory and in the marketplace), intending that technology developed in the program could ultimately have an impact in that environment.

1.1 PHASE I

Phase I contracts were awarded to five contractors, including Minicars, to perform analytical studies and, from the studies, to develop new vehicle concepts. Minicars began by studying the circumstances and mechanisms associated with societal costs — fatalities, injuries and property damage — that result from automobile accidents. To facilitate the analysis, a specific cost was assigned to each injury and fatality. We then sought to identify the overall vehicle configuration that would provide the maximum net benefit.* The analysis showed that the anticipated shift toward smaller cars (due to higher fuel prices) and the inherent disadvantages of small cars in collisions would, by 1985, cause most of the societal loss to occur in smaller cars (Figure 1-1). To maximize the net benefit, therefore, we specified that Minicars' RSV would be in the subcompact size class, would seat four passengers, and, to maximize fuel economy, should weigh approximately 2000 pounds (900 kg).

At that time, however, there was little precedent for building crashworthiness into a 2000 pound vehicle. The Experimental Safety Vehicle (ESV) Program had indicated that it was possible to improve the crashworthiness of conventional automobiles, but only by increasing their structural weight – the ESVs of the early 1970's all weighed more than 5500 pounds (2500 kg). It was clear that conventional structural design techniques would not be satisfactory for the RSV.

We therefore specified a new, completely integrated design with a unibody structure consisting of closed, thin gauge steel boxes which would be filled with rigid polyurethane foam. The inherent rigidity of the closed box configuration meant that the RSV structure would actually weigh less than a comparably sized conventional automotive structure; the foam would enhance its crash performance by assuring excellent energy-absorbing abilities. Our analysis also considered the relationship between societal loss and vehicle damage area (Figure 1-2**), and concluded that the structure should offer the greatest protection in front impacts, that it should offer a high degree of protection in side impacts, and, moreover, that its ability to absorb energy should be omni-directional (another attribute of foam-filled sheetmetal compartments).

In computer simulations, candidate restraint systems (matched to hypothetical RSV structures) were evaluated on the basis of cost and projected performance. Because most injuries and fatalities are suffered by front seat occupants (due

*Net benefit is the total benefit (typically expressed in dollars) accrued by a system, less the total cost (production, maintenance, etc.) of the system.

**Figure 1-2 was constructed from National Crash Severity Study (NCSS) data during Phase III of the program (Reference 1). The Phase I analysis was actually based on Multidisciplinary Accident Investigation (MDAI) data. We show the NCSS data here because they better reflect the current situation.

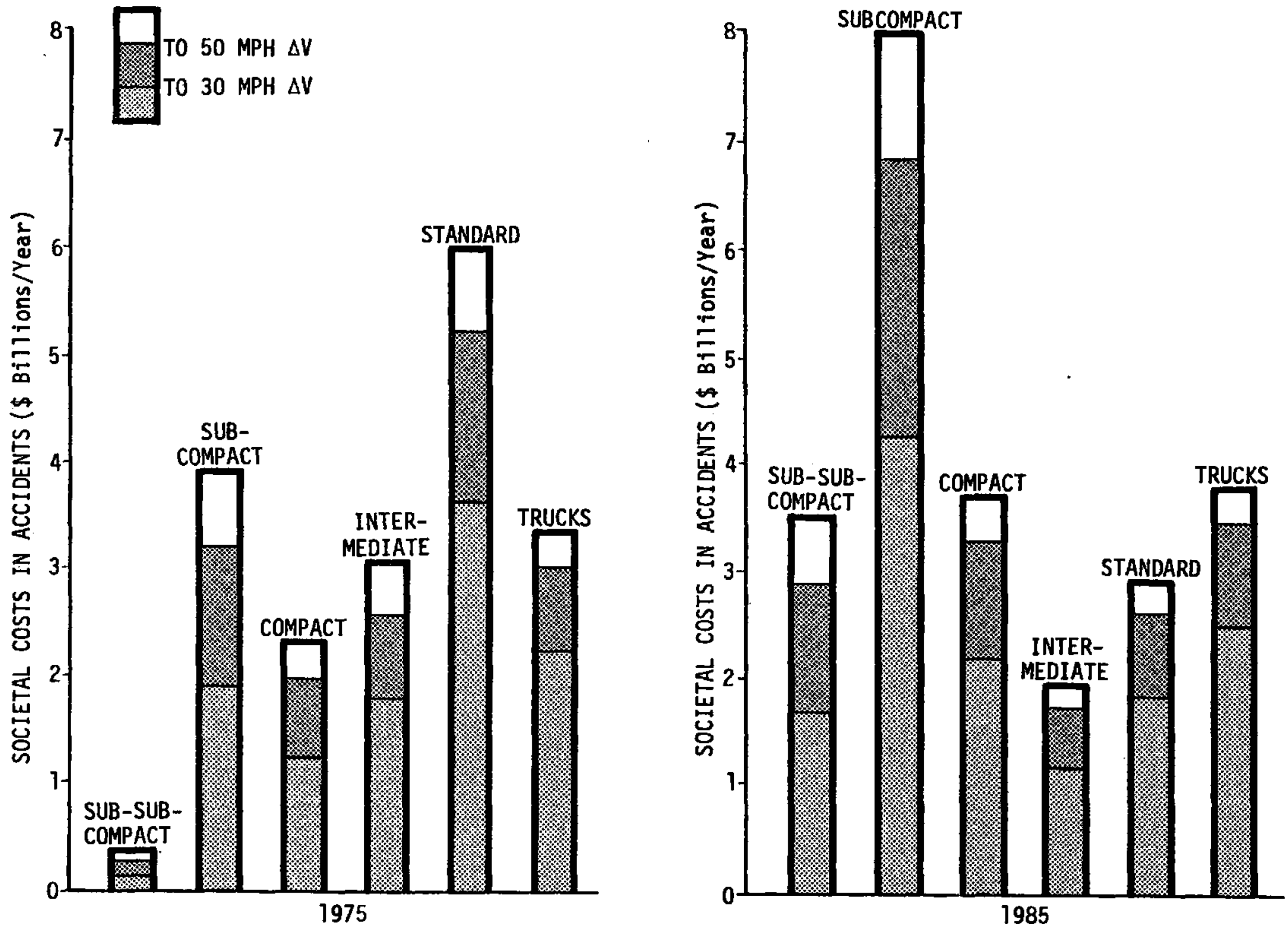

FIGURE 1-1. SOCIETAL LOSSES BY VEHICLE SIZE CLASS

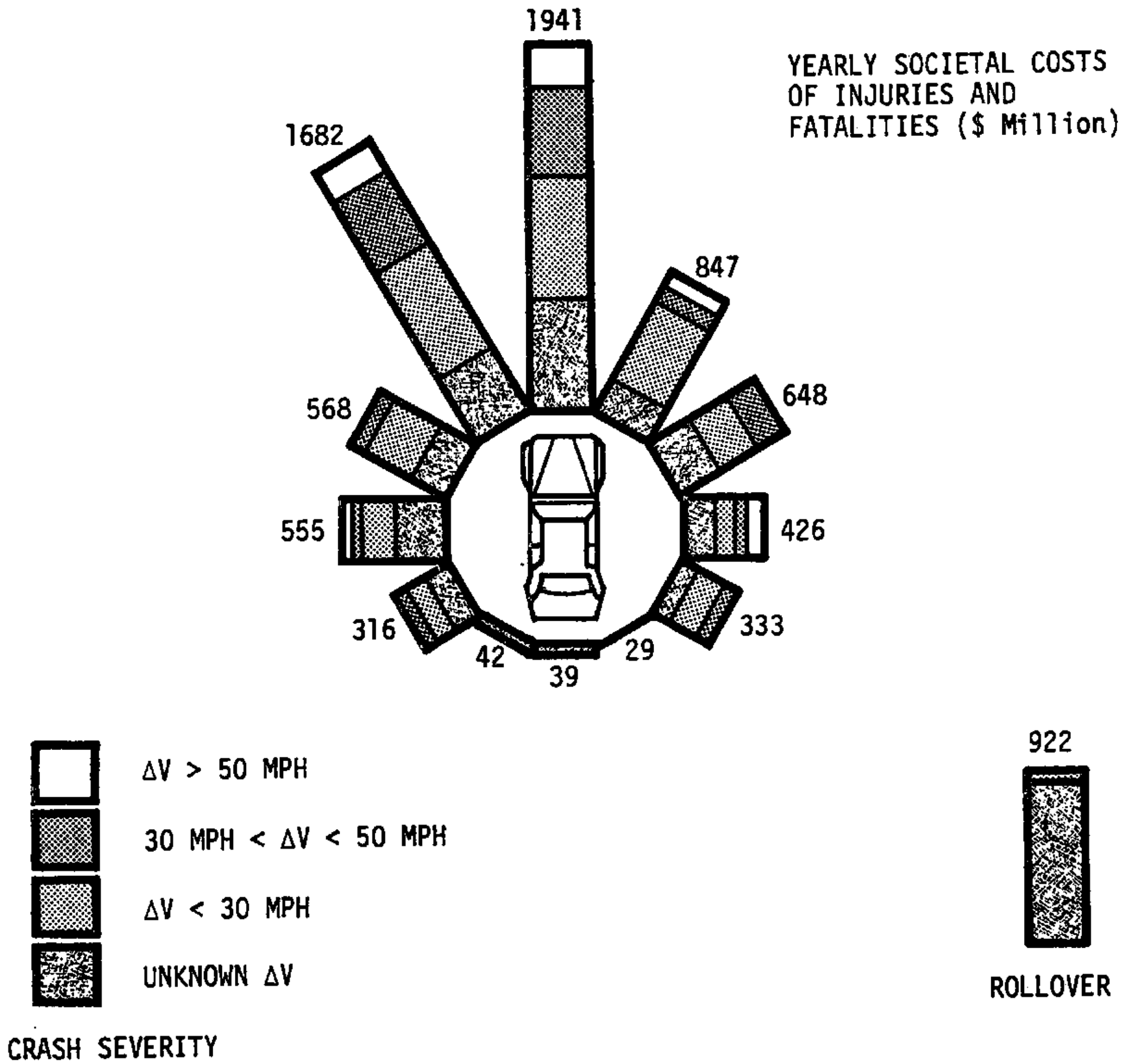

FIGURE 1-2. SOCIETAL LOSSES FOR THE VEHICLE DAMAGE AREAS

especially to the higher occupancy rates of the front seats), it was worthwhile to spend more for their protection. Since the observed usage rates of seat belts were so low, we specified passive restraints – and, from the possible passive restraint systems, we selected rapidly deploying air cushion systems because they had the highest expected net benefits. For the rear seat passengers (who are comparatively rare) only simple lap belts could be justified on a cost/benefit basis. Nevertheless, we chose to investigate the high-speed protection potential of three-point, force-limited belts for their protection. As the program progressed, the RSV's occupant packaging ultimately incorporated an energy-absorbing steering column, foam padding and a number of other features to protect occupants in all accident modes.

Our analysis showed that substantial net benefit might result from several other features, such as:

- Pedestrian impact protection (obtained by contouring the RSV's front end and adjusting the surface stiffness)
- Compatability (the minimization of the consequences of a two-car crash for the occupants of the other car)
- Reduced damageability with 10 mph (16 km/h), no-damage front and 5 mph (8 km/h) rear bumpers and soft fenders
- Repairability with a replaceable nose section that prevents significant damage to the main structure when the impact velocity is below 20 mph (32 km/h)
- "High technology" driver aids that incorporate radar and microprocessor electronics to avoid or mitigate collisions.

Our Phase I analysis generated a preliminary vehicle design that included all of these features, plus specific propulsion, braking, riding and handling, and ergonomical systems that were either commensurate with or more advanced than those of the projected conventional automobiles of 1985. The preliminary Phase I design is shown in Figure 1-3.

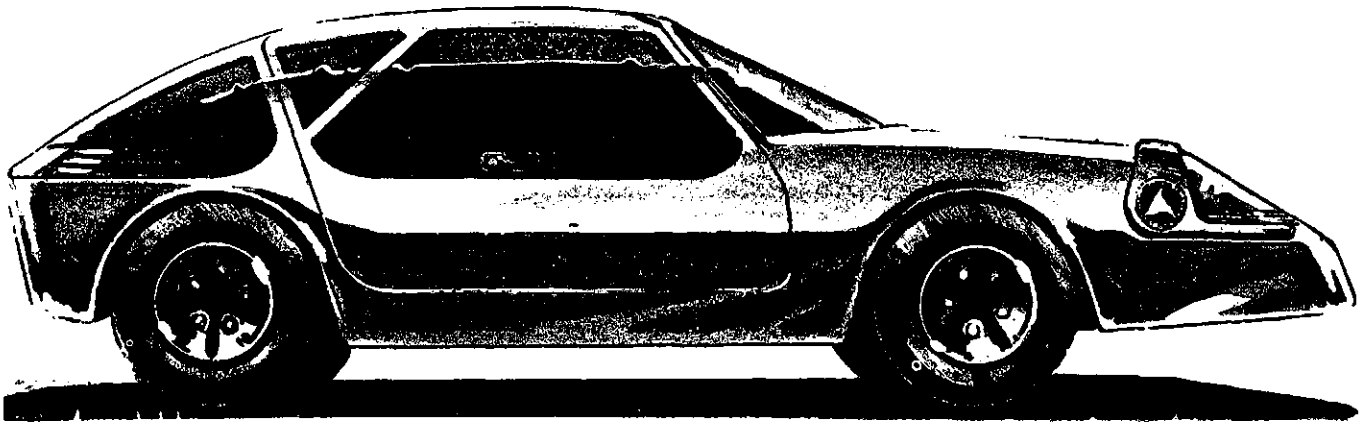

FIGURE 1-3. PHASE I PRELIMINARY DESIGN

1.2 PHASE II

At the conclusion of Phase I the NHTSA evaluated the preliminary RSV designs and awarded Phase II contracts to Minicars and Calspan. The general objective of Phase II was to develop the preliminary design into a hardware design, and to use that to build test and demonstration vehicles. This process furthered the RSV concept and provided additional research applicable to rulemaking.

We refined the design with the assistance of several subcontractors, including the Budd Company (body structure), Monsanto Research Corporation (polyurethane foam), Marc Analysis Corporation (stress analysis), Man Factors, Inc. (human factors), RCA Laboratories (radar and electronics), Stanford Research Institute (scale model crash testing), Systems Technology, Inc. (ride and handling), the University of Utah (braking), and the California Institute of Technology (aerodynamics). Minicars itself developed the occupant packaging and protection systems, began the task of integrating all of the necessary automotive systems, and constructed mockups in which the restraints and many other systems were fully operational. (One of these is shown in Figure 1-4.) Unfortunately, as its design became more defined, the RSV's curb weight increased to about 2300 pounds (1050 kg).

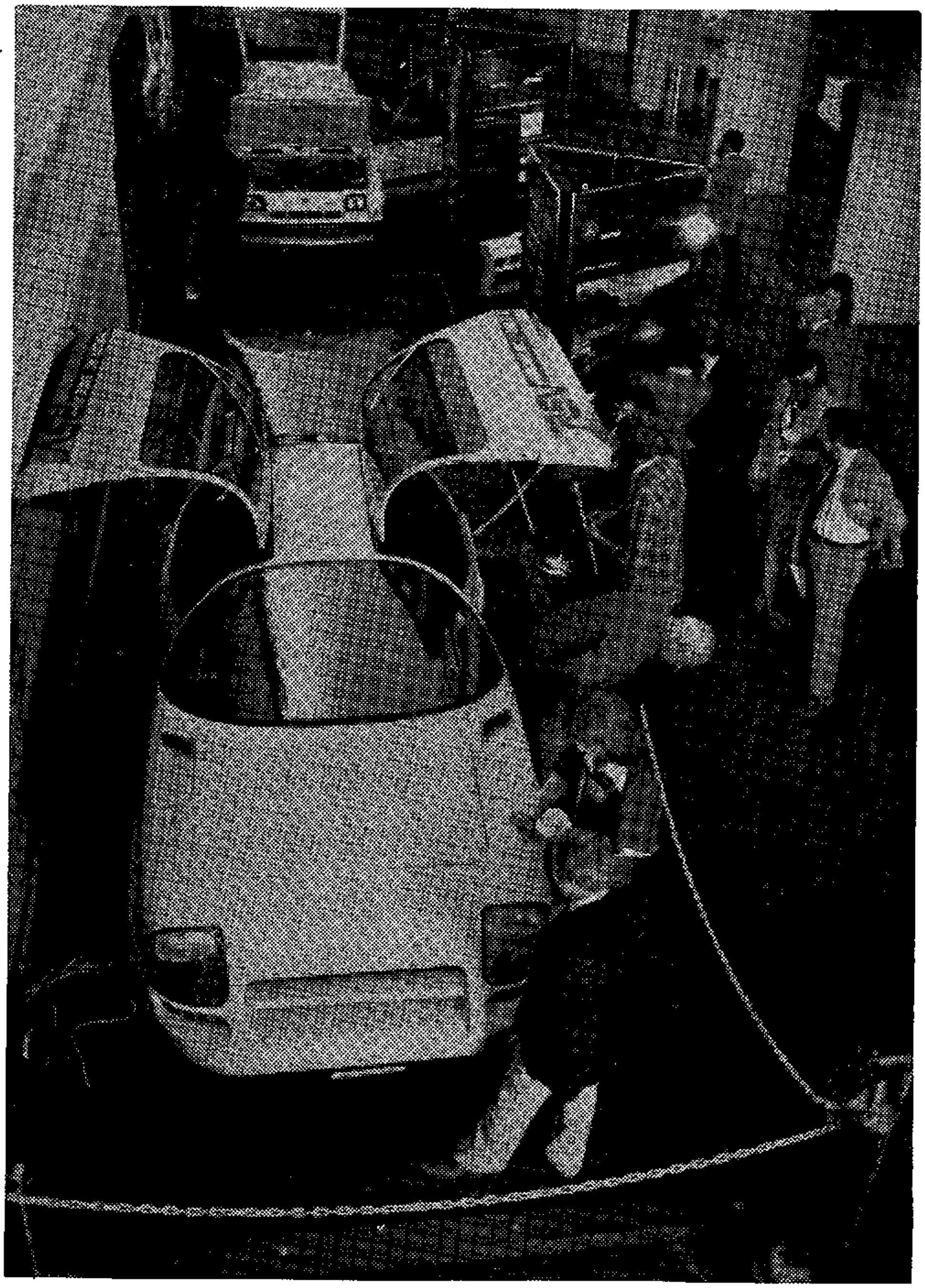

FIGURE 1-4. NHTSA DISPLAY OF A PHASE II MOCKUP

Phase II also included a comprehensive test program of pedestrian impact tests, braking tests, ride and handling tests, crush tests for structural development, sled tests for restraints development, and full-scale crash tests for overall evaluation. The Phase II test series reached its epitome in 1976 when an RSV (with two 50th percentile male dummies in its front seats) perpendicularly impacted a fixed barrier at 50.8 mph (81.8 km/h). The test results indicated that similarly sized human occupants would have survived the same collision without life-threatening injuries. Encouraging results were also obtained in crashes in other front impact modes and in side, rear and rollover tests. When Phase II ended, we had demonstrated that it was indeed possible to substantially improve the crashworthiness of small cars.

1.3 PHASE III

The present report covers the program's third phase, conducted from 1977 through 1980. The Phase III objectives were to refine the Phase II design (where necessary), to explore questions not answered in Phase II, to illustrate selected design alternatives, to produce functionally representative cars for Phase IV testing, and to show that the RSV concept is feasible.

In many respects, Phase III was simply a part of the process through which a vehicle concept matures into a production automobile (although the program was never intended to complete that process). The program advanced to the point that fully operational research prototypes (Figure 1-5) were constructed and tested. These prototypes, which have superior crashworthiness and relatively good fuel economy, emissions performance, styling and ergonomics, would be both practical and cost effective if mass produced in 1985. The next step in the RSV's evolution would be to develop a production prototype. While a production prototype would make a more convincing case for the concept's feasibility, it would also increase the program's scope (and hence its funding) by several times. Consequently, the NHTSA plan went no further than the building and testing of research prototypes.

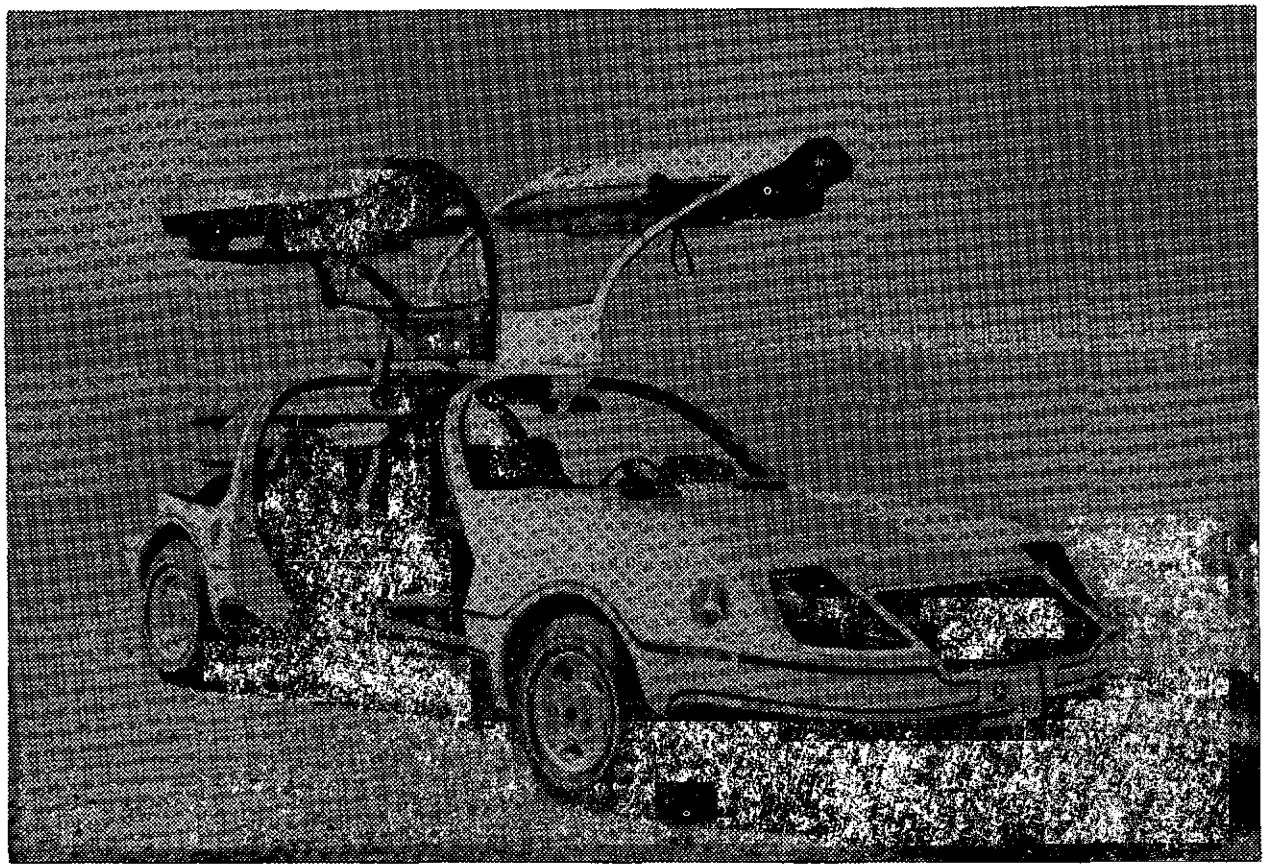

FIGURE 1-5. PHASE III RESEARCH PROTOTYPE

We refined the RSV design throughout the duration of Phase III. Some of our primary objectives were to:

- Integrate the systems required to make the RSV fully operational
- Incorporate the improvements developed through testing
- Make the design more producible (by designing systems, when costs permitted, for large quantity production)
- Reduce weight.

Because of the program's limited scope, our treatment of the last two objectives has been relatively superficial. (A comprehensive treatment would require a full production engineering effort.) This is evident in the final prototypes, which weigh almost 2600 pounds (1180 kg) – nearly 300 pounds (135 kg) over the final Phase II weight and 600 pounds (270 kg) over the original target. The excess weight, due in part to the hand-building and hand-finishing operations performed by Minicars, had some detrimental effects on the RSV's performance in the later tests, since most of its systems had been designed for use in a lighter vehicle.

In all, 15 prototypes with the final design structure were hand built during Phase III (see Figure 1-6). Most of these were complete automobiles that had all of the systems normally found in standard production cars. These prototypes allowed us, for the first time, to test complete vehicles.

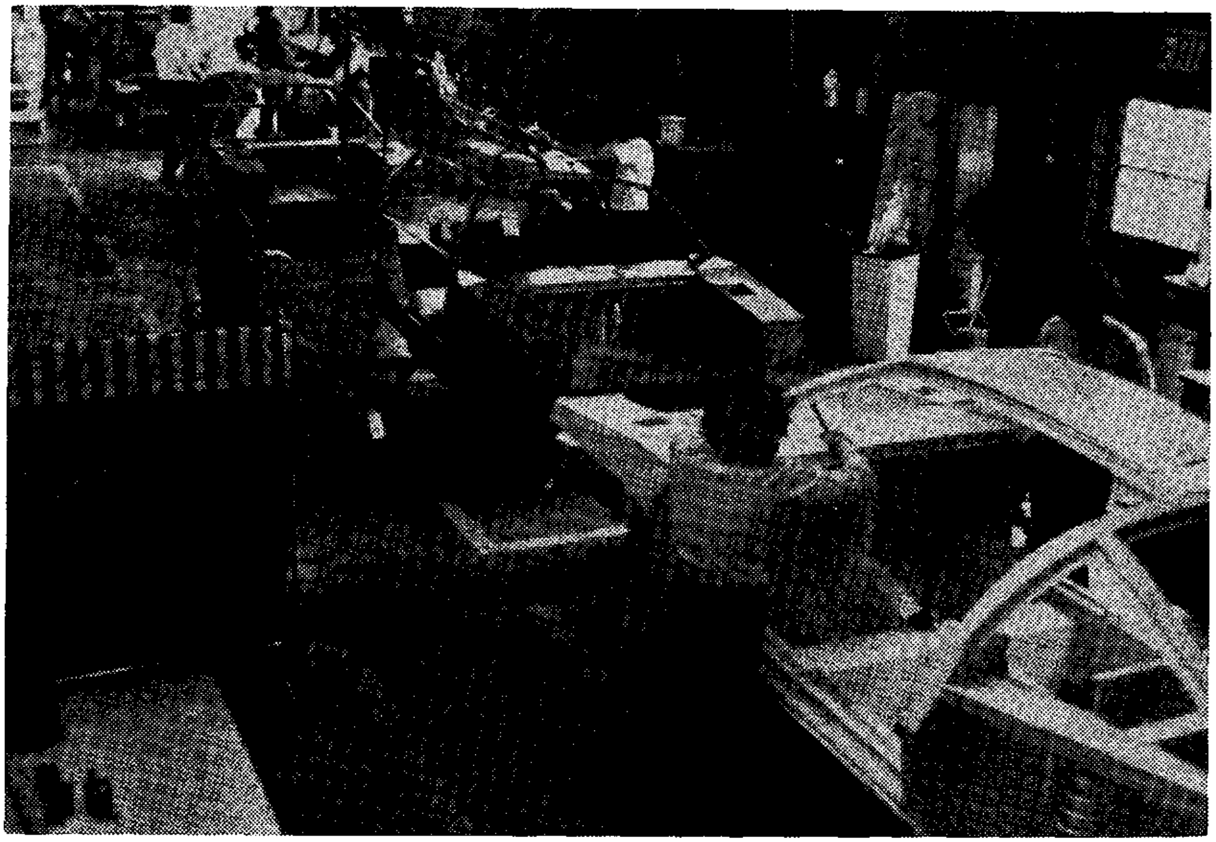

FIGURE 1-6. PHASE III RSV PRODUCTION AT MINICARS

The Phase III test program, which was similar to that of Phase II, included tests for crashworthiness, braking, ride and handling, fuel economy, emissions and aerodynamic drag. Ultimately, most of the RSV prototypes were destroyed in crash tests (primarily front and side vehicle-to-vehicle impacts). To complement Minicars' in-house testing, several finished Phase III prototypes were shipped to foreign countries for the Phase IV test program, which included braking, ride and handling, driver environment and visibility tests — and, of course, more crash tests.

A "high technology" RSV was also constructed during Phase III. The high technology prototype is virtually identical to the conventional RSV in appearance, but has a number of advanced technological features. These include radar-actuated antiskid brakes, radar headway control, an automatic-shifting, five-speed transmission and a digital driver display — all controlled by microprocessor-based computer systems. The high technology systems have the potential to significantly reduce societal accident costs and to improve driver comfort, but there is insufficient evidence to prove that they are practical and cost-effective in the near term automotive environment. We therefore distinguish between the high technology RSV and the conventional RSV.

In Phase III the program was also expanded to study the feasibility of improving the crashworthiness of larger vehicles by employing the technologies developed in the RSV. Thus the Large Research Safety Vehicle (LRSV) Program was begun; its objective was to develop a full size safety vehicle prototype having a curb weight of less than 3000 pounds (1360 kg). The prototype was to be a modification of a full size production car, which meant that a substantial weight reduction effort was required. We subsequently designed, constructed and tested LRSVs (based on Chevrolet Impalas) that incorporated the RSV structures and restraints technology, as well as advanced engine technology to improve the full size car's crashworthiness, fuel economy and emissions.

1.4 REPORT FORMAT

Section 2 provides a quick look at the standard and high technology RSVs, and the differences between the two. It summarizes the design specifications, characterizes the systems that were integrated into the RSV, and lists the weights of each system.

Section 3, Structures, and Section 4, Occupant Packaging, document perhaps the most valuable research conducted in the RSV Program and tabulate the important results of the most recent crash test in each mode. Sections 5, 6, 7 and 8 describe the RSV's braking and handling, propulsion, body exterior and driver environment systems, respectively. These sections are considerably shorter than Sections 3 and 4, reflecting the lower priority attached to those systems.

Section 9, Radar and Electronics, discusses some of the high technology RSV's electronic systems. Other high technology systems are described in the relevant sections: antiskid braking and collision mitigation hardware in Section 5, automated manual transmission in Section 6, and driver display in Section 8. All computer hardware is described in Section 9.

Section 10, Final Design and Performance Specifications, provides a quantitative engineering description of the RSV.

Section 11, Large Research Safety Vehicle, discusses the theory and results of the LRSV Program. Section 12, Accident Environment Analysis, describes our Phase III analytical efforts – which did not directly influence the RSV design, but provided useful tools to project the effects of incorporating various safety systems into the vehicle population.

Finally, Section 13 gives Minicars' conclusions and recommendations after nearly 7 years and more than $14 million of effort in the Research Safety Vehicle Program.

The Final Reports of our three subcontractors, RCA Laboratories, Volvo of America Corporation and the Bendix Automotive Control Systems Group, are presented as Appendices A, B and C, respectively.

SECTION 2
BRIEF VEHICLE DESCRIPTION

2.1 DESIGN SPECIFICATIONS

The Research Safety Vehicle is a mid-engine, four passenger, two-door sedan with a curb weight of 2578 pounds (1169 kg). It includes a number of several unique, technologically advanced crash management systems in a package that is fuel efficient, practical and marketable. Figure 2-1 is an exploded view of the RSV.

Some important design parameters of the final Phase III prototypes are listed in Table 2-1. (Complete specifications are found in Section 10.) It should be emphasized that these parameters - and all other information in this report - apply only to the prototype design. There are inherent differences between prototypes and finished automobiles, and a mass produced automobile employing the basic RSV concepts would show a large number of detail design changes. For example, the foam-filled sheetmetal concept would be executed with stampings rather than brake-formed parts - reducing the number of parts, the assembly labor content, and the weight.

2.2 STRUCTURE

Body-in-White

The RSV body-in-white is a significant departure from conventional automotive design. It is formed of closed box sections fabricated from light-gauge, low carbon steel; the steel typically has thicknesses of 0.030 to 0.050 inch (0.8 to 1.3 mm). Some of the sections are filled with rigid, low density (2 lb/ft^3) polyurethane foam, which stabilizes the sheetmetal and contributes to the structure's ability to absorb energy when crushed in a variety of directions. The boxes are welded into a single unibody which offers exceptional stiffness for its weight. Among the body-in-white's noteworthy design characteristics are energy-absorbing front structures of varying crush strength, a replaceable,

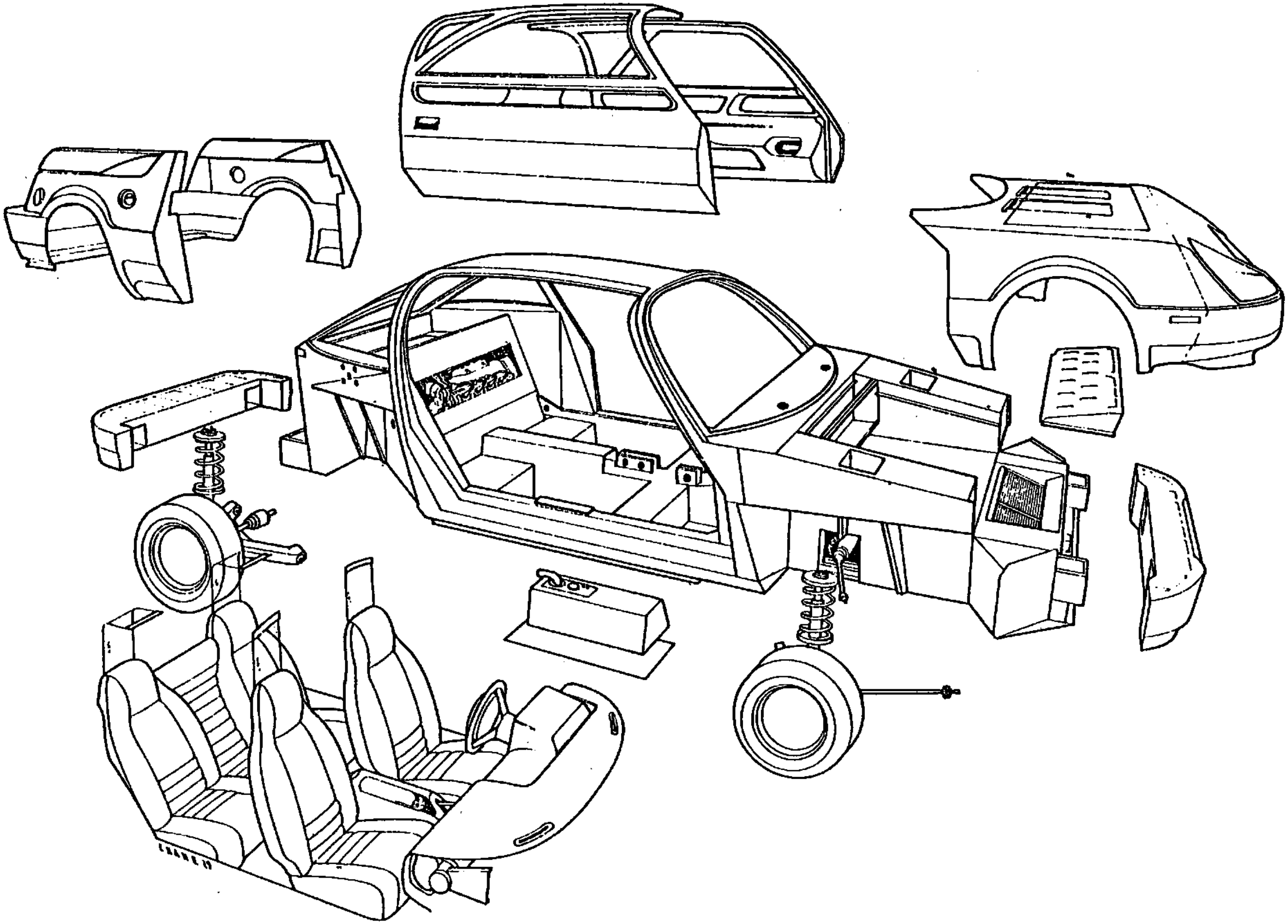

FIGURE 2-1. MAJOR RSV INTERIOR AND EXTERIOR BODY COMPONENTS

TABLE 2-1. MINICARS RSV DESIGN DESCRIPTION

Specification Category	Final Design Specifications
GENERAL	
Body style	Sedan (2 gullwing doors)
Curb weight (with full fuel tank)	2,578 lbs (1,169 kg)
Vehicle capacity	750 lbs (340 kg)
Fuel tank capacity	8.3 U.S. gals (31 liters)
EXTERIOR DIMENSIONS	
Wheelbase (L101*)	104" (264 cm)
Overall length	177" (450 cm)
Wheel tread (W101, W102)	62" (157 cm)
Overall width (W103)	71" (180 cm)
Overall height (loaded)	55" (140 cm)
Ground clearance at curb weight	6.1" (15.5 cm)
Turning circle	40' (12.2 m)
Angle of approach	20 degrees
Angle of departure	37 degrees
Angle of ramp breakover	11 degrees
INTERIOR DIMENSIONS	
Front capacity	Two 95th percentile males
Rear capacity	Two 50th percentile males
Effective front head room (H61)	38.0" (96.5 cm)
Effective rear head room (H53)	38.0" (96.5 cm)
Effective front leg room (L34)	44.0" (112 cm)
Effective rear leg room (L51)	42.0" (107 cm)
Effective shoulder room (W3)	51.0" (130 cm)
BRAKES	Four-wheel disc (8.9" dia.) with power assist

Specification Category	Final Design Specifications
STEERING	
Type	Fiat X1/9 rack and pinion
Overall ratio	20:1
Turns, lock-to-lock	3.0
SUSPENSION	
Front	Modified Fiat X1/9 (Chapman) Strut and X1/9 rear spring
Rear	Fiat X1/9 rear (Chapman) strut and Chevrolet Chevette rear spring
ENGINE	
Location	Transverse mid-engine
Type	1978 Honda CVCC four-cylinder, in-line, OHC, stratified charge
Bore x stroke	74.0 x 93.0 mm
Displacement	1599 cc
Compression ratio	8.0:1
Fuel requirement	91 Octane, unleaded
TRANSMISSION	
Type	1978 Honda 5-speed manual
Gear ratios:	
5th	0.72
4th	0.85
3rd	1.18
2nd	1.82
1st	3.18
Final drive ratio	4.27
TIRES	200/65 HR370 Dunlop Denovo 2 run-flat
WHEELS	Denloc 370 x 125 x 33

*L101, W101, etc. refer to Motor Vehicle Manufacturers Association (MVMA) specifications.
**For complete specifications, see Section 10.

damage-limiting, bolt-on nose section, a passenger compartment with exceptional resistance to intrusion, and a rounded upper structure.

Doors

The RSV has two gull wing doors which offer superior ingress and egress without compromising crashworthiness. Each door is counterbalanced by two gas struts that hold it stationary in any open position through 90 degrees of arc. The geometry of the doors permits them to be fully opened when the RSV is parked as close as 21 inches (53 cm) to a wall - and 16 inches (41 cm) next to most other cars. The upper portion of the door contains two large fixed windows and a narrow, horizontal, sliding glass window. During impacts the lower door structure, which is foam-filled, becomes structurally integral with the body-in-white.

Bumpers

Each bumper consists of flexible urethane foam, two "rubrics" which attach to the body-in-white, and a flexible reaction-injection molded (RIM) urethane skin. Rubrics are elastic sandwiches (consisting of an elastomeric core covered by woven polyester) formed into "U" shapes which can elastically absorb large amounts of energy for their weight. The rubrics and front bumper foam and fascia were fabricated by the Bailey Division of the Imhart Corporation* (Seabrook, New Hampshire). Minicars fabricated the rear bumper foam and fascia. The front and rear bumpers are designed to absorb 10 mph (16 km/h) and 5 mph (8 km/h) impacts, respectively, without damage.

*Formerly, the United Shoe Machinery Corporation, Seabrook, New Hampshire.

2.3 PROPULSION, BRAKING AND HANDLING SYSTEMS

Engine

The RSV is propelled by a 1978 Honda Civic CVCC four-cylinder, in-line engine mounted transversely over the rear wheels. The overhead cam engine displaces 1599 cc, develops 68 maximum horsepower (51 kW) at 5000 rpm, and breathes through a standard Honda carburetor. In order to maximize package efficiency and minimize rear weight bias, it was necessary to tilt the engine 15 degrees rearward (30 degrees from the standard Honda position) and to install a special manifold wedge to level the carburetor. Emissions control is furnished by conventional Honda techniques: stratified charge combustion, spark advance control, exhaust gas reaction and positive crankcase ventilation.

Drivetrain

The RSV uses the Honda Accord five-speed manual transmission, clutch assembly and differential, which were designed to mount directly to the Honda CVCC engine. Thus the RSV powertrain is basically a production Honda assembly. The Fiat rear wheel hubs and U-joints are driven through specially fabricated half-shafts which mount to the Honda U-joints at the transaxle output. Since the shift lever is configured as a typical floor shift and the transmission is in the rear, modified Chevrolet Citation push-pull shift cables are used to connect the lever to the transmission.

Fuel Cell

An 8.3 gallon (31 liter) fuel cell is located inside the center tunnel between the rear seat foot wells, where there is minimal exposure to impacts. The cell was constructed by Aero Tec Laboratories, Inc., (Waldwick, New Jersey) and is essentially the same unit as used in NASCAR race cars. It has a flexible urethane outer skin to resist penetration and interior blocks of porous, low density foam to retard fuel leakage (in the unlikely event a puncture does occur).

Cooling System

A stock Fiat X1/9 radiator and integrated fan are used for engine cooling. The radiator is mounted in the front of the car, and coolant feed and return tubes run along the sills to the rear mounted engine.

Suspension and Steering

The fully independent suspension and the rack and pinion steering are based on Fiat X1/9 components. (The X1/9 also has a mid-engine design and a rear-biased weight distribution.) The front control arm and forward stabilizer strut are stock X1/9 front suspension parts, and the rest of the front suspension consists of modified X1/9 rear (Chapman) struts and stock X1/9 rear springs. The rear suspension has unmodified X1/9 Chapman struts, Chevrolet Chevette rear springs and X1/9 folded channel A-arms outfitted with a special cross brace to carry longitudinal structural loads in rear crashes. All four upper shock mounts have longitudinal and lateral adjustments for caster and camber. There also are provisions for adjusting toe-in.

The Fiat rack and pinion steering system was modified to facilitate its installation in the RSV body-in-white and to maintain proper steering kinematics (the RSV has a wider track). Two U-joints (installed in phase) connect the pinion shaft to the energy-absorbing steering column.

Brakes

The RSV has power-assisted, four wheel disk brakes. Essentially all of the brake hardware is made by Fiat. The 8.9 inch (22.6 cm) disks, pads and fittings are from the X1/9; the calipers are from the Model 124; and the master cylinder and vacuum boost system are from the Spyder 2000. Flexible, braided stainless steel hoses are installed throughout.

The parking brake system has a Fiat lever and control cable with a specially designed, pivot-type equalizer assembly mounted on the rear compartment crossmember. The rear brakes and cable actuators are stock Fiat.

Wheels and Tires

Aluminum wheels and Dunlop "Denovo 2" radial run-flat tires are specified for the RSV. The Denovo 2's run-flat capability comes from its low profile (size 200/65 HR370), reinforced sidewalls, "Denloc" bead locking, and self-lubricating and sealing features. After sustaining a large diameter tire puncture, the RSV is capable of being driven 50 miles (80 km) at 40 mph (64 km/h) at full load.

Electrical System

The battery and alternator are standard Honda components. The wiring harnesses were designed and fabricated in-house. The fuse box is located in the luggage compartment.

2.4 OCCUPANT PACKAGING AND ENVIRONMENT

Driver Restraint, Steering Wheel and Steering Column

The RSV driver is protected in front impacts by a passive air cushion restraint system (ACRS). The ACRS includes a dual chambered airbag, a Thiokol Corporation (Brigham City, Utah) solid pyrotechnic inflator and a reaction plate, all mounted in a modified General Motors ACRS steering wheel. There are two concentric cylindrical airbags: a fast acting inner bag (1 ft^3 volume) restrains the driver's upper torso; this bag then vents to a larger (2.7 ft^3) outer bag which provides softer head restraint.

The shallow-angled steering column absorbs most of the driver's upper body kinetic energy and ensures that the restraint loads are correctly applied. The energy-absorption device is a tube and mandrel design (a spherical mandrel is forced through a thin wall stainless steel tube of slightly smaller inner diameter). It compresses at a 3100 pound (1400 N) plateau load and has 5.88 inches (14.9 cm) of total travel.

The driver's lower body energy is absorbed by a knee restraint composed of a 10 inch (25.4 cm) thick billet of extruded multicellular polystyrene between a steel reaction plate and an acrylonitrile butadiene styrene (ABS) surface plate (attached to the dash).

Passenger Restraint

The passenger ACRS also has a pyrotechnically inflated, dual chambered airbag. The fast acting lower bag provides torso restraint and vents to the upper bag, which provides head restraint. The bags have a combined volume of 5.75 ft^3.

The bag assembly, inflator, brackets and cover all mount in the dash. The passenger knee restraint is a solid, low density (2 lb/ft^3), cored polyurethane foam billet installed between a steel reaction plate and the ABS dash. A 5 inch (13 cm) crush space is provided.

Current is sent through both inflators when any of three sensors detects an 11 to 15 mph (18 to 24 km/h) front impact. Two Technar, Inc. (Arcadia, California) "Curve 3" sensors are located in the front bumper and another is mounted directly atop the left front shock tower. The ACRS firing circuitry is regularly monitored by a special diagnostic circuit.

Rear Passenger Restraint

The rear passenger restraint system is a single-retractor, force-limited, three-point lap and shoulder belt harness. The base system uses modified 1976 Chevette hardware with force limiters located at the anchor points. The standard nylon webbing was replaced with low-stretch polyester webbing, and force-limiting* is provided by a mild steel tape which is pulled around a pin mounted to the anchor.

Interior Padding and Trim

The doors, A-pillars, B-pillars, hatch pillars and roof are all padded for added occupant protection. A molded fiber-reinforced plastic (FRP) shell is attached to the inner door surface; this shell covers rigid, low density (1.8 lb/ft^3) urethane foam at the hip and shoulder side impact areas. Decorative Ensolite pads are attached to the FRP shells. The other interior padding is high density (6.5-8.5 lb/ft^3) flexible urethane foam covered with low density vinyl foam and standard automotive vinyl upholstery. The foam padding is 1/2 to 3/4 inch (13 to 19 mm) thick.

Glazing

The windshield, doors and quarter panels are glazed with typical AS-1 safety glass consisting of 0.125 inch (3.2 mm) thick annealed glass outer layers and a 0.031 inch (0.8 mm) thick PVB core. Each window is bonded to the supporting structure using urethane adhesive.

Seats

The front seats are constructed from modified Dodge van seats (1971 to 1976 model year) and are adjustable to accommodate all occupant sizes between a 5th percentile female and 95th percentile male. The seat frame backs carry a thin sheetmetal panel to resist intrusion by the knees of back seat occupants in rear impacts. Each seat frame top is narrowed and attached to a 0.06 inch (1.5 mm) thick clear Lexan sheet. The Lexan, in turn, is connected to the roof, which substantially improves the seat's structural integrity in rear impacts. The

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*The inboard attachment point has a limit of 1100 pounds (500 kg), the outboard seat belt attachment a limit of 900 pounds (400 kg), and the outboard shoulder belt attachment a limit of 600 pounds (270 kg), rising to 800 pounds (360 kg).

Lexan attachment to the seat frame incorporates mild steel tape force limiters which provide 700 pound (320 kg) load limiting. The foam seat cushions are also narrowed, then built up with additional foam to form a more desirable contour. All four seats, front and rear, are covered with standard automotive vinyl.

Each rear seat has a seat back composed of 2 inches (5 cm) of urethane foam mounted to a 1/8th inch (3 mm) sheet of ABS and covered with vinyl, an FRP headrest support, and a Dodge van seat cushion modified to reduce its width and reshape its contour. The rear seats are non-adjustable, but will comfortably seat two 50th percentile males.

Dash

The dash is a nonstructural cover for the passenger airbag, the knee restraints, and the heating, venting and air conditioning plenums, ducting and outlets. It is composed of a molded ABS shell (approximately 1/16 inch thick) covered by 1/4 to 3/8 inch (4 to 6 mm), high density urethane foam padding. Its cover is fabricated of nylon-backed flexible vinyl.

Center Spine Cover

The center spine cover is fabricated from ABS. This cover protects the wiring and the controls that connect the driver station with the rear of the car. It also contains a housing for the fire extinguisher.

Instrument Panel

The instrument panel contains conventional automotive controls, warning lights and gauges. The panel itself is fabricated from FRP. There are "BATTERY," "DOOR AJAR," "HI BEAM," "BRAKE FLUID" and "PARKING BRAKE" warning lights, as well as a speedometer, a tachometer, and water temperature, fuel level and oil pressure gauges. The radio/cassette tape player is also installed in the panel.

Heater, Air Conditioner and Defroster

A three-speed squirrel cage motor draws air from the vented front luggage compartment into a specially designed plenum. The air then passes through either a Toyota evaporator or a Toyota heater core, and then through a Dodge Omni defroster/diffuser. Driver controls regulate the airflow to the heater and defroster, the relative amounts of recirculated and outside air, and the flow of hot water to the heater core. A standard Honda compressor is used for air conditioning.

Floor Covering

The inner sill surfaces, floor panels and exposed surfaces of the compartment crossmembers are covered with standard automotive cut-pile nylon carpeting. Standard jute or equivalent backs the carpeting in the four floor areas. The walls and floors of the forward and rear luggage compartments are also carpeted.

Indirect Vision

The RSV is equipped with three standard Ford rear view mirrors. The inside mirror is fastened to the windshield and a remote controlled mirror is fastened to the lower front corner of each side window.

2.5 EXTERNAL AND OTHER SYSTEMS

External Surfaces

Most of the external surfaces are fabricated from reaction-injection molded (RIM) urethane. RIM has lower weight than standard surface materials and provides damage resistance in low speed impacts. The Bailey Division of the Imhart Corporation produced the front fascia and front and rear fenders; Minicars fabricated the simulated RIM urethane rear bumper fascia using a wood mold sprayup technique.

A number of other exterior parts are made of FRP. These include the rear upper fenders, the rear body panel, the hood surround (which supports the hood), and the front bulkhead (which mounts on the bolt-on nose and provides mounting surfaces for the front fascia and fenders, the hood surround and the headlights).

The hood consists of two layers of FRP with a 1 inch (2.5 cm) layer of rigid urethane foam sandwiched between them. This design provides both the stiffness necessary to maintain the hood shape and the flexibility to cushion pedestrian impacts.

The rear hatch is composed of stretch-formed aluminum and standard automotive safety glass. The hatch is hinged at its top and is counterbalanced by gas struts. It also functions as an escape route for emergency egress — the latching mechanism includes an articulated striker plate which will open when pushed from the inside.

Engine Cover

The engine cover, located directly beneath the rear hatch, separates the engine and passenger compartments. It consists of a two layer aluminum hat section frame, a layer of spun fiberglass insulation, a layer of cloth and a piano hinge (along its forward edge).

Body Weather Sealing

Production neoprene foam extrusions are bonded to the body at the door and rear hatch openings. The door seals also serve as rain gutters when the doors are open.

Windshield Wiper/Washer

The RSV uses a single General Motors 27 inch (69 cm) bus blade powered by a Volvo wiper motor. The motor is placed even with the centerline of the passenger seat, to allow more crush space for the knee restraint. The washer bottle, pump and switch are standard Ford components.

Lighting

A variety of production lights are used on the RSV: GM rectangular, single lens, dual beam headlights, Ford truck front side markers, Porsche 914 rear side markers, Chevrolet van rear tail lights, and Volkswagen courtesy lights (on the insides of the B-pillars). The RSV also has a brake-activated light mounted on the rear hatch, where it will be more visible to approaching drivers. This so-called "Knaff" light is manufactured by Minicars.

Audible Warning Systems

The RSV has dual Honda horns in its bolt-on nose section and a buzzer in its engine compartment. The buzzer, similar to those used on many heavy vehicles, beeps whenever the transmission is in reverse.

Accessories

The RSV also has a first aid kit and a tools/spares kit, both located in the trunk, and a fire extinguisher mounted on the center spine cover.

2.6 HIGH TECHNOLOGY RSV

The high technology RSV, shown in Figure 2-2, includes all of the standard RSV systems, plus some advanced engineering concepts designed to improve safety, fuel economy and driver comfort. The advanced concepts include radar headway control (described in Section 9), anti-skid and radar-activated collision mitigation braking (Section 5), digital driver display (Section 8), and automated shifting (Section 6). The radar-related systems were all developed by the RCA David Sarnoff Research Laboratories (Princeton, New Jersey).

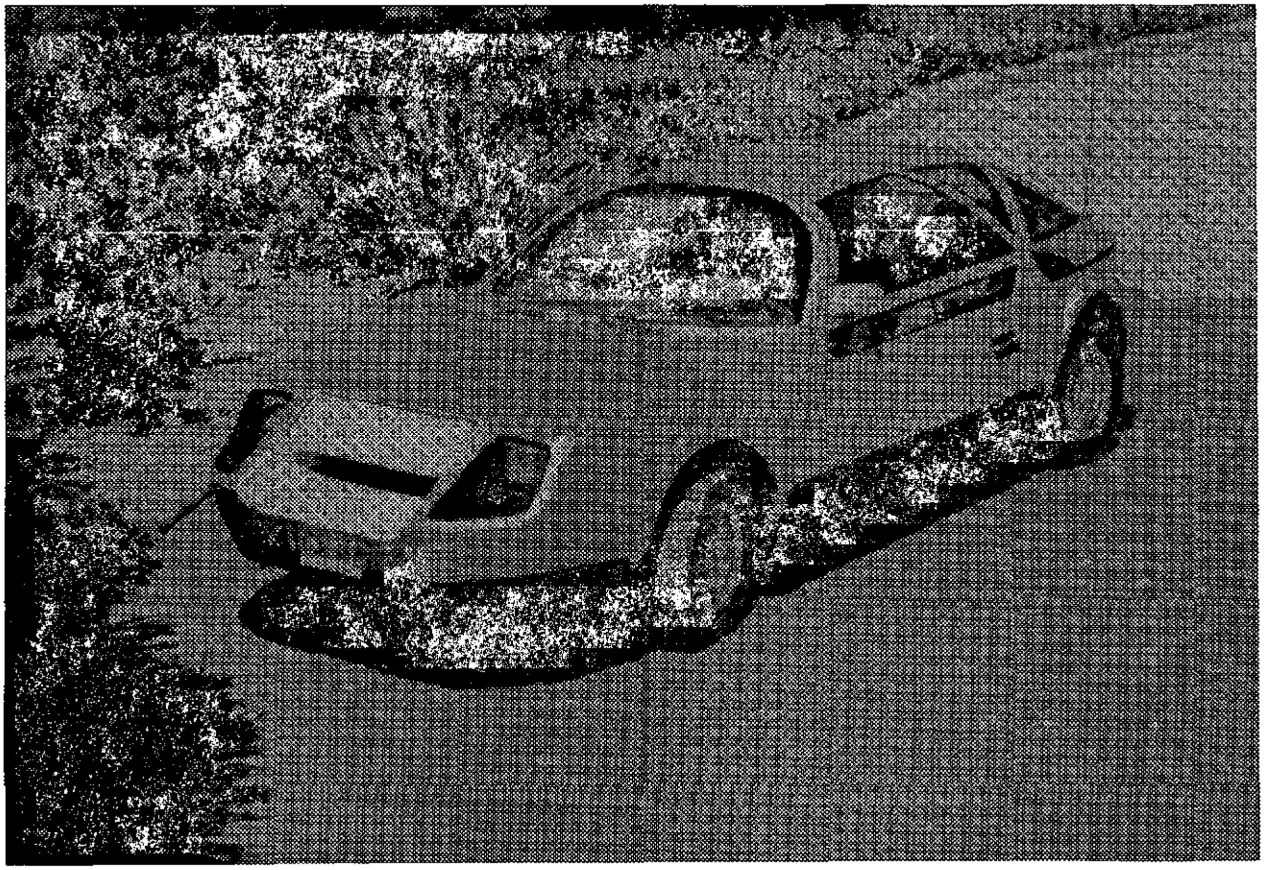

FIGURE 2-2. HIGH TECHNOLOGY RSV

Radar

The frequency-modulated/continuous-wave (FMCW) bistatic radar system operates at a frequency of 17.5 GHz in the Ku-band, has horizontal and vertical beamwidths of 3 and 5 degrees, and can acquire targets at ranges up to 165 feet (50 meters). The system can identify range rates of up to 135 mph (60 m/sec).

Two radar antennas are mounted directly behind a foamed polystyrene radome. The radome and antennas are located on the bolt-on nose.

Collision Mitigation System

A collision mitigation system (CMS) automatically applies the brakes when it determines that a severe, unavoidable collsion is impending. This occurs when the reflected radar signal indicates that a target lies within a range of 82 feet (25 meters) and is approaching at a closing velocity of at least 36 mph (16 m/sec) and there are no driver inputs to the steering wheel or brake pedal. Under such circumstances, pressurized fluid is admitted into the brake lines less than 200 msec after the target is first discerned.

Headway Control

The radar-activated headway control functions as a standard cruise control (that is, it maintains a preselected speed) until another vehicle comes in front of the RSV at less than a safe following distance (2.2 feet per mph of traveling speed). When that happens, the throttle is automatically adjusted to achieve and then maintain the safe following distance. Throttle control is provided by a pneumatic cylinder.

Anti-skid Braking

A Bendix Automotive Systems (South Bend, Indiana) anti-skid brake system complements the CMS. The control system measures the speeds of all four wheels and modulates the individual front wheel and two rear wheel brake pressures to prevent lockup. The anti-skid system operates with either driver-actuated or CMS-actuated braking.

Automated Transmission

The high technology RSV also has an adapted five-speed Honda manual transmission with computer-controlled automated shifting. This transmission combines the convenience found in automatics with the fuel efficiency of manuals. The computer selects the gear and the engine speed that will both meet the power requirements and provide optimum fuel efficiency. Solenoid valves are used to control the air pressure to cylinders attached to the shift rails, throttle and clutch.

Instrumentation

A Burroughs self-scan alphanumeric plasma display is installed above the instrument panel. It has a 32 character, single line capability and displays vehicle speed, fuel level, engine speed, time, water temperature, oil pressure, fuel economy and battery condition, using two formats that are driver-selectable. Warning messages are also flashed to the driver.

Processing Hardware and Sensors

The high technology RSV uses five microprocessors to control the CMS, headway control, anti-skid brakes, automated transmission and driver's display. A number of transducers supply information to the microprocessors; the inputs include vehicle speed, wheel speeds, engine speed, clutch and throttle position, gear position and driver inputs.

2.7 WEIGHT

The RSV was originally envisioned in Phase I to be a 1900 pound (860 kg) automobile, but its weight has steadily grown through the years. The final Phase III prototypes weigh 2578 pounds (1169 kg) – almost 300 pounds (135 kg) more than the best Phase II estimate. Table 2-2 documents the Phase III weight increase and lists the individual system weights for the entire car. Much of the weight increase was necessitated by the car's prototype status. We expect that a production engineered, mass produced RSV would have a weight much closer to the Phase II estimate.

TABLE 2-2. RSV WEIGHT BY SYSTEM

System	Phase II Estimated Weight (lbs)	Final Phase III Prototype Weight (lbs)	Difference (lbs)	Reasons for Major Differences
Body-in-white (including foam)	579	632	+53	Bolt-on nose, side sills, rear structure, etc., redesigned for increased stiffness; thicker gauge mild steel parts substituted for HSLA steel parts.
Powertrain/rear suspension (including engine cradle and accessories)	609	532	-77	Poor initial estimate, engine cradle redesigned.
Wheels and tires	166	194	+28	Specified heavier run-flat wheels and tires.
Fenders, fascias, hood surround, rear air scoops and body panel and attaching hardware	56	135	+79	Poor initial estimate, in-house fabrication techniques resulted in unnecessarily thick FRP parts, wheel houses added.
Two doors (including glazing)	142	250	+108	Latching and locking mechanisms moved from body-in-white to doors, added structure to increase strength and stiffness.
Front suspension and steering	102	102	0	
Steering wheel and column, driver ACRS	43	44	+1	

TABLE 2-2 (cont'd)

System	Phase II Estimated Weight (lbs)	Final Phase III Prototype Weight (lbs)	Difference (lbs)	Reasons for Major Differences
Electrical system (including battery)	43	43	0	
Body Glazing	29	49	+20	Advanced single-ply Mylar-backed glazing replaced with conventional double-ply safety glass.
Brake system (includes assembly and brake lines; does not include disks, calipers or pads)	23	41	+18	Vacuum boost system added.
Cooling system	23	39	+16	Aluminum tubing substituted for plastic tubing.
Rear hatch (including glazing)	25	34	+9	
Hood	11	32	+21	Redesigned for increased rigidity and pedestrian protection.
Fuel Cell, filler and emissions	27	31	+4	
Bumpers (excluding fascias)	18	30	+12	Rubrics added.
Driver seat	29	28	-1	
Passenger seat	29	28	-1	

TABLE 2-2 (cont'd)

System	Phase II Estimated Weight (lbs)	Final Phase III Prototype Weight (lbs)	Difference (lbs)	Reasons for Major Differences
Rear seat	12	21	+9	
Passenger ACRS	25	21	-4	
Heater, defroster and ventilation	20	18	-2	
Floor covering	12	18	+6	
Interior padding and trim (excluding doors, dash)	25	15	-10	
Dash	8	12	+4	
Weather sealing	6	11	+5	
Lighting	11	11	0	
Rear passenger restraints	16	10	-6	
Gear shift	3	10	+7	
Windshield wiper and washer	8	10	+2	
Instrument panel	4	8	+4	
Parking brake	6	7	+1	
Front bulkhead	5	7	+2	

TABLE 2-2 (cont'd)

System	Phase II Estimated Weight (lbs)	Final Phase III Prototype Weight (lbs)	Difference (lbs)	Reasons for Major Differences
Engine cover	4	6	+2	
Accessories	8	5	-3	
Center spine cover	10	4	-6	
Indirect vision	1	3	+2	
Door latches, locks and controls	6	0	-6*	
Paint, body putty, deadeners	74	50	-24	Initial estimate also included allowances for miscellaneous items.
Fluids	87	87	0	
Curb weight	2305	2578	+273	

*During Phase III, the door latches, locks and controls were moved from the body-in-white to the doors and are now included in the door weight.

SECTION 3
VEHICLE STRUCTURE

3.1 INTRODUCTION

The structure of the Minicars RSV was designed to

- Maintain the integrity of the passenger compartment during collisions
- Absorb impact energy - and thereby minimize passenger compartment accelerations during collisions
- Be durable over a wide range of operating conditions
- Minimize the weight of the vehicle
- Minimize the expense of the vehicle, when produced in large quantities.

In general, accidents are much harsher for small cars. During serious accidents the passenger compartments of small cars are often severely deformed - making it very difficult for restraint systems to work adequately. In extreme circumstances, occupants are crushed by the interiors of their own cars.

Our approach to this problem was simple and straightforward: maintain structural integrity by making the passenger compartment substantially more rigid than the rest of the RSV. This enables the passenger compartment to remain intact and to resist intrusion, while the rest of the car deforms and absorbs the crash energy.

But absorbing impact energy (the second objective) is also more difficult for small cars. Not only are small cars exposed to more severe accidents due to their weight disadvantage, they also have less cushion ("crush space") surrounding their passenger compartments. A simple addition of crush space (making the exteriors of the cars larger - or their interiors smaller) would help, but adding weight and reducing occupant space are obviously not acceptable answers. Better use must be made of the available space.

A structure can cushion impacts by mitigating the severity of the passenger compartment dynamics, thus enabling the padding and restraint systems to function effectively. In general, the best dynamics is that which produces the lowest peak accelerations. Figure 3-1 shows an "ideal" crash pulse (acceleration versus time history) for occupant protection. The compartment acceleration rapidly increases to a maximum level (a) and remains there until the velocity change is completed. In addition, the time t_1 is just long enough that all of the available crush space is utilized. If the restraint system prevents the occupants from moving relative to the passenger compartment (which is not necessarily the best strategy), they will never be subjected to an acceleration greater than a.

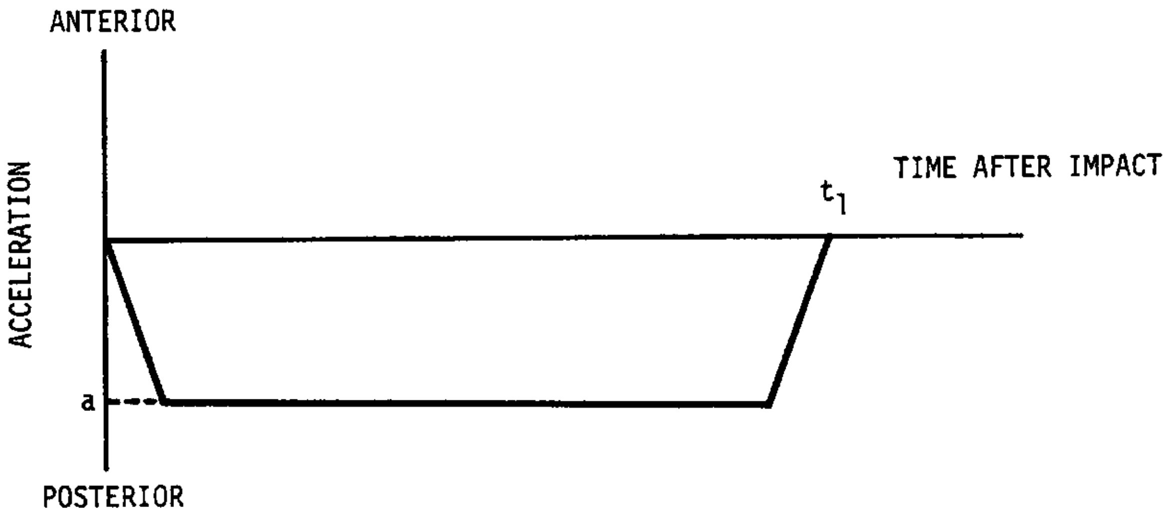

FIGURE 3-1. "IDEAL" CRASH PULSE

During a collision the passenger compartment is accelerated by the structural load paths connecting it to the object struck. The significant load paths are determined by the impact's location and direction. The force (and, therefore, the acceleration) transmitted to the passenger compartment is a direct function of the stiffness of the applicable load paths. To keep accelerations constant and manageable, we endeavor to use constant load mechanisms for load paths. We also try to use structures that are good inelastic energy absorbers. (A structure that stores energy elastically must also release it, thus contributing to rebound and actually increasing the impact's severity.)

One basic problem with conventional automotive structures is that their behavior under plastic deformation is often erratic and unpredictable. A good example is the conventional subframe which dominated automotive design for many years. The subframe, among its other functions, furnishes a load path from the front bumper to the passenger compartment. In front impacts the subframe buckles, initiating a bending moment. A plastic hinge develops at the buckle, and the structure collapses while the hinge rotates. As the subframe deforms, the load falls off substantially until it is only a small fraction of the original level.

A unibody structure offers better crashworthiness at less weight than does a subframe body structure, but its use does not necessarily guarantee adequate performance. Figure 3-2 shows a crash pulse for a Chevrolet Vega, whose structure has a unibody design. The curve, obtained from a crash test in another Minicars program (Reference 2), shows the Vega's passenger compartment acceleration during a 30 mph (48 km/h) frontal barrier impact. Early in the event the operational load paths are too soft and the compartment velocity remains essentially unchanged. The passenger compartment eventually must come to a stop, however, and in this case it does so with a sudden jolt (approximately 55 msec into the crash). This sort of behavior significantly limits the performance obtainable with the car's restraint system. It is also noteworthy that after this impact, the Vega had essentially no frontal crush space remaining. Thus, in a 40 or 50 mph impact one of two things would have to happen: the passenger compartment would either experience an even higher peak acceleration, or it would be forced to absorb the crash energy itself, by deforming and possibly crushing its occupants.

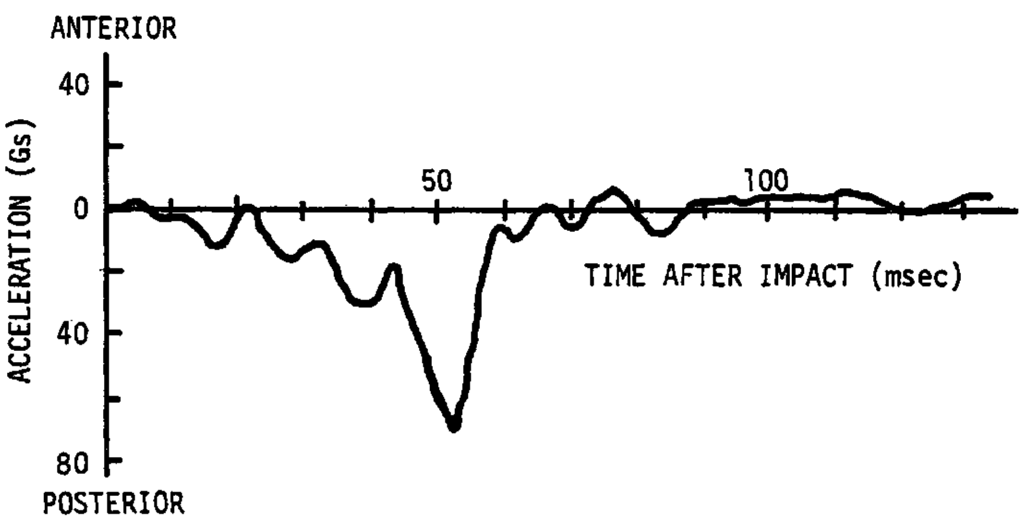

FIGURE 3-2. CHEVROLET VEGA LONGITUDINAL MID-COMPARTMENT ACCELERATION DURING 30 MPH ALIGNED FRONTAL BARRIER IMPACT (MINICARS TEST 1060-2)

More recent unibody designs show improved crashworthiness. As General Motors has demonstrated with the X-body cars, a sheetmetal structure can be made into an energy-absorbent, (relatively) constant load mechanism which will produce a well shaped crash pulse in moderately severe aligned front impacts.

Foam Filling

Early in Phase I, Minicars selected thin-walled sheetmetal boxes filled with rigid urethane foam as the basic RSV structure. The decision was based on the inherent advantages of these structures:

Weight. Large section, thin-walled boxes (with or without foam) provide the stiffness required to support road loads at less weight than other structures.

Energy Absorbency. A rigid foam core inhibits the formation of buckles in a sheetmetal box and restricts the size of buckles once they do form. This causes the structure to maintain a more uniform stiffness as it deforms. Figure 3-3 illustrates the constant load properties of a foam-filled box in compression.

Omnidirectionality. Unlike other structures, foam-filled sheetmetal boxes do not exhibit erratic behavior under loading in different directions. Although crashworthiness is frequently characterized by researchers as performance in aligned frontal barrier impacts, such occurrences are rare in the real world, and a structure should be designed to accommodate impacts in all directions.

Predictability. The inclusion of foam makes a structure's behavior more predictable.

Damping. Because they are excellent energy absorbers, foam-filled structures are very proficient at damping road induced vibrations.

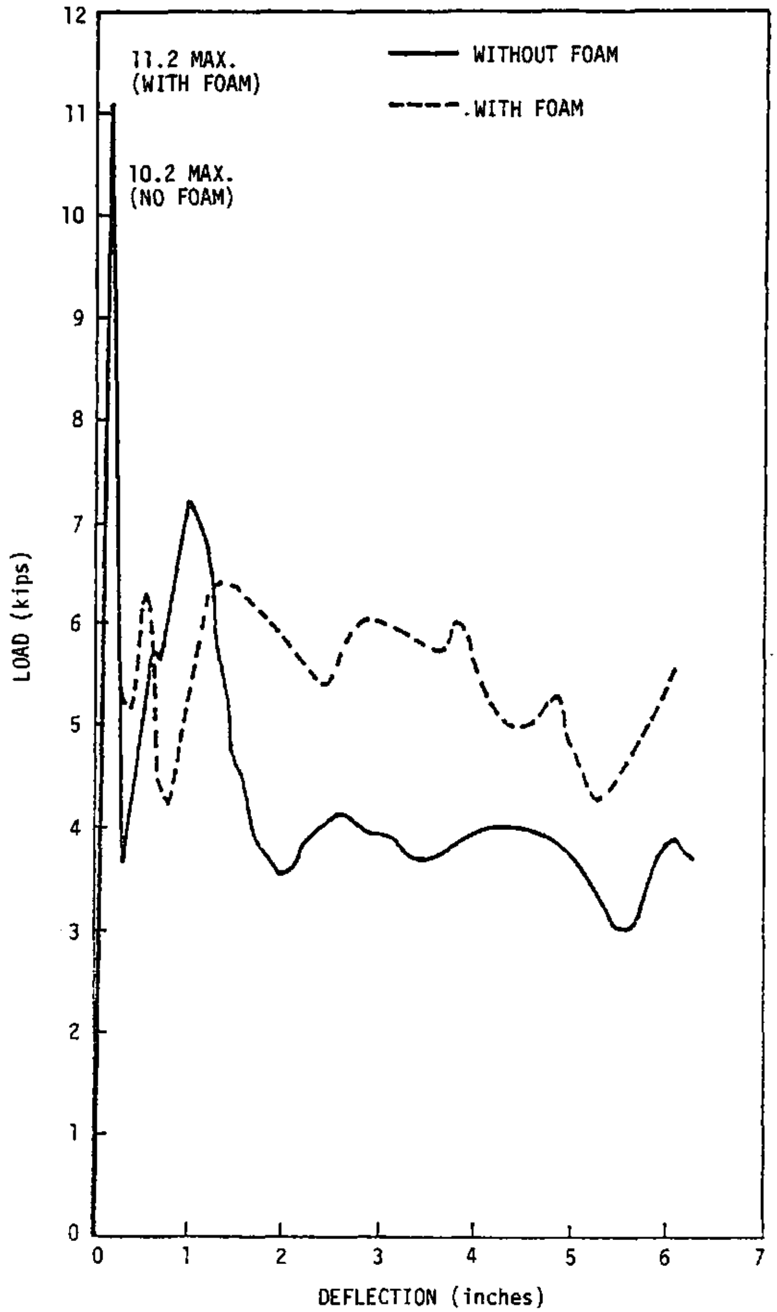

FIGURE 3-3. STATIC CRUSH DATA FOR AN 8 INCH BY 8 INCH (20.3 CM BY 20.3 CM) CLOSED SHEETMETAL BOX

Despite its weight advantage, a foam-filled sheetmetal structure takes up more volume and thus reduces packaging efficiency. However, the RSV demonstrates that adequate roominess can still be designed into a small car.

Another disadvantage of foam-filling is cost. Nevertheless, in the Phase I studies it was found that the benefits of incorporating foam-filling, however quantified, would outweigh the cost.

There are some aspects of foam-filling (such as vibrational and thermal degradation, flammibility and susceptibility) that cannot be fully and finally evaluated until the design concepts are production engineered and incorporated in production automobiles. By and large, these have been identified and found to be non-significant (Reference 3); we expect that, should problems emerge, near term solutions could be found.

Frontal Crashworthiness

The various available data files suggest that one can achieve the greatest benefits by protecting occupants in front impacts. Accordingly, the RSV design maximized the available frontal crush space. Most importantly, the engine and the front wheels can form excessively stiff load paths as the structure crushes against them. We therefore located the engine in the rear of the car and designed the torque box/A-post structure so that the wheels will move laterally, away from the body, during front impacts. These efforts have given the present RSV design 50 inches (127 cm) of effective frontal crush space.

An early goal in the RSV Program was to provide survivability in 50 mph (80 km/h) barrier impacts (in order to address a significant part of the societal cost in front collisions). To bring the passenger compartment from this speed to a complete stop in 50 inches requires an average deceleration of approximately 20 Gs, which is well within the capabilities of a well designed restraint system. We therefore used a 40,000 pound (180,000 N) crush strength as a basis for the RSV's frontal stiffness, since that is the force required to decelerate a 2000 pound (910 kg) mass at 20 Gs.

The problem with optimizing a fixed-force structure for 50 mph impacts is that it will be above the optimum stiffness for any accident that is less severe – i.e., for most accidents. Minicars' solution was to design the structure in stages of varying stiffness, with the softest stage in front. The stages consist of a foam bumper with a crush strength of approximately 16,000 pounds (70,000 N), then a detachable bolt-on nose with a crush strength of approximately 25,000 pounds (110,000 N), and finally the wheelhouse and luggage compartment with a crush strength of approximately 50,000 pounds (220,000 N). Together, these sections have an "average" crush strength of about 40,000 pounds (180,000 N) and will provide satisfactory performance in a 50 mph impact. Compared to a uniform structure, the staging results in a more severe crash pulse at 50 mph (later accelerations are somewhat higher), but the resulting severity increase is more than offset by the benefits of the softer pulses produced in the lower speed crashes.

There are other good reasons for designing the front structure in stages. A soft bumper will help reduce the injuries and fatalities of pedestrians struck by the RSV – and will, in general, improve the load distribution on the struck vehicle. The softer front end will help protect the occupants of cars that the RSV strikes in side impacts (see Subsection 3.2). The multi-stage design will also help to reduce property damage costs. In severe accidents we willingly sacrifice the car to save the occupants, but in moderate accidents the vehicle repair costs become significant relative to the societal costs of occupant injuries. Recognizing that the concept of stages can help to reduce repair costs, we set two additional goals for front impacts:

- The front bumper is to provide a no-damage capability at speeds up to 10 mph (16 km/h).
- The bolt-on nose and the bumper, both of which can be easily and relatively inexpensively replaced, will absorb all energy in front impacts at speeds up to 20 mph (32 km/h), without significant damage to other parts of the car.

By accomplishing these objectives, we expected that the RSV would incur much lower repair costs than would conventional cars in low speed front impacts. An estimate of the savings that these subsystems can achieve is found through the Kinetic Research Property Damage Algorithm (described in Section 12).

The nose, fender boxes and luggage compartment floor are shown in Figure 3-4. The sill catcher, located beneath the nose, insures that the RSV structure will engage the sills of other cars during side impacts. The sill catcher, nose, luggage compartment floor, sills, tunnels and seat boxes together form lower load paths similar to those of the conventional subframe. The fender boxes, door beams (not shown) and quarterpanels form upper load paths. To prevent passenger compartment deformation, each of the structures behind the A-pillars has been designed to be considerably stiffer than those in front.

An important consideration in front impacts is the balancing of crush strength between the upper and lower load paths. A balanced structure prevents pitching during impacts. (Pitching makes it more difficult to properly manage crash forces and may deteriorate the restraint system performance.) Cars with subframes and nonstructural fenders show a strong tendency for the rear to pitch upward in front collisions. By balancing stiffness in the upper and lower load paths, Minicars has almost eliminated pitching tendencies in the RSV.

Figure 3-5 gives a good example of the RSV structure's performance during a severe front collision. It shows the passenger compartment acceleration in a 47.6 mph (76.6 km/h) aligned front barrier impact. In this test a dynamic crush of 45 inches (114 cm) was observed, but there was no significant deformation of the passenger compartment. The cyclical response (solid line) can be disregarded because the airbags will effectively damp any input at this frequency. Thus, the dotted line is more representative of the passenger compartment kinematics. The restraint systems were able to translate this crash pulse, which peaked at approximately 30 Gs, into dummy injury measures that easily met the survivability criteria of Federal Motor Vehicle Safety Standard (FMVSS) 208.

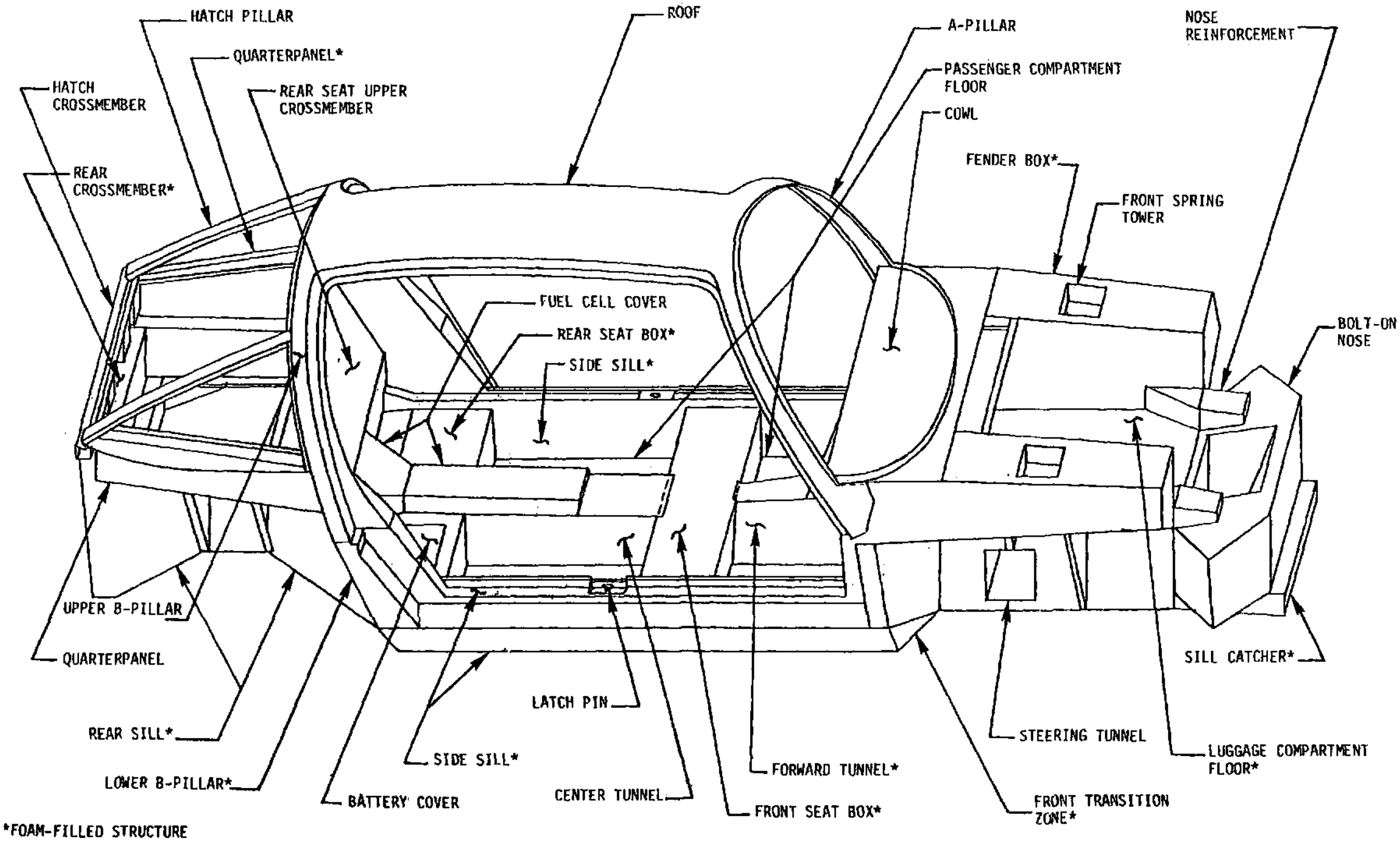

FIGURE 3-4. BODY-IN-WHITE

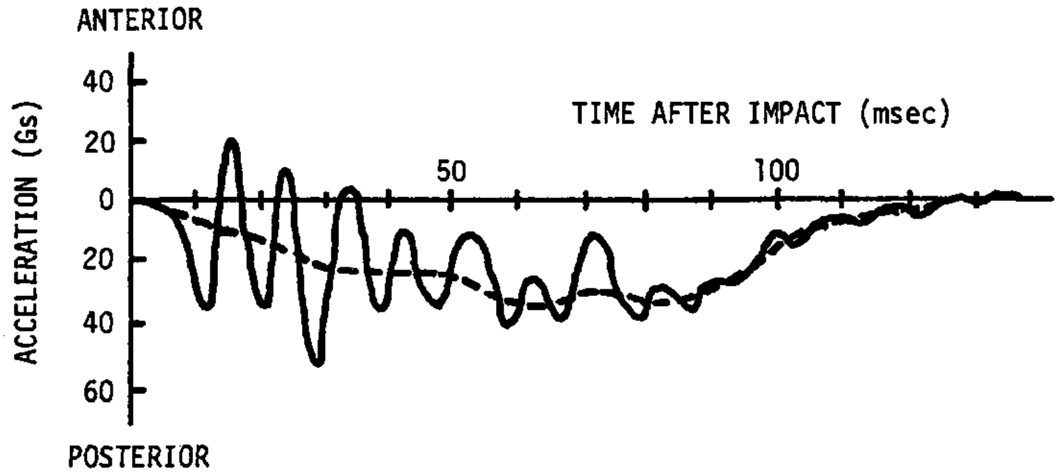

FIGURE 3-5. RSV LEFT REAR COMPARTMENT LONGITUDINAL ACCELERATION DURING 47.6 MPH ALIGNED FRONTAL BARRIER IMPACT

Side Crashworthiness

In side collisions there is a strong correlation between injury severity and the speed at which the occupant strikes the interior surfaces of the vehicle. Proper design of the side structure can significantly reduce this impact speed.

As was discovered in the Phase II and Phase III crush tests, the conventional automobile side structure is surprisingly soft and weak. When the conventional automobile is struck in the side, its structure may easily be pushed into the passenger compartment and strike its occupants at an unnecessarily high velocity. A stiffer structure, on the other hand, would compel the striking force to act on the entire vehicle rather than just its side. Thus the side structure itself would not be accelerated as much early in the crash event, and the speed at which it struck its occupants would likewise be less. Minicars therefore designed the RSV side structure to offer maximum stiffness at minimum weight.

The locations of the doors and their integration into the side structure are of fundamental concern in designing for side crashworthiness. Obviously, one would prefer (from a crashworthiness point of view) not to use doors at all, but simply to have an unbroken side structure. We originally intended the RSV to have a high structural sill beneath a nonstructural gull-wing door, but we found that a sill high enough to match the bumper heights of other vehicles would excessively constrict ingress and egress. We therefore lowered the sill to an acceptable height (it is still higher than is customary) and added the necessary structure to the door. The gull-wing design was retained because it offers excellent ingress and egress for its weight, and enables the door to be more easily integrated into the RSV's side structure.

The structure of the door is illustrated in Figure 3-6. Its lower half is critical in side impacts, since it may be struck by the bumpers of other vehicles. The lower door basically consists of a foam core sandwiched between aluminum inner and outer skins. This construction (which may accurately be described as a "stubby beam") exhibits an exceptionally high bending modulus, compared to that of conventional car doors. Because of the large shut faces on the pillars and sills (see Figure 3-4), it is virtually impossible to push the door through the side structure and into the passenger compartment. Further discussion of the door structure and its behavior in side impacts is contained in Section 3.4.

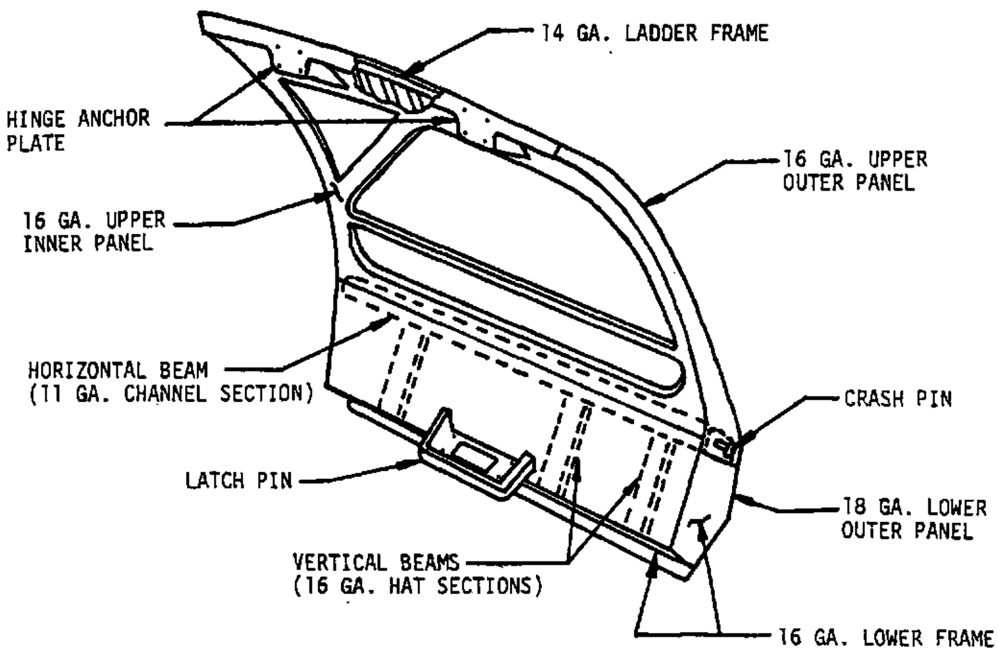

FIGURE 3-6. GULL WING DOOR STRUCTURE

Similarly, the sills and pillars are much stiffer than comparable structures in other cars. During side impacts they feed loads into the cowl, seat boxes, rear seat upper crossmember, and through to the other side of the car. The sills, B-pillars and seat boxes also are foam-filled.

Rear Crashworthiness

The location of the RSV engine limits the available rear crush space. As in side impacts, our primary objective in rear impacts is to limit intrusion into the passenger compartment. If the structure is too soft, the impacting vehicle will push the engine into the rear seat.

Several load paths combine to feed loads from the rear of the RSV into its other structures. Loads in the rear sills, quarterpanels and hatch pillars are fed into the side sills, seat boxes, tunnels and roof (see Figure 3-4). The structural stiffness is then increased by the engine support struts and a special (triangulation) strut added to the rear suspension A-arms (shown in Figure 5-2). The design also includes a 5 mph (8 km/h) no-damage bumper.

Rollover Crashworthiness

We expect the RSV structure to be more crashworthy than other cars in rollover accidents, because of its:

- Structural Integrity. The extensive tumblehome of the pillars and doors effectively spreads forces and supports large radial loads (in contrast to the squarish shapes of conventional upper body structures).
- Smoother Kinematics. In addition to distributing loads and furnishing stiffness, the rounded upper structure allows the RSV to roll more smoothly (i.e., without sharp vertical displacements of its center of gravity).

- Occupant Ejection. The doors are not likely to open and the fixed side windows (because they a-- laminated) will not shatter, preventing the occupants from being eje... from the RSV during an accident.

3.2 COMPATIBILITY ANALYSIS

A central task of this contract was the definition of an RSV structure that would not only protect the occupants of RSVs, but would also give the greatest benefit to society in general. This goal required the RSV to be maximally "compatible" to the other cars expected to populate the 1985 automotive environment. We therefore performed a compatibility analysis that evaluated the tradeoffs between protecting RSV occupants and protecting "other car" occupants.

Methodology

In the compatibility analysis, Minicars formulated a computerized algorithm which processes inputs describing possible RSV front structures into outputs estimating societal cost. The algorithm requires

- A description of the accident environment
- Vehicle structures and restraints models which, if given basic crash parameters (vehicle mass, impact direction, crash severity, etc.), will calculate dummy injury measures
- Transformation functions that will convert dummy injury measures into average societal costs.

To be consistent with the work in Phases I and II of the program, we used Multidisciplinary Accident Investigation (MDAI) file data (adjusted to produce marginal distributions corresponding to the CAL II file) for the analysis of front impacts. To reduce the overall complexity, we divided the accident types into fixed-object and vehicle-to-vehicle groups, then subdivided the latter according to the size of the other vehicle – small (2400 pounds) or large (3800 pounds).

To simulate crash mechanics, we used lumped mass models similar to those originally employed to develop the RSV structure. The models separate a vehicle into coplanar point masses (engine, bumper, driver, etc.) coupled by springs. The springs' force-displacement characteristics usually are nonlinear and often are strain rate dependent. For side impacts, we started with a rigorous 15 degree of freedom model which included 13 lumped masses and 25 force-displacement curves. Then, using the results of crash and crush tests, we were able to simplify that model to 7 masses, 8 force-displacement curves and 10 degrees of freedom.

Two approaches developed in Phases I and II were used to correlate dummy injury measures to societal cost. The relationship between the chest severity index (CSI) and the societal cost shown in Figure 3-7 was used in front impacts, and the peak chest acceleration versus societal cost relationship of Figure 3-8 was used for side impacts.

Vehicle Testing

To study an accident environment in which RSVs collide with 2400 and 3800 pound cars, we made detailed analyses of the crash behavior of the Chevrolet Chevette and Chevrolet Impala. Crash pulses and structural deformation measurements were taken from both Phase II and Phase III dynamic crash tests:

- High and low speed RSV aligned frontal barrier impacts
- RSV into Chevette side
- RSV into Pinto side
- RSV into Volvo side
- Impala into RSV side.

We also conducted several static crush tests of Chevette and Impala side structures. In each test the vehicle was supported at a number of locations, and side loads were applied to selected structural elements. While the load increased, the deformation was monitored at several locations to help formulate the force-displacement curves. Comprehensive descriptions and discussions of the test procedures and results are given in Reference 5.

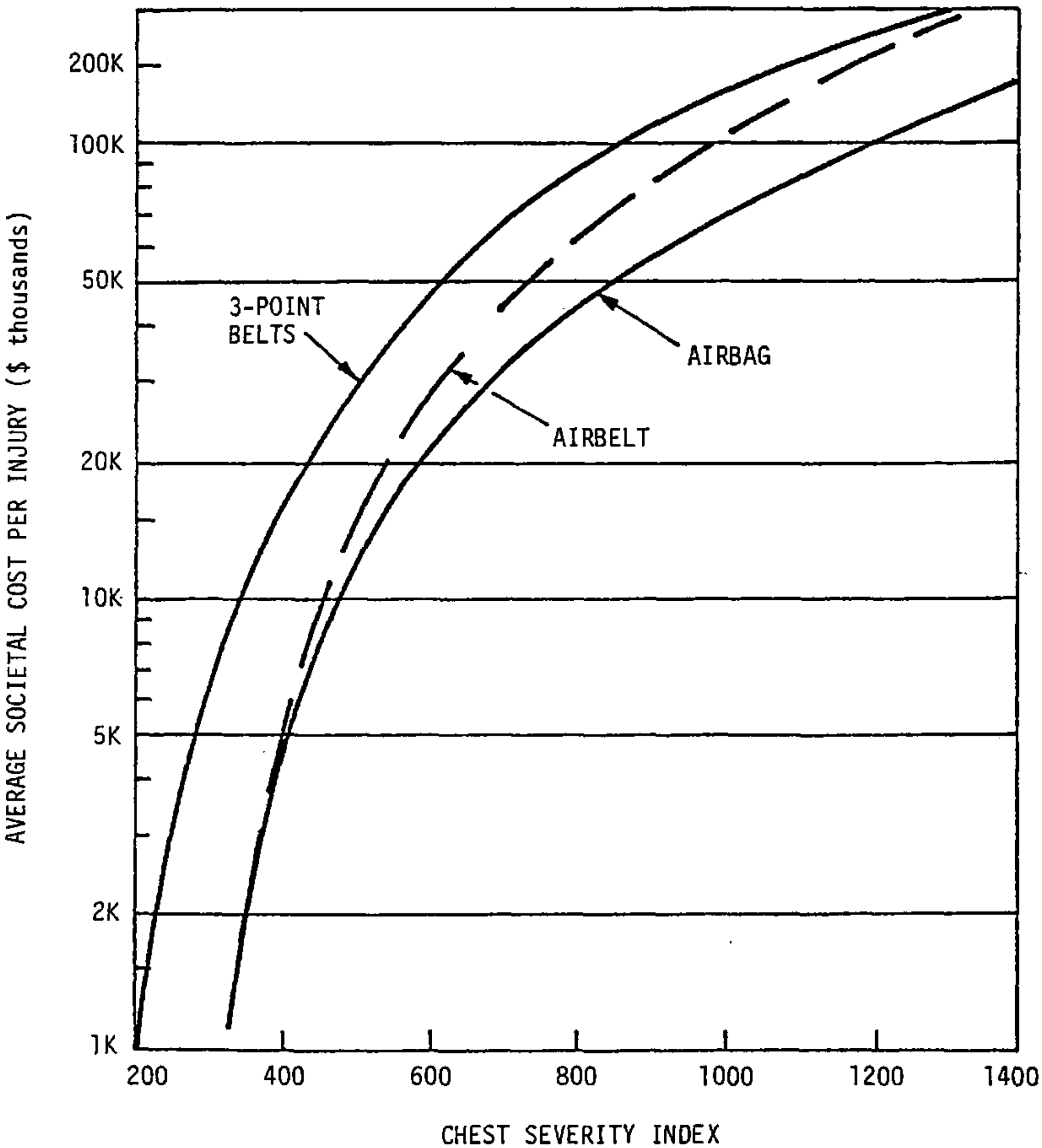

FIGURE 3-7. PHASE I TRANSFORMATION FROM LABORATORY INJURY MEASURE TO SOCIETAL COST

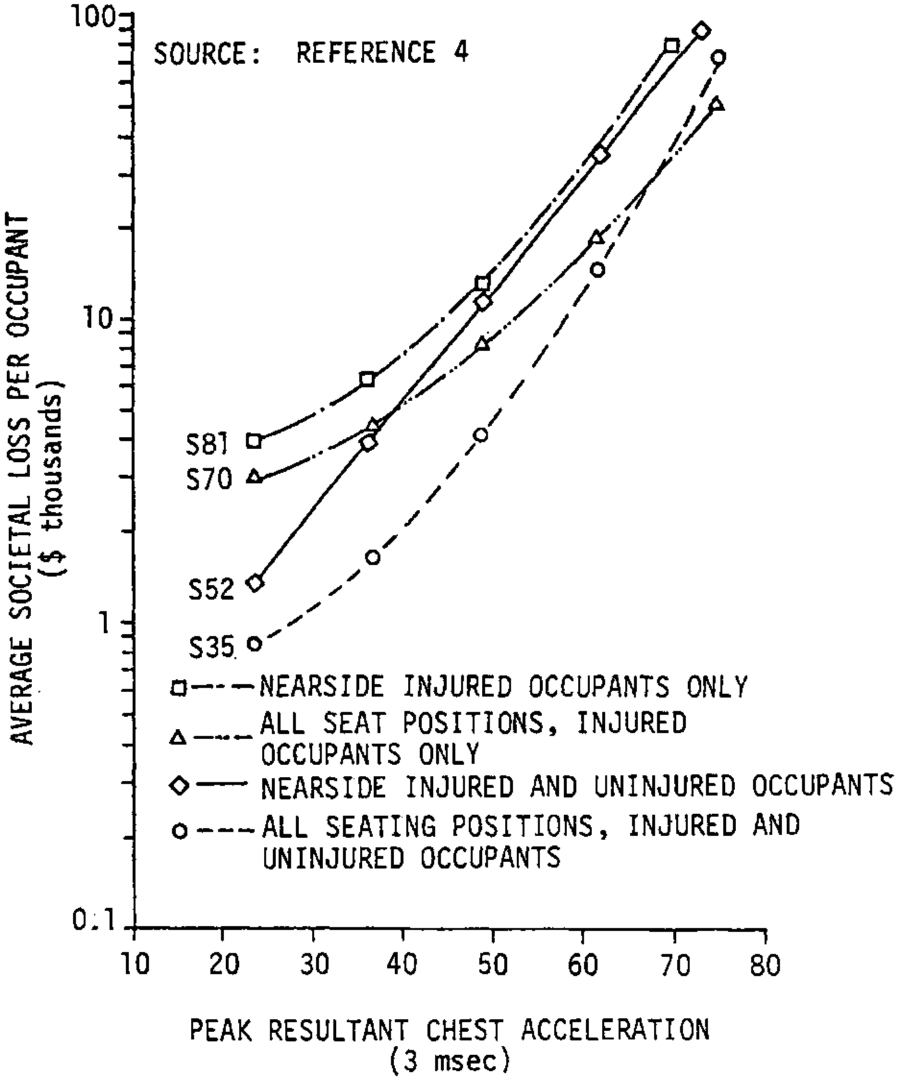

FIGURE 3-8. INJURY MEASURE-TO-SOCIETAL COST TRANSFORMATIONS, WITH CRUSH AS A PARAMETER

Results

It quickly became apparent that the RSV front has a negligible effect on occupants in other vehicles during front impacts, because the other vehicle's structure tends to filter the transients caused by the RSV's structure. Therefore, societal loss calculations in front impacts were restricted to RSV occupants. Occupants of cars struck in the rear by RSVs were also ignored, because of the relatively low severity of such accidents. Thus, the compatibility analysis was limited to RSV occupants in front impacts with fixed objects and large and small cars, and to occupants of large and small cars struck in the side by RSVs.

We simulated three RSV front structures — intermediate (our best representation of the current RSV front), soft and hard. The soft and hard fronts were obtained by softening and stiffening, respectively, each element of the intermediate structure by 25 percent. A table of results, expressed in terms of average cost per injury, is given in Reference 6.

As one would expect, the "other car" occupants were shown to be better off when struck with the soft RSV. Interestingly, the soft RSV also reduced the societal costs to the RSV's own occupants. This is a result of the relative scarcity of high speed impacts; the benefits gained at lower speeds appear to outweigh the penalties at higher speeds. One might conclude that the RSV front should be made softer, particularly in view of the assumed 1985 small car/large car split of 69/31.

There are, however, other considerations. First, the results were influenced by the specified societal cost versus injury level functions (Figures 3-7 and 3-8). Second, if property damage had been analyzed, it might well have increased with the soft (presumably easily damaged) front structure. Last, there is a question about the amount of protection the RSV structure can provide for the occupants of other cars struck in their sides. Our results suggest that the answer to this question is "very little." A 25 percent reduction in RSV stiffness reduced the societal cost of their injuries by only 2 percent. The blame for this result must lie with the side structures of the other cars. They simply do not have the strength to apply the force necessary to decelerate a 2100^{+} pound mass in the time and distance allotted. Thus, the solution is not to make front structures softer than that of the RSV; the solution is to make side structures stronger.

3.3 BODY-IN-WHITE

The RSV body-in-white design was refined in Phase III under a subcontract to the Budd Company (Fort Washington, Pennsylvania). Minicars and Budd then further refined the design in order to

- Improve crashworthiness
- Improve durability
- Reduce weight
- Simplify the design and improve assembly procedures (reducing the number of welds, where possible)
- Incorporate brackets, routing holes, etc.
- Make necessary changes in foam composition and filling techniques.

The design changes were based on the results of the crash and crush tests, braking and handling tests, durability tests and further analytical study.

The Budd Company ran an extended durability test on the RSV early in Phase III. The body-in-white, suspension and wheels were ballasted to 2765 pounds (1255 kg) and the rear wheels were secured. Then a nominal 3 G vertical input was applied to the front wheel hubs. The setup was later reversed, and the rear wheel hubs were excited. When the test was complete, the structure had undergone over 1,000,000 cycles of excitation at a number of frequencies. The shock absorbers bottomed at 2 and 4 Hz, but the suspension limited the maximum structural acceleration to less than 1.75 Gs at all higher frequencies. Some failures occurred; our corrective actions are discussed later in this subsection.

Budd also conducted a modal survey to identify all structural modes between 0.5 and 35 Hz. They applied a 0.25 G input (using the same test setup as above), measuring accelerations at various locations on the body. The only resonance occurred at 12 Hz (lateral engine pitch on the engine mounts), and the suspension effectively filtered everything above that frequency. Below 12 Hz no sharp resonance peaks were found in either bending or torsion. Some very flat peaks appeared to be highly damped resonances. The foam-filling could produce considerable damping and was probably the contributing factor.

Bolt-on Nose

Minicars refined the bolt-on nose to meet the goals of no damage in 10 mph (16 km/h) impacts and confined damage in 20 mph (32 km/h) impacts. Tests 1376 (8 mph) and 1154 (9.7 mph) both produced minor local buckling of the nose. We subsequently added a lateral 3 inch by 5 inch (7.6 cm x 12.7 cm), foam-filled, high strength, low alloy (HSLA) steel beam at the forward bumper mounting surface, longitudinal side stiffeners, and reinforcements at the rear interface with the luggage compartment floor. No-damage performance was then demonstrated in an 8.3 mph (13.2 km/h) test.

Three RSV/Impala crash tests emphasized the fact that a collision with another car can be quite different from a collision with a barrier. In the first aligned frontal crash between the two cars (Test 1622: 66 mph closing speed, 40 mph RSV delta-V), the nose crippled asymmetrically and rotated upward, allowing the Impala to override the RSV. This forced the RSV's fender boxes to absorb most of the crash energy (since the lower load paths were left inadequately loaded). The test was not run at the intended 75 mph because the tow cable slipped. If the test had been run at the correct speed, the fender boxes alone could not have absorbed sufficient energy to prevent passenger compartment intrusion.

To discourage upward rotation, Minicars added two reinforcements to connect the nose's upper surface to both the fender boxes and the luggage compartment floor (see Figure 3-4). The test was then run (Test 1660) at the correct 75 mph (121 km/h) closing speed. This time the nose rotated downward, lifting the RSV over the Impala bumper and reversing the override.

We then shortened the reinforcements (which originally extended to the front of the nose) to give the nose's upper surface a greater opportunity to buckle, and put buckling initiators in the nose's lower surface to encourage more symmetrical buckling. These modifications proved to be successful. In the last RSV/Impala aligned front test (Test 1856: 79.2 mph closing speed, 45 mph RSV delta-V) the nose buckled evenly and the upper and lower load paths were both adequately engaged.

Front Structure

During Phase III we also refined the front structure to comply with the 20 mph confined damage criteria. In Test 1377 (15 mph) the luggage compartment floor buckled near the nose interface. To better distribute the loads that had caused the buckling, we installed the reinforcements described above and added a flat reinforcement at the interface of the nose and floor. In a subsequent 17 mph (27 km/h) test, all damage was successfully confined to the nose and bumper.

We redesigned the front spring tower to simplify assembly, reduce weight and remedy the "oil canning" observed after the Budd durability tests. Another design deficiency was detected during the ride and handling tests, when the steering tunnel deformed at the steering rack mounting brackets. We replaced the two brackets with a larger single assembly that better distributes the loads from the rack into the body-in-white.

Side Sills and Adjoining Areas

During Test 7.5a (an offset frontal crash conducted in Phase II) the left sill crushed excessively in the forward transition area. This caused part of the firewall to move rearward and to strike the driver's left leg, producing an unacceptable injury measure. We subsequently added a "Z" section to the inside of both the front and rear transition areas to increase longitudinal stiffness. In a later offset frontal test (Test 1529: RSV/Impala), the strengthened structure prevented significant intrusion near the sill.

Unacceptable intrusion into the passenger compartment also occurred during Test 1466 (Impala into RSV side, both cars traveling at 34.9 mph). The lower B-pillar was severely deformed and separated from the sill. To prevent recurrence, we spot welded three brake-formed gussets inside each sill. One is attached just opposite the B-pillar, to transfer loads from it into the rear seat box. The others are on either side of the latch pin box, to help transfer loads from the doors into the sill. We also added metal inert gas (MIG) welds to the outside seams between the sill and B-pillar. Finally, we spot welded a steel plate inside the B-pillar to more securely attach the striker plate (discussed in Subsection 3.4).

Rear Structure

Minicars made a number of design changes in the rear structure to improve crashworthiness and to better support the engine and suspension loads. Figure 3-9 shows many of the rear structural elements. The most significant structural changes were:

- The rear sills were lengthened to provide more crush space and lowered to prevent underride. This allowed us to move the rear seat rearward 1-1/4 inches (3 cm).
- A reinforcement beam was added to the rear crossmember to increase stiffness in rear impacts and to provide better mounting surfaces for the engine cradle and for the rear suspension brackets (see Figure 3-9).
- The engine cradle was redesigned to provide better support and to improve engine alignment.
- The quarterpanel was redesigned to increase overall rigidity and to reduce excessive deformations found in durability tests.

Upper Body Structure

To reduce cost, the RSV body-in-white is fabricated almost entirely from sheet steel parts. In limited quantity production this usually means brake-formed parts. However, the compound curvature of the doors and upper body structure requires that many of their components be stamped. Not surprisingly, most of our Phase III effort on the upper body went into solving fabrication problems, particularly those relating to the fit of outside upper body surfaces.

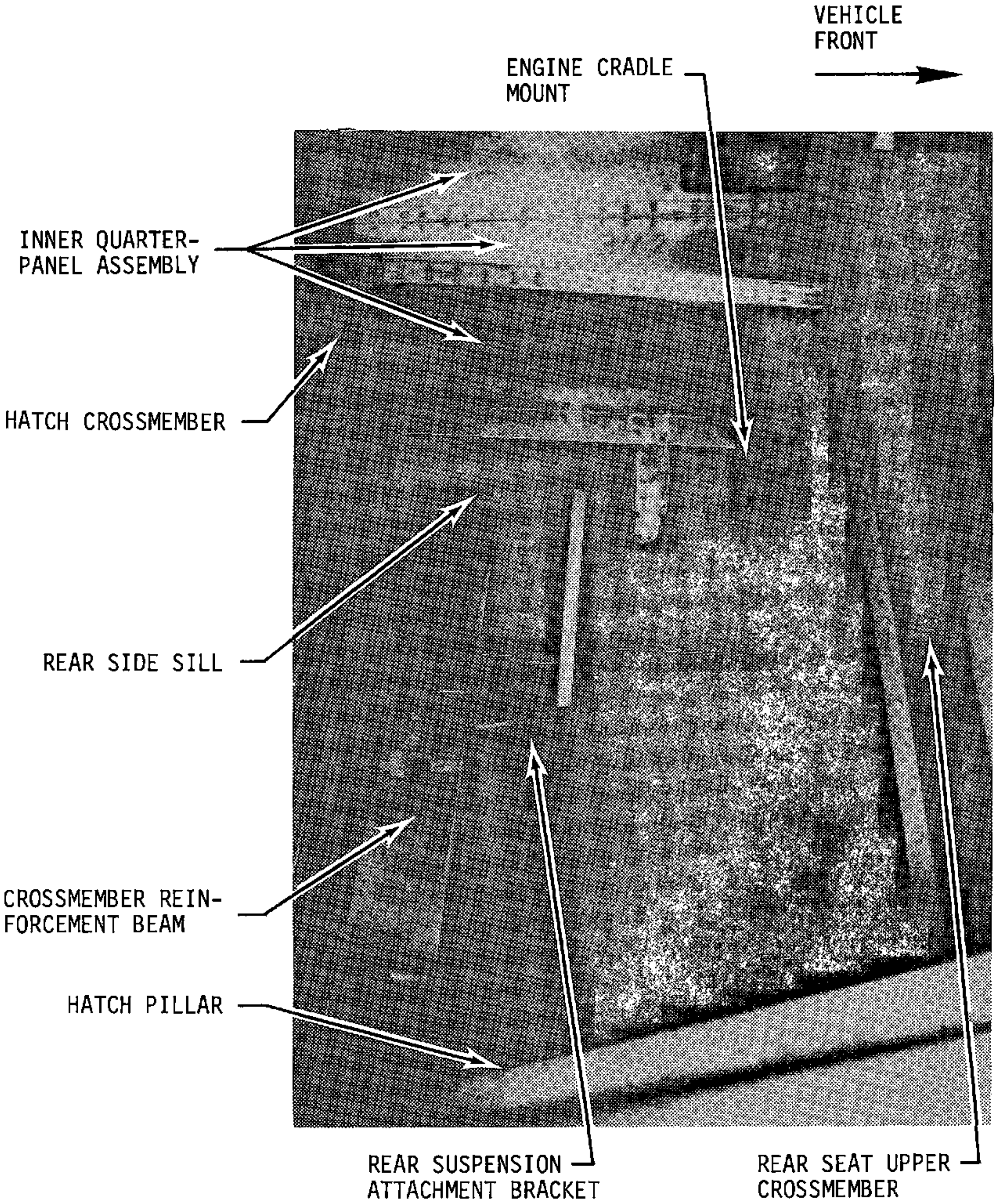

FIGURE 3-9. ENGINE COMPARTMENT

The Phase III design refinements included replacing the longitudinal roof elements with closed sections which have greater torsional rigidity, displacing the lateral hat sections in the roof to accommodate the relocation of the door hinges, improving the design of the head restraints and door support mechanism, and switching some parts from HSLA to SAE 1010-1018 mild steel. The last change was necessary because the HSLA parts retained high residual stresses after stamping, and warped when they were trimmed to their final dimensions.

Minicars conducted a finite element analysis of the modified structure. The upper body was modeled as 14 straight beam elements (six in each pillar and two longitudinal roof rails) in the General Electric timeshare program STRESS. The results indicated that the modified, mild steel structure would remain elastic under the crush loads defined in FMVSS 216, Roof Crush Resistance, and SAE J374a, Passenger Car Roof Crush Test Procedure (Reference 7).

Foam

During Phase II, Minicars and its subcontractor, the Monsanto Corporation, Dayton, Ohio, selected the body-in-white foam-filling on the basis of weight, reproducibility, flammability resistance, uniformity of cell structure and energy absorbency. We tried varying the density from section to section to control stiffness, but the higher density foams did not behave well in collisions. All body-in-white foam now has a density of 2 lb/ft^3 (32 kg/m^3). Table 3-1 shows the chemical mix.

The combustion of foam in an enclosed space is an important concern, since it produces two toxic gases: carbon monoxide and isocyanate. Flammability was tested by dousing foam-filled sheetmetal boxes with gasoline and setting them afire. The foam did not ignite – it only smoldered until the gasoline was consumed. In view of the foam's nonflammability, its lack of exposure to the atmosphere, and the RSV's well-protected, flexible fuel cell, we do not expect toxic gas release to be a significant post-crash problem.

TABLE 3-1. RIGID POLYURETHANE FOAM COMPOSITION

	Percent by Weight
Isocyanate (iso)-Papi-27	45.49
Pluracol 642	32.22
Fyrol 6 (flammability retardant)	5.69
Silicone oil	0.38
Dimethylethalol Amine (DME)	0.11
H_2O	0.19
Freon F-11B (blowing agent used to control density)	15.92

Producibility

As with any prototype, the RSV body-in-white could be substantially improved if it were thoroughly engineered for mass production. If mass produced (in quantities of 300,000 units per year), the more than 300 body-in-white parts, most of which are brake-formed, could be replaced with possibly half that number of stampings. The RSV's large sheetmetal boxes are amenable to die stamping in a fashion similar to conventional fuel tanks and plenums. Stamping, of course, is considerably cheaper in high volume production than fabricating smaller parts and welding them together. Stamping would also allow the incorporation of considerable contour into the sheetmetal topography, in order to both stiffen the structure and provide better component interfaces.

The structure of the RSV would undoubtedly benefit from more sophisticated computerized analysis. The advanced finite element techniques available for production engineering are extremely valuable tools for developing the greatest efficiency (strength to weight ratio) in a structure. We estimate that the body-in-white, which without foam weighs 539 pounds (867 kg), could be lightened considerably if fully production engineered.

A mass-produced RSV would probably be fabricated out of standard automotive low carbon steel, with HSLA steel used in critical areas. The structure's extensive use of thin gauge panels (typically, 22 gauge is now specified) requires more closely spaced and more reliable welds. This (together with the vehicle's unique construction) means that somewhat higher quality control costs must be expected.

The body-in-white will cost more to prime (due to the closed sheetmetal cells), but less to paint, than conventional automotive structures. The interior surfaces of foam-filled cells will have to be primed to prevent corrosion from residual moisture in the foam. However, the body-in-white only requires one coat of finish paint because it is covered by the body glove.

The rise time of the foam presently being used may be too long for some mass production approaches. In production a faster rising foam could be used, but that requires a special fixture to stabilize the structure (due to the internal pressures caused by the expanding foam). Although the foam is thought to take approximately 72 hours to fully cure, it will stabilize in less than 5 minutes, after which the vehicle could advance to other stations in the assembly line. In its producibility study (Reference 8), the Budd Company proposed a carousel (with a three car capacity) which could handle all foaming operations and still be integrated into a 120 second per cycle assembly line. This study indicates that the cost, in 1975 dollars, of the RSV's structure would be $183 (39 percent) higher than that of the Ford Pinto.

3.4 DOORS

The all aluminum structure of the gull-wing door is illustrated in Figure 3-6. The lower door provides the necessary crashworthiness, while the upper door attaches the lower door to the roof and provides mounting surfaces for the side glazing. Each door is secured to the roof with two stainless steel hinges and is counterbalanced with two gas struts.

Lower Door

The foam-filled lower door consists of a horizontal beam, a lower frame and three vertical beams between its inner and outer panels. The horizontal beam has only limited effectiveness in side impacts, since it is too high to engage most bumpers. However, it performs an important function in front and rear impacts, where it completes the wheelhouse/quarterpanel upper load path. The lower frame helps to stiffen the door and resist intrusion. It also contributes to the luggage compartment floor/side sill/rear sill load path. The vertical beams, added early in Phase III, provide inner door stiffening to carry the latch mechanism loads and also to help resist intrusion.

A crash pin on each end of the horizontal beam transmits tensile loads between the door and striker plates mounted on the A- and B-pillars. The pins and plates were added as a backup intrusion prevention mechanism. So far, there has been no indication of significant pin/plate loading in any of our tests, because the small amount of door bending produces very little end shortening of the horizontal beam. In any event, we are skeptical of tensile loading as a means of resisting intrusion - if door bending is sufficient to produce catenary action, the resulting forces may be much higher than the impact loading, resulting in a failure of the pins or the support structure.

The lower door design has performed very well in the RSV Phase II and III tests, and significant redesign to improve crashworthiness has been unnecessary. In the only Phase III side impact test (Test 1466), an Impala struck an RSV at 90 degrees. Both cars were traveling at 34.9 mph (56.2 km/h). The door effectively limited intrusion and protected the front seat passenger.

One penalty of this enhanced crashworthiness is a lack of space within the lower door for a glass run. Consequently, we have fixed the two upper windows, but have incorporated a thin horizontal sliding window just above the horizontal beam. The door could be redesigned for a limited roll-down capability, but full roll-down windows can only be included at substantial penalties in weight, crashworthiness, or roominess. In side impacts and rollovers, roll-down windows would also introduce the possibility of occupant ejection, which is precluded by the fixed laminated side glazing of the RSV.

For human factors reasons, during Phase III we removed the door latching and locking mechanism from the sill/B-pillar area and placed it inside the door to provide a more conventional arrangement. Structurally, however, it would be better not to have the mechanism inside the door, because it increases weight and complexity and interferes with the impact padding.

Upper Door

An early Phase III finite element analysis of the upper door structure did not accurately model the gas strut support brackets or adequately take into account the changes in cross-sections under stress. This was demonstrated when a test door deformed at the hinge attachments, strut attachments and upper pillars. We subsequently added a "ladder" frame between the inner and outer panels at the top of the door to better distribute loads and to increase stiffness under normal loading. However, static load tests indicated that the door still had only marginal structural strength, particularly in its pillars. To increase its strength, we artificially aged the entire aluminum door structure by heating it to 350^{o}F (177^{o}C) for 5 hours. The artificial aging hardens the 6009-T4 and 6010-T4 alloys to a T6 condition, significantly increasing their yield strength.

Other structural door changes included the addition of several gussets between the horizontal beam and the inner door panel, the redesign of the strut mounting brackets, and the substitution of larger diameter hinge pins.

Counterbalancing

Gas struts were selected to counterbalance the gull-wing doors because they are simple, relatively inexpensive, and have acceptable force-displacement characteristics. Each strut reaches a maximum axial load of approximately 450 pounds (2000 N) when the doors are fully closed. This force is sufficient to open a door past the second latch (about 10 degrees of arc) when the handle is released. Above that angle, the door is self-supporting at any location through 90 degrees of arc.

Electric and hydraulic actuators were not considered, because they were too expensive and produced apprehensions about their utility in emergencies. Torsion bars could provide acceptable torque-deflection characteristics, but conventional designs would be too long to fit into the RSV and too difficult to integrate with the RSV's roof curvature.

Fit

The fit between the doors and the body-in-white was a problem throughout the later stages of the RSV Program. Despite our attempts to standardize dimensions, each door ultimately had to be hand fitted (at substantial expense) during assembly. There were a number of reasons for the door fit difficulties:

- Hinge and Strut Placement. The hinges and gas struts are placed relatively close together, which tends to magnify any misalignment or dimensional variations. Moreover, the strut locations do not give them optimal leverage (thereby increasing the local stresses and strains).
- Body-in-White Tolerances. Presently, the body-in-white has over 300 parts, which makes it very difficult to hold close tolerances on the door openings.
- Stressing of Glazing. It was found that glass mounted in an unstressed door broke when the door was mounted on the RSV. To prevent further breakage, the doors were prestressed before the glazing was mounted.
- Welding. Some aluminum parts warped after they were welded, leading us to replace many welds with rivets.
- Tooling Accuracy. In some instances, the dies were inaccurate and required modification.
- Weight. The doors, as the rest of the car, steadily gained weight during Phase III. The addition of the latching/locking mechanism, vertical beams, and polyester body filler for surface finish all made substantial weight contributions. (Each door now weighs about 125 pounds, not including the body filler.) This weight increased the stresses and strains, which also affected the door fit.

In sum, we found that the effort required to production engineer crashworthy gull-wing doors is substantial. However, there is nothing inherent in gull-wing doors that precludes their use in a production car.

3.5 BUMPERS

The front and rear bumpers were fabricated by Bailey and Minicars, respectively. Each bumper consists of flexible, low density polyurethane foam and two "rubric" modules covered by a reaction-injection molded (RIM) urethane fascia. To reduce cost, the rear bumper fascia was fabricated from a sprayed urethane surrogate for RIM urethane. All of these components exhibit excellent resilience.

The rubrics are U-shaped elastic bodies which can manage exceptional amounts of energy for their weight. Each consists of an elastomeric core and two or three plies of woven polyester fabric. A rubric absorbs energy by compressing, buckling and bending with a force-deflection characteristic close to a square wave. Rubrics also have the ability to compress to 30 percent of their original length and then elastically rebound without permanent deformation.

Figure 3-10 shows the front bumper, which received a great deal of design effort. The first design using rubrics was very similar to this, except that there were no voids and the entire volume between the rubrics was filled with foam. The solid foam configuration was abandoned after Test 1230, a 50.2 mph (80.7 km/h) frontal barrier impact in which the foam's dynamic crush behavior caused a 32 G acceleration peak early in the crash pulse. This acceleration spike was attributed to the foam's hardening (concave upward) force-deflection characteristic. The two voids shown in Figure 3-10 were subsequently added. An excellent crash pulse (Figure 3-11) was obtained when the front bumper was later tested in an 8.0 mph (12.9 km/h) impact (Test 1376).

The design shown in Figure 3-10 was influenced by two other objectives set during Phase III. One was to pass the Part 581 no-damage standard for a 5 mph (8 km/h) pendulum impact. It was for this reason that we retained the thin foam center strip. This strip, together with the rubrics, provides sufficient force to elastically withstand a pendulum impact at any location along the bumper.

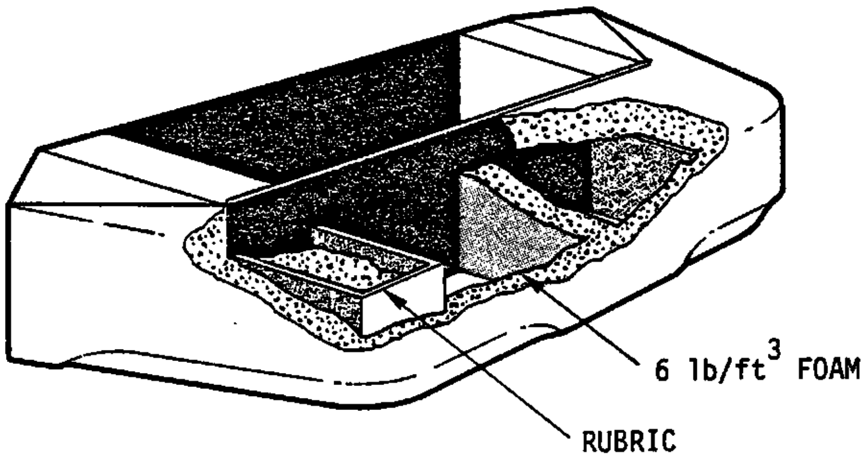

FIGURE 3-10. RSV FRONT BUMPER CONFIGURATION

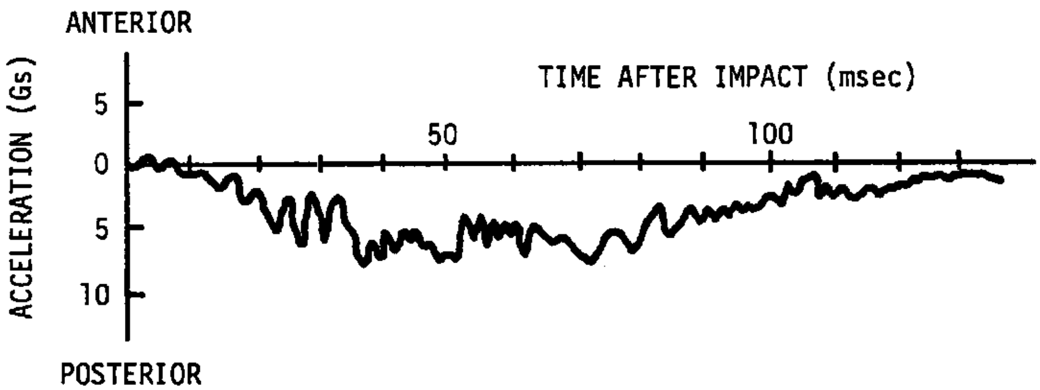

FIGURE 3-11. RSV FRONT COMPARTMENT LONGITUDINAL ACCELERATION DURING 8.0 MPH FRONTAL BARRIER IMPACT

The other objective was to achieve an acceptable level of pedestrian impact protection. The goal was to ensure that a dummy leg impacted by an RSV traveling at 25 mph (40 km/h) would undergo no more than a 70 G peak acceleration. To this end, we subcontracted a number of pedestrian impact tests to Battelle Laboratories in Columbus, Ohio. Battelle measured the displacement, velocity and acceleration of a 7 pound (3.2 kg) impact device driven into a bumper by an air-over hydraulic cylinder. In most cases the impactor struck the bumper 10 inches (25.4 cm) from its centerline at a speed of approximately 25 mph. The bumper configuration shown in Figure 3-10 was among the designs tested.

The results were discouraging. When the impactor struck the base RSV bumper at 24.6 mph (39.6 km/h), its maximum penetration was only 2.3 inches (5.8 cm) and it rebounded with a peak acceleration of 180 Gs, more than double our 70 G objective. The impact point was aligned with one of the voids, which meant that the impactor was striking a fascia with only 2 inches (5 cm) of foam behind it. When the impactor struck a rubric, the accelerations were even more severe.

It soon became apparent that both the foam and the rubrics were too stiff to provide adequate pedestrian leg protection. Further testing (described in Subsection 7.3) indicated that the fascia, by itself, could provide much lower acceleration levels.

We tested for damagability at 8.9 mph (Test 1244) and observed a minor permanent set in the rubrics. The foam shape was subsequently changed to accommodate rubric deformation. This modification proved to be successful at 8.0 mph (Test 1376) and 8.3 mph (13.4 km/h). In the latter test the dynamic deformation was almost 6 inches (15 cm), but the only permanent damage to the RSV was minor scuffing on the fascia.

The rear bumper also contains two rubrics. Its design is somewhat different from the front bumper; the flexible urethane foam is actually molded inside the rear fascia. The rear bumper foam has a density of only 2 lb/ft^3 (32 kg/m^3) versus 6 lb/ft^3 (96 kg/m^3) for the front bumper and contains no voids. We have not tested the bumper's damagability performance, but expect it to remain elastic at crash severities even beyond 5 mph (8 km/h).

3.6 SUSPENSION ATTACHMENTS

Failures during the durability and ride and handling tests led to several changes in the suspension attachments. The forward rear suspension bracket distorted and cracked during the Bendix braking tests and the Phase IV J-turn tests at Japan Automobile Research Institute, Inc., Tsukuba, Japan. After the tests a more rigorous finite element analysis of the bracket was conducted; this analysis accurately predicted the failures and enabled us to design a new bracket that would operate in the elastic regime. We also added a doubler to the body-in-white for better load distribution.

A more rigorous analysis of the front suspension attachments was also conducted. As a result, we modified the rearward bracket for better integration into the body-in-white.

No further failures were observed during the more recent braking and handling tests, including J-turn maneuvers, at Minicars' Santa Maria test track.

SECTION 4
OCCUPANT PACKAGING

4.1 SECTION ORGANIZATION

This section of the report describes the RSV occupant packaging system as it now exists and defines its performance in the various crash and sled tests conducted during Phase III. The section is organized into five major subdivisions: Subsection 4.2 presents a brief review of the status of the RSV occupant packaging system, as of the completion of Phase II; Subsection 4.3 states the objectives of the Phase III efforts; Subsections 4.4 and 4.5 describe the current driver and passenger restraint systems, respectively; and Subsection 4.6 discusses the features of the interior for side impact, rear impact and rollover protection. Specific test results are presented and, when appropriate, analyzed in Subsections 4.4, 4.5 and 4.6. Finally, the performance limits (as indicated by Phase II and Phase III crash tests) are described in Subsection 4.7.

4.2 PHASE II OCCUPANT PACKAGING SYSTEM – OVERVIEW*

During Phase I of the RSV Program Minicars performed an analysis to determine what safety features the RSV should have – i.e., what features would produce the highest safety payoff. The results of that analysis strongly indicated that front seat occupants should be provided with advanced technology air cushion systems for high-speed (50 mph delta-V) front impact protection. Front seat passive protection in lateral, rear and rollover accidents was to be provided via interior padding, energy-absorbing glazing and seat design. The analysis also indicated that only lap belts would be justified (again, in terms of overall safety payoff) for rear seat occupants. However, it was decided that a research safety vehicle should possess superior protection for these seat positions as well. Hence, active force-limited three-point belts were selected for the rear seats.

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*For a detailed account of the Phase II RSV occupant packaging system, see Reference 4.

4.2.1 Phase II Driver Restraint System

The Phase II driver air cushion system was a refinement of an earlier system developed by Minicars for 50 mph front impact protection in a structurally modified Pinto (Reference 8). The RSV system was composed of a hub-mounted air cushion module, a shallow-angle stroking steering column and a mechanical (foam) knee restraint. In the air cushion module a production-type solid propellant inflator supplied gas to a dual airbag (Figure 4-1). This module was adapted to fit in the enter of a GM ACRS* steering wheel. The dual bag system was necessitated by the requirement to rapidly couple the driver torso to the occupant compartment for optimum ridedown. The inflation of the relatively small (1.0 ft^3) inner bag produced torso decelerations early in the crash event; the later inflation (via vented inner bag gas) of the larger (2.7 ft^3) outer bag provided head restraint.

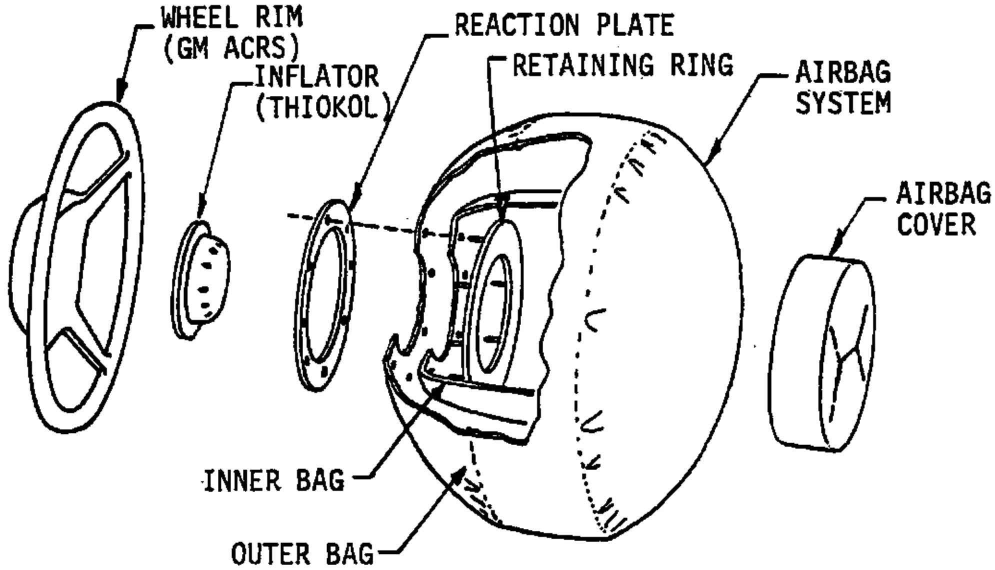


FIGURE 4-1. PHASE II DRIVER AIRBAG MODULE

*The term "GM ACRS" refers to the pair of restraint systems, driver and front passenger, developed and produced by General Motors as optional equipment on certain models of GM vehicles during the 1974 through 1976 model years.

The steering column assembly was designed to absorb a significant portion of the driver's upper body kinetic energy in a high-speed front impact. Oriented at a relatively shallow angle (7 to 8 degrees), the Phase II column (Figure 4-2) absorbed energy by telescoping against the forces provided by a rollerless tape mechanism and by friction at internal reaction points. Although significantly refined over the earlier "Pinto" column, the Phase II RSV column had production drawbacks and was more friction-dependent than desired. (Friction accounted for about 40 percent of the total estimated stroking force.) Nevertheless, it performed its function reasonably well in the Phase II testing.

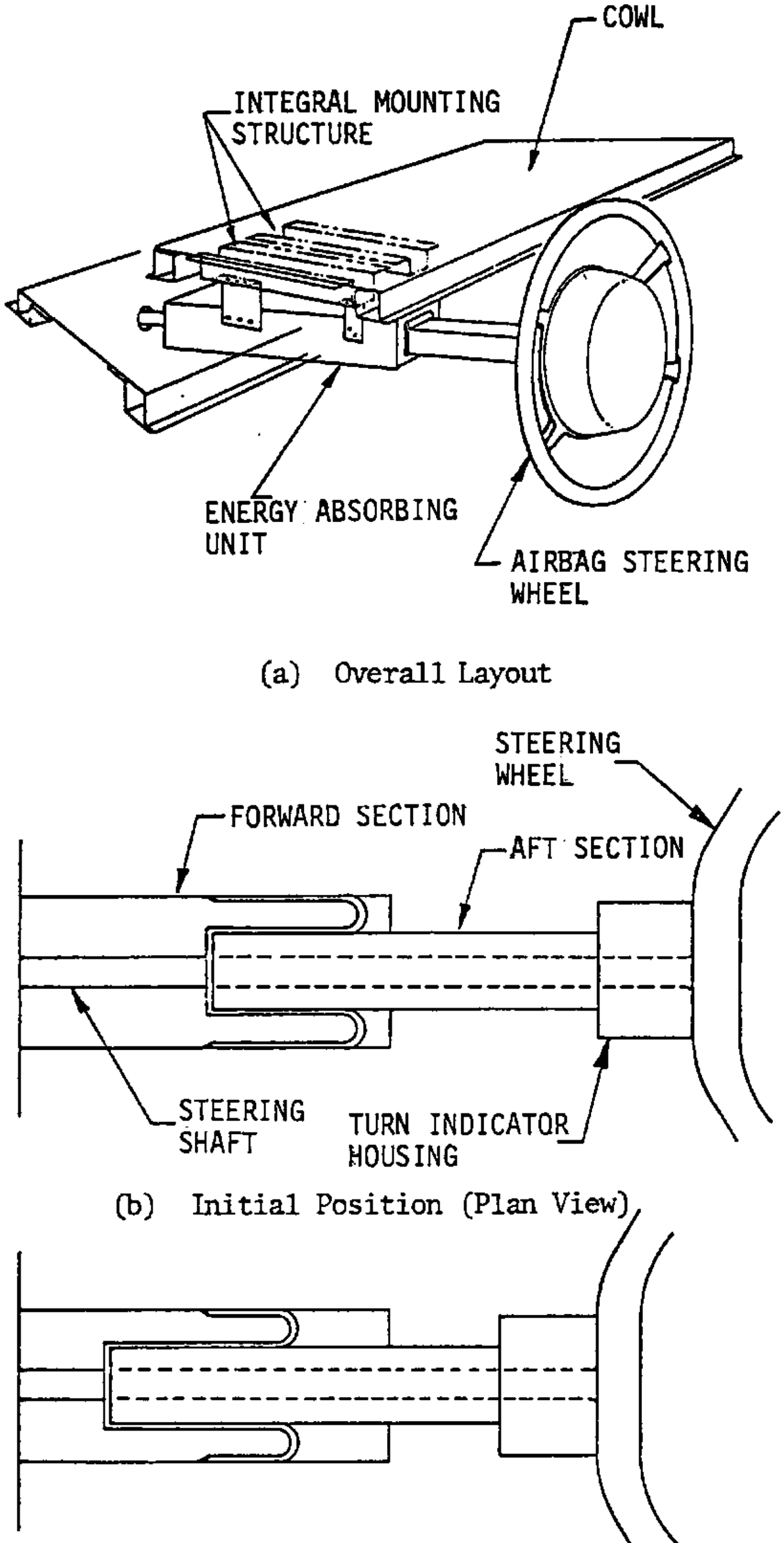
A mechanical knee restraint provided lower body kinetic energy absorption and trajectory control. The restraint was comprised of a shaped billet of rigid DB styrofoam* which reacted against a sheet steel back-up plate. The plate spanned from the aft portion of the cowl forward to the lower firewall. The foam billet had a flex-foam backed cover for protection in normal use.

4.2.2 Phase II Passenger Restraint System

The Phase II passenger restraint system (Figure 4-3) was similar to the driver system. The passenger restraint was a so-called "high-mount" system - one in which the air cushion is used for upper body restraint and a mechanical knee restraint (crushable lower dash) is used for both lower body energy absorption and trajectory control. The most significant features of the system were:

- A pyrotechnically-inflated dual-chambered bag. In order to enhance vehicle ridedown while minimizing deployment energy, the airbag was chambered to form a lower torso bag and an upper head bag. Similar to the driver system, the inflator provided gas only to the torso bag, the head bag being inflated later (and to a lesser pressure) by gas vented from the torso bag.

*Registered trademark of Dow Chemical Company.



(a) Overall Layout

(b) Initial Position (Plan View)

(c) Stroked Column (Plan View)

FIGURE 4-2. PHASE II STEERING COLUMN SYSTEM

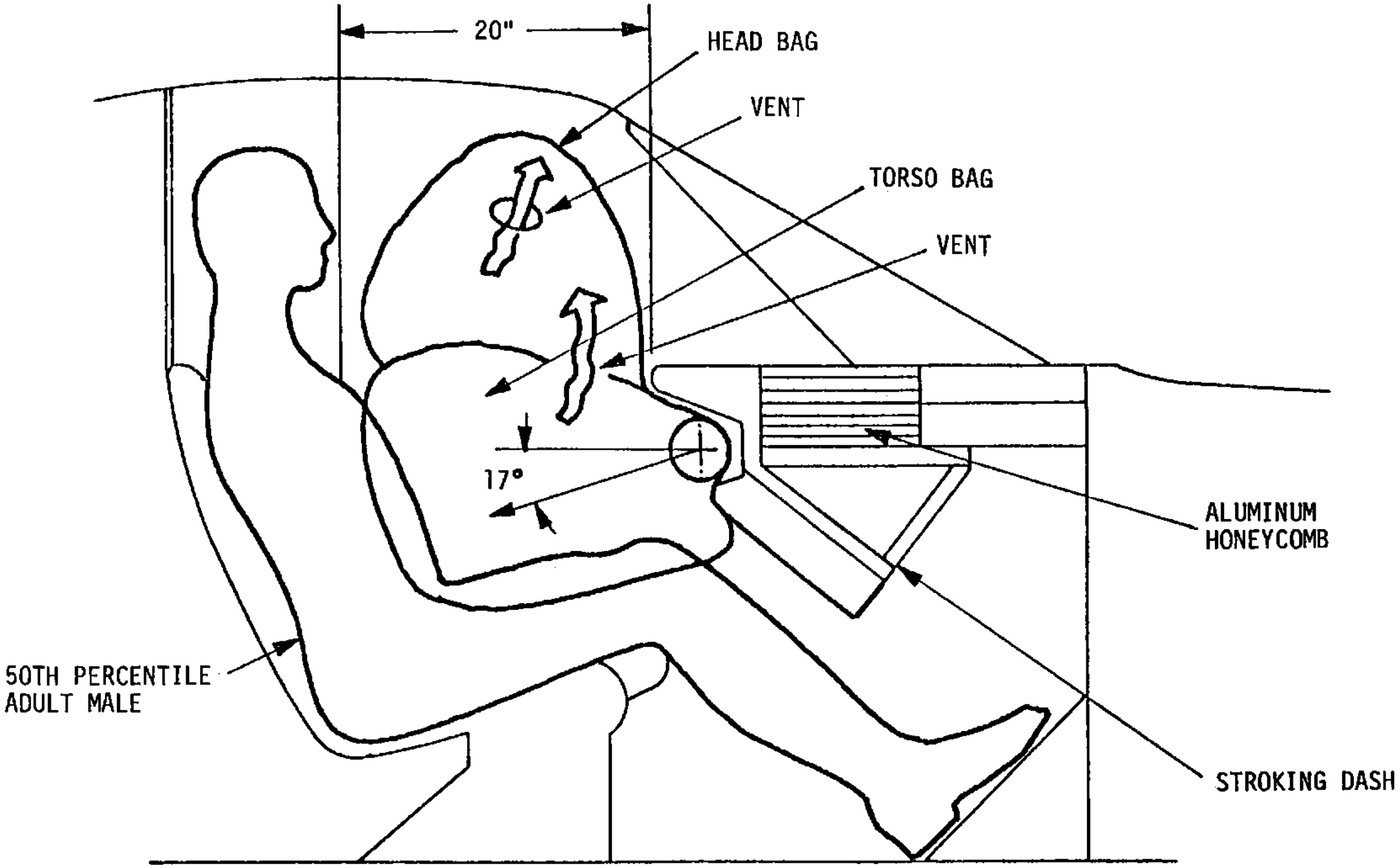


FIGURE 4-3. PHASE II PASSENGER RESTRAINT

- A stroking dash. The reaction surface for the airbag and knee cushion was a portion of the right side dashboard that was designed to stroke forward and absorb energy through approximately a 6 inch displacement. The stroking dash, therefore, was designed for the same, force-limiting function as was the steering column in the driver system.

4.2.3 Phase II Passive Restraint Sensing System

Figure 4-4 shows the sensor system used in Phase II to initiate the deployment of the front seat air cushion systems. The system contained three sensor packages – two bumper-mounted and one cowl-mounted – wired in parallel so that the activation of any one of the sensors would initiate deployment of both the driver and passenger systems. The switches used in Phase II were all off-the-shelf units produced by GM for their 1974 through 1976 ACRS vehicles. The bumper sensors achieved sensing times of around 9 msec during high-speed barrier impact testing. The cowl sensor was more sensitive (as a predictive* sensor has to be) but triggered the airbags in only one Phase II test (one in which a moving RSV was struck perpendicularly in the side by another vehicle). The deployment of the airbags was judged to have a negligible effect on the (successful) outcome of that test.

4.2.4 Phase II Side Impact Protection

The primary side impact protection was provided by the safety features of the RSV side doors. The design of these doors controlled the door accelerations (a primary threat to the near side occupants of vehicles struck in the passenger compartment), controlled the occupant accelerating forces produced by the door interior, and controlled occupant ejection (through door latch and side glazing design).

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*The term "predictive" refers to the fact that a sensor located remote from the crash zone must trigger before its base impulse is complete. This differs from a "reactive" sensor (located in the crush zone) which can respond to the crash delta-V.

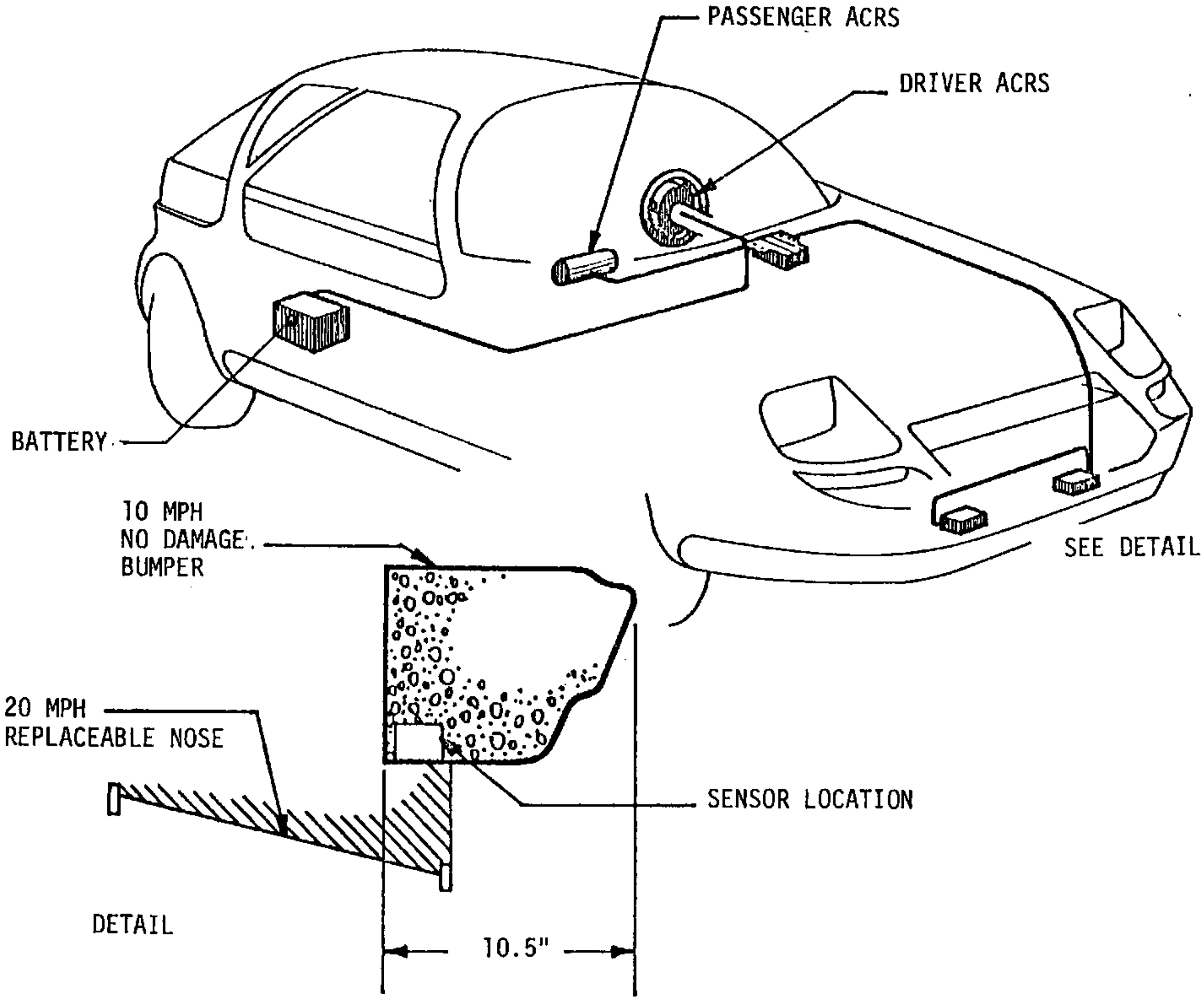


FIGURE 4-4. PHASE II SENSOR SYSTEM

Figure 4-5 illustrates the contouring and construction of the RSV Phase II door interior padding. As shown in this figure, shoulder and hip targets of rigid foam were intended. The Phase II efforts, however, did not successfully identify the desired foams; we had to conduct testing with a cored styrofoam shoulder target and an impregnated paper honeycomb hip target. But even with these surrogates the test results were excellent.

For the fixed side windows, we chose a Sierracin glazing that had successfully limited head accelerations in our impact tests. Figure 4-6 illustrates the construction of this glazing and its intended method of securement to the door window opening. For emergency egress we developed a spring clip and wire retention scheme in which a pull on a finger ring would remove the Number 9 wire (shown in the figure), thereby allowing the glazing to be removed.

4.2.5 Rear Impact Protection

The seat back is the critical factor in rear impact protection. The RSV Phase II front seat was a so-called "semi-suspended" seat – in which the seat back and integral head restraint were suspended from the roof. The RSV Phase II head restraints were Mylar laminate with a PVB interlayer; they were designed to be mounted to the roof via a transverse curved steel tube. Unfortunately, the time and funding limitations were such that the Phase II testing only confirmed that, if the seat-to-roof link could be maintained, excellent rear impact protection would result for the front seat occupants.

4.3 PHASE III OBJECTIVES/ACHIEVEMENTS

The Phase II effort to develop an RSV occupant packaging system that would meet or exceed the goals established in Phase I were, by any reasonable measure, highly successful. Nevertheless, it was felt by both Minicars and the NHTSA that it would be desirable to bring the system closer to a production engineered design and, therefore, to enhance the value of the RSV as a demonstrator not only of feasibility but also of practicality and cost effectiveness. We therefore established a number of goals for refining the occupant packaging system. These

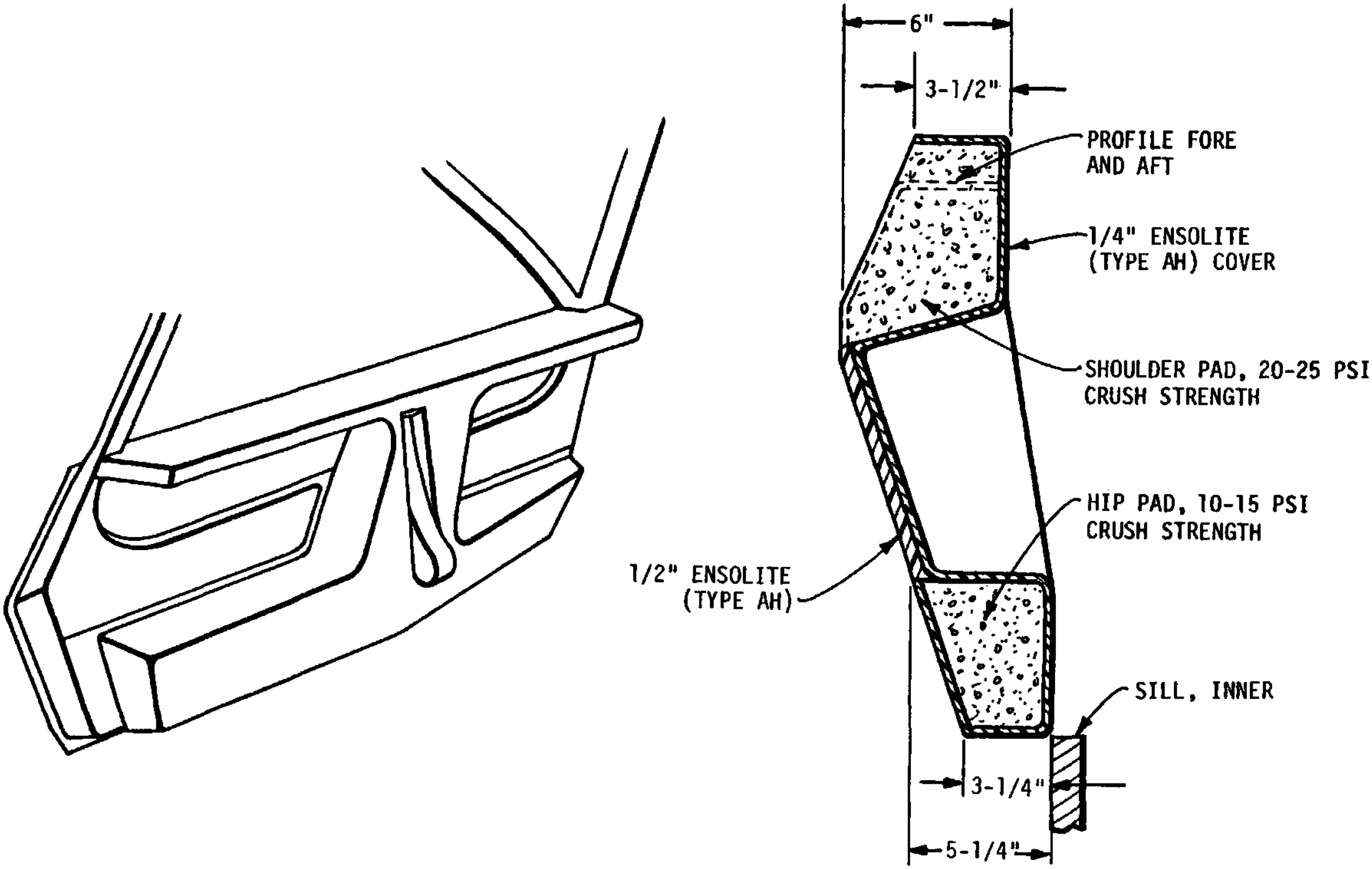


FIGURE 4-5. PHASE II DOOR INTERIOR PADDING

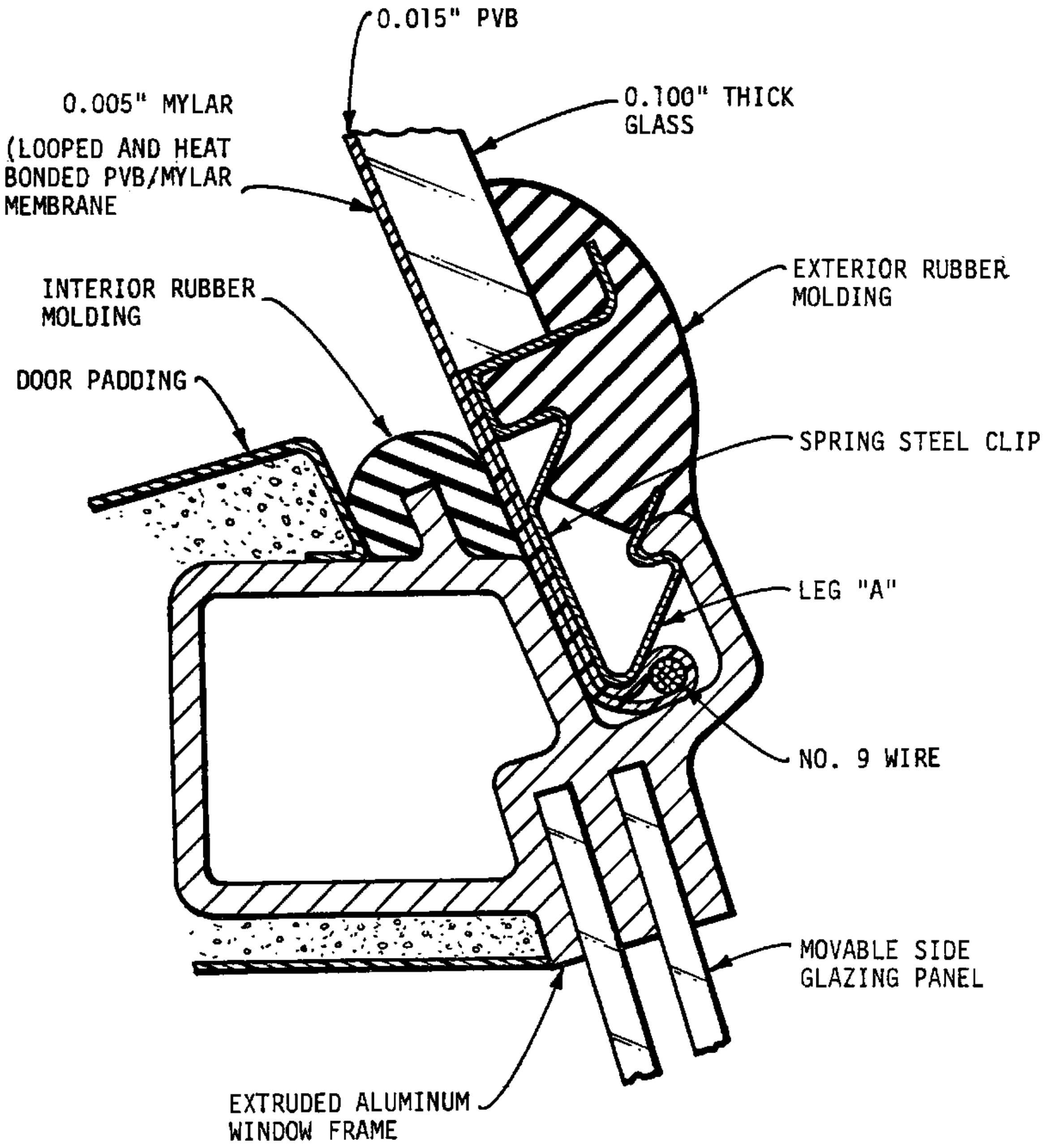


FIGURE 4-6. PHASE II SIDE GLAZING – CROSS-SECTION OF LOWER ATTACHMENT AREA

were goals for the Phase III program – preferably to be accomplished before the production of vehicles for evaluation. Table 4-1 lists, for each of the areas discussed above, features of the RSV occupant packaging system that were significantly advanced during Phase IIIa.

4.4 PHASE III DRIVER RESTRAINT SYSTEM

Subsection 4.4.1 will focus primarily on those items that have been significantly changed or refined since the Phase II Final Report. Subsection 4.4.2 will present the Phase III results that serve to define the performance characteristics of the system.

4.4.1 Driver System Description

The driver air cushion system (Figure 4-7) is made up of a wheel module, steering column assembly, knee restraint, seat, and sensor/diagnostic system.

Wheel Module

The RSV wheel module is composed of a bag assembly, reaction plate assembly, inflator, cover assembly, and steering wheel.

The function of the wheel module assembly is to provide a cushion for the restraint of the driver's upper body – that is, to rapidly link the driver with the steering column assembly. In that way, the driver's crash energy can be effectively absorbed through bag penetration, steering column stroke and vehicle forestructure crush (ridedown). Because the RSV must provide occupant protection in very severe front impacts, it is imperative that the link-up be accomplished quickly and that the bag be an extremely efficient absorber of occupant crash energy. The dual bag system described in Section 4.2, when deployed by an uploaded driver pyrotechnic inflator, accomplishes these goals.

TABLE 4-1. RSV OCCUPANT PACKAGING FEATURES SIGNIFICANTLY UPGRADED DURING PHASE III

Item	Nature of Improvements
Driver Restraint System	
Steering column design	Made more producible; made performance more consistent
Air cushion module	Made bag cover design more producible
Steering linkage	Made more crashworthy; improved steering characteristics; made more producible
Knee restraint subsystem	Improved integration into driver station dashboard layout
Passenger Restraint System	
Air cushion module	Simplified and productionized design of attachment bracketry (eliminated stroking dash); developed production-oriented bag cover
Knee restraint subsystem	Converted to a fixed mechanical system; integrated into the lower dash layout
Sensor System	
Bumper sensors	Improved characteristics at threshold level
Secondary (back-up) sensor	Improved response characteristics
Diagnostic circuitry	Designed and developed system tailored to RSV needs
Side Impact and Rollover Protection	
Side door padding	Made more producible
Side glazing/retention	Improved practicality via switch to windshield-type configuration; improved practicality and producibility via redefinition of emergency egress path
Rear Impact Protection	
Front seats	Made more producible; improved performance in rear impacts
Head restraints	Refined design; improved performance in rear impacts

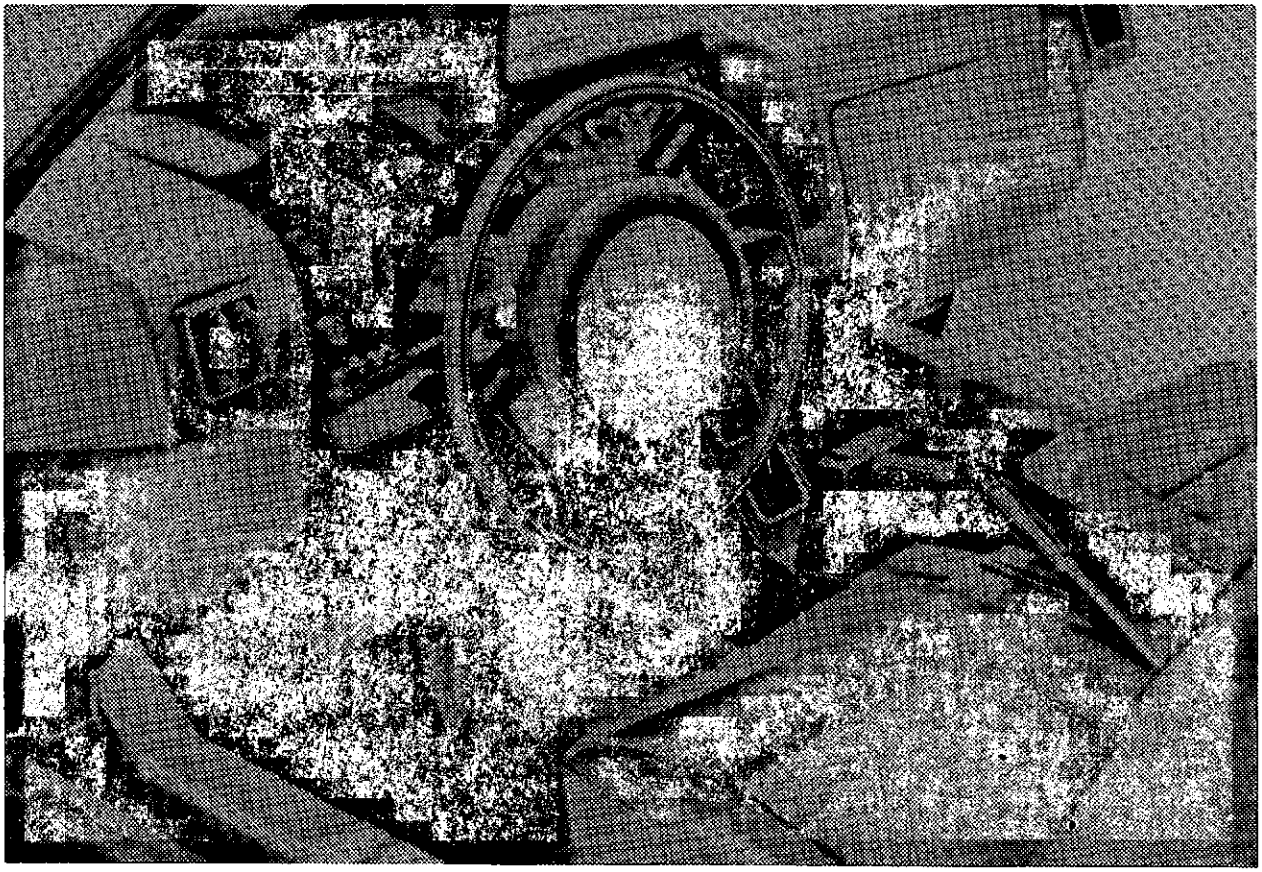


FIGURE 4-7. DRIVER AIR CUSHION RESTRAINT SYSTEM
(IN THE HIGH TECHNOLOGY RSV)

The dual airbag, pyrotechnic inflator, reaction plate and (GM ACRS) steering wheel were not changed during Phase III. We did, however, refine the cover assembly. The RSV Phase II bag cover was to be a vacuum-formed low-density polyethylene container with a pre-slit tear pattern in its outer face; this pattern was to be covered with a decorative tape. Unfortunately, we later found this configuration to have producibility problems; it therefore was redesigned during Phase III.

Figure 4-8 shows the cover configuration (not including the decorative center piece) finalized in Phase III. In this design a Kydex outer shell gives the wheel hub a firm shape. In the center of the hub the Kydex has been stamped out to expose the pre-slit polyethylene inner cover. A circular-patterned decorative pad, secured around its perimeter by adhesive and the clamping action of the Kydex lip, aesthetically covers the polyethylene inner cover. Notches in the Kydex outer shell ensure a "petalling" action during deployment. Sled tests and crash tests conducted during Phase III established that the opening of the cover during deployment is repeatable and has no apparent adverse effects, whether on the airbag or on the driver.

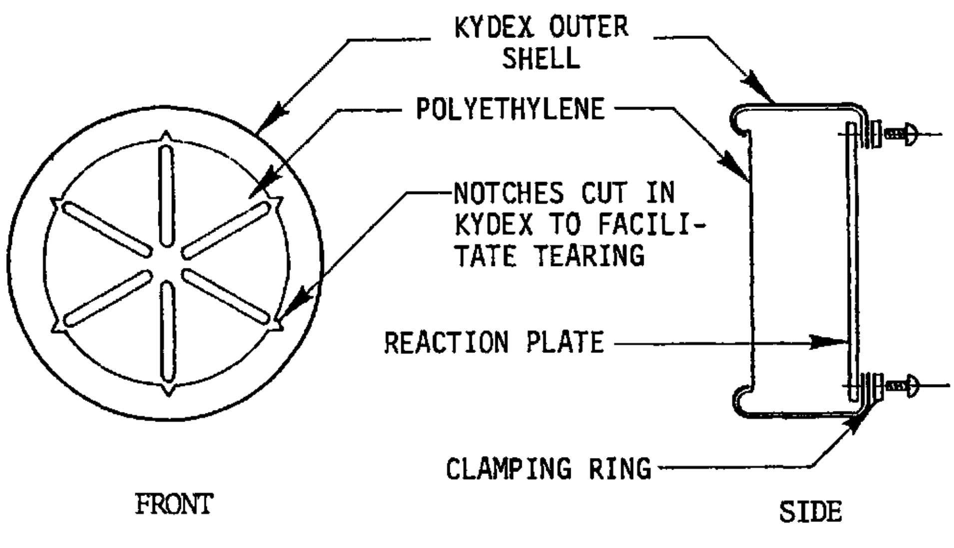


FIGURE 4-8. AIRBAG COVER CONFIGURATION

Steering Column Assembly

The RSV steering column assembly has two vital restraint functions: to correctly orient the application of torso restraint loads, and to serve as a principal absorber of the driver's upper body crash energy. To provide these functions, the steering column assembly has been designed to telescope a maximum of 5-7/8 inches (15 cm) and to remain stable in front impacts - where it is subjected to non-axial restraint forces (principally upward loads at the wheel rim). "Stability" has a dual meaning in this context, referring both to the maintenance of the correct column orientation during the event and to the control of the column collapse force in the presence of non-axial forces.

During Phase III the steering column assembly was completely redesigned to improve both its producibility and the uniformity of its collapse force. Figure 4-9 shows a cross-section of the final RSV steering column. Externally the column is very similar to a GM ball-jacket telescoping column. In fact, the aft external telescoping tube (the "column mast") is a GM part. (It is being manufactured for the next generation of GM air cushion vehicles.)

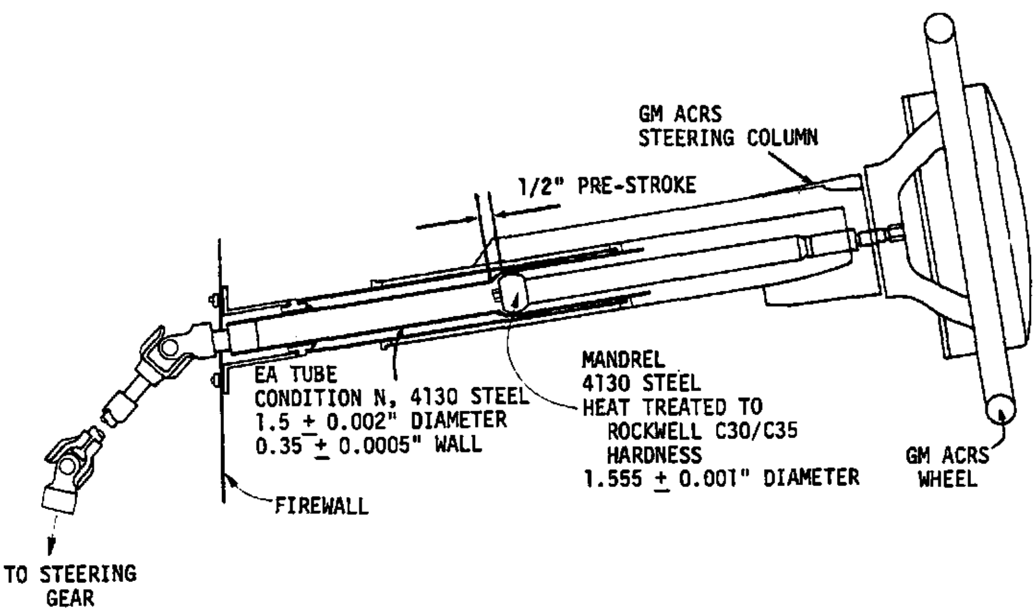


FIGURE 4-9. COLUMN STROKING MECHANISM

The use of GM's column mast greatly facilitated the "productionizing" of the RSV column, as the mast contains a number of items (especially the turn signal hardware and the air cushion slip ring assembly) that would be difficult and costly to design and manufacture in a program of this scope. However, a drawback of the GM air cushion mast is the relatively weak moment-carrying capacity of the junction between the turn signal housing and the mast itself. In the RSV this junction must be much stronger than it is in the GM vehicles - otherwise the air cushion loads on the steering wheel will cause the housing and wheel to rotate upward during front impacts (thereby misorienting the air cushion).

In Phase III this drawback was overcome by modifications that established a strong load path from the upper surface of the column mast to the upper junction of the plastic turn-signal housing and the steering wheel. This load path (Figure 4-10) consists of a channel section welded to the top of the mast and a curved sheetmetal sheath welded to the channel section. The metal sheath spans the plastic turn signal housing. The aft edge of this sheath engages a lip in a special wheel support disk which is placed between the wheel and the housing.

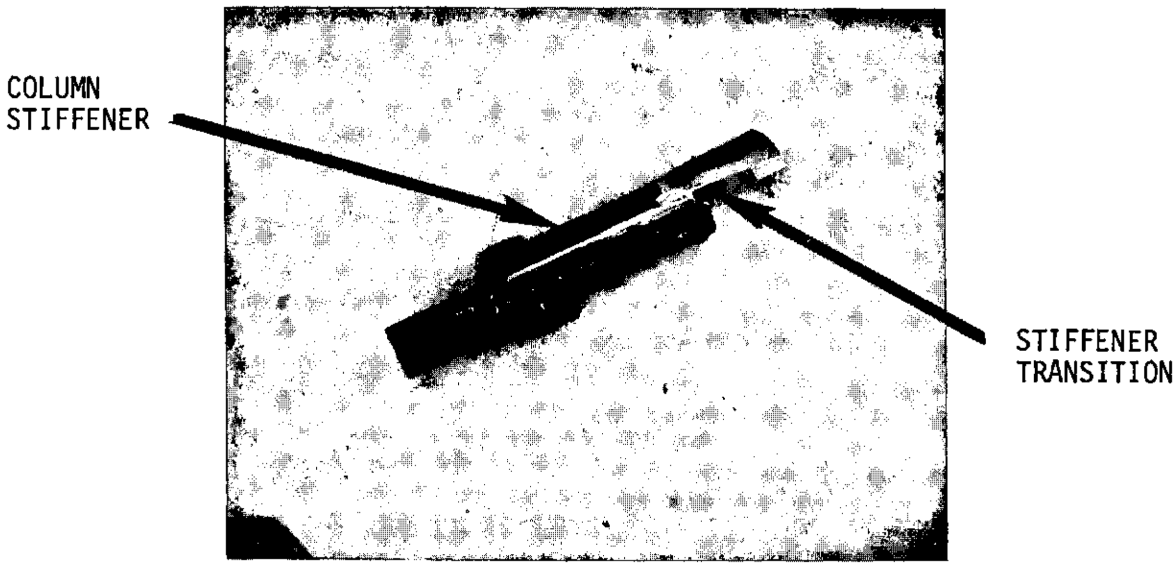


FIGURE 4-10. STIFFENER TRANSITION AND COLUMN STIFFENER ASSEMBLY

A mounting plate at the front of the external (telescoping) tube of the outer column distributes column loads into the firewall. Both external and internal Delrin bushings are used between the telescoping members to make the column stable.

Internally, the steering shaft assembly runs coaxially from the steering wheel forward to the steering linkage in front of the firewall. The shaft assembly is designed both to transmit steering torque and to absorb energy. The latter is accomplished by a tube and mandrel system. A spherical mandrel end is attached to the male (aft) section of the two-part telescoping steering shaft. This mandrel is of slightly larger diameter than is the thin-walled 4130 seamless steel tube that serves as the female (forward) section of the steering shaft assembly. As the column telescopes, the mandrel expands the tube, producing a constant force of about 500 to 600 pounds (225 to 275 kg) over an initial stroke of 1/2 inch; after that the force rapidly increases to a second plateau of 3100 pounds (1406 kg). The low initial force allows the column to leave the shear capsule brackets (which secure the mast to the vehicle cowl). The low force portion of the stroke is produced in assembly by inserting the mandrel the same 1/2 inch beyond its final assembly position and then withdrawing it to its correct position. A key-and-ring mechanism allows the positive rotational locking of the two steering shaft sections, so that steering torques can be safely transmitted.

Column uploads are transmitted to the strong RSV cowl through the stock mounting bracket on the column mast. This "winged-U" shaped bracket (which must be welded to the mast to prevent its detachment during severe uploads) is secured to the cowl via conventional shear capsules. In addition to the necessary pair of mounting studs, the cowl bracket also has a pair of Delrin skids or runners on which the "wings" of the mast bracket bear as the column strokes. This arrangement minimizes the frictional components of the axial collapse force, but allows a slight increase (rather than a decrease) in collapse force during stroking (for a constant upload on the steering wheel). It was found in Phase III that this design significantly improves the repeatability of the stroking behavior.

Knee Restraint

The knee restraint has two primary functions: to ensure that femur axial loads stay well below the FMVSS 208 criterion of 2250 pounds per femur, and to act together with the upper body restraint system to produce a controlled submarine trajectory. The requirements of providing protection in severe front impacts dictate a knee restraint system capable of controlling lower body forces through knee strokes of up to 7 to 8 inches (18 to 20 cm). In the RSV this is accomplished by installing a 10 inch (25 cm) thick billet of extruded multicellular polystyrene foam behind the upholstered ABS dash.

It was determined during Phase III testing that the polystyrene billets were susceptible to splitting, and thus required lateral support surfaces. We subsequently found that the outboard surface could be provided by the ABS dash structure and the inboard surface by a combination of the heater assembly and a reaction plate.

The emergence of the ABS dashboard during Phase III presented a problem: how to allow the knees to penetrate the ABS dash (and proceed forward through the foam) without femur load spikes. This problem was resolved by molding the lower dash on either side of the column with a raised "breakaway pattern." (The breakaway pattern is an arrangement of holes in the ABS; this pattern is designed to encourage knee penetration at a specific area – where maximum stroking is obtained.) Sled and crash tests conducted during Phase III indicated that the final configuration performs exactly as intended.

Driver's Seat

The seat is an important element in the front impact protection system. It must properly locate the driver with respect to the restraint system, control superior/inferior forces on the driver as he or she translates forward, and absorb rebound energy (through seat back deflection). In addition, it must remain in place throughout the impact – otherwise it could either compress the driver during the crash or prevent subsequent egress from the vehicle.

Considerable attention was given to the seat design during Phase III. The resulting seat is a modified 1971-1976 Dodge van seat which uses Volvo seat tracks for fore and aft adjustment. The modifications were a narrowing of the seat width, reduction of the angle between the seat back and pan, reinforcement of the seat back with sheet steel to prevent the rear passenger's knees from striking the driver, modification of the Volvo seat tracks to limit seat translation (via stops) during front and rear impacts, addition of an energy-absorbing head restraint connecting the upper seat back to the roof, and modification of the front transverse seat frame member to control crash-induced accelerations along the occupant's spine. The final seat is shown in Figure 4-11. Sled and crash tests have demonstrated that this seat not only is extraordinarily crashworthy, but also correctly and comfortably positions drivers ranging from 5th percentile females to 95th percentile males.

Sensor System

The primary function of the sensor system is to initiate the inflation of the restraints. Importantly, the sensor system is also designed to provide a diagnostic circuit both to monitor the condition of the air cushion electronics and to signal the driver if the system has been misassembled or damaged. During Phase III we improved the sensor system and developed a special RSV diagnostic circuit.

The first improvement to the sensor system was the replacement of the GM ACRS sensors (the GM Bumper Impact Detectors) used in Phase II with units whose characteristics are more appropriate to the RSV. The replacement Technar "Curve 3" sensors are based on the Rolamite principle, the term "Curve 3" referring to the specific unit's response characteristics. These units respond in about the same time (approximately 8 to 9 msecs at 50 mph) as do the GM Bumper Impact Detectors; the principal difference is that the Technar sensors are also able to achieve the desired 11 to 15 mph (18 to 24 km/h) barrier threshold velocity for bag deployment.

The second refinement of the bumper sensors was the rerouting of their circuits to minimize the possibility of circuit disruption prior to deployment. Car-to-

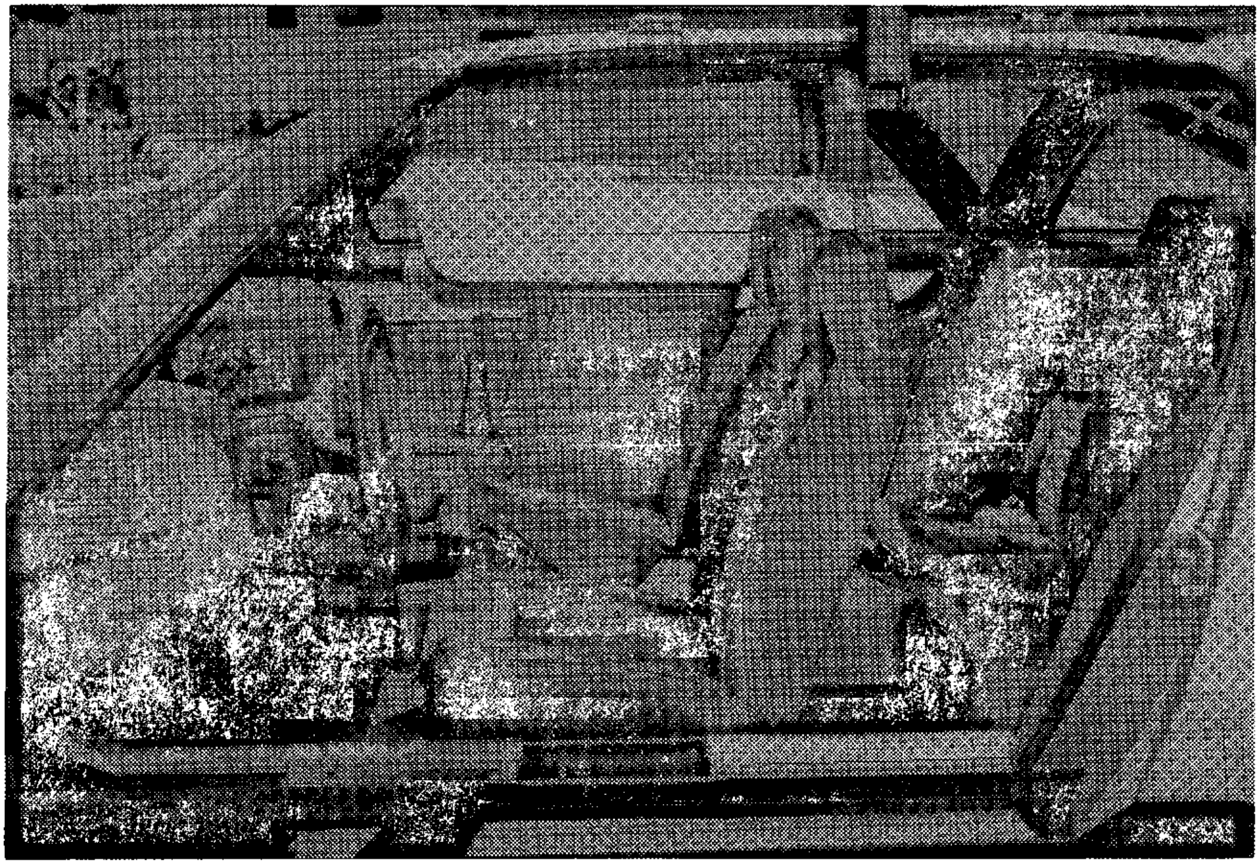


FIGURE 4-11. RSV SEATING

car crash testing conducted in Phase III indicated that in some kinds of crashes these lines could be cut before the airbags were deployed. Figure 4-12 shows the new position of one of the two bumper sensors. When the wiring harness is routed to this location, a "service loop" is installed at the sensor to provide wiring slack.

The cowl sensor used in Phase II was replaced by a third Curve 3 Technar sensor in the driver-side wheel well. We eliminated the GM cowl sensor because of the uncertainty of its future availability, the complexity it required of the diagnostic circuit, and its extreme sensitivity. The third sensor is now located at the top of the left spring tower (Figure 3-4) and is intended for frontal oblique impacts which do not directly involve the bumper structure. Accident statistics indicate that in such crashes the predominance of societal loss is associated with impacts on the driver's side of the vehicle – hence the location of the sensor in the left wheel well.

Diagnostic Circuit

The diagnostic circuit is designed to comply with both FMVSS 208 and the specific RSV requirements. Both sets of specifications stipulate that there be a visible and audible warning should the restraint system become inoperative; the RSV specifications also require that the warning be sounded if the brake system does not perform properly. The circuit used in the RSV

1. Has indicators that the system is operative. When the ignition is turned on, the passive restraint system warning light and buzzer signal for approximately 7 seconds, then turn off if the system's operation is satisfactory. If they do not work, there is a failure in the diagnostic system.
2. Does not have a backup power supply (charged capacitor). Since the RSV's battery is located under the rear seat, the probability of damage occurring to the battery in the crash is very small and a backup was deemed unnecessary.

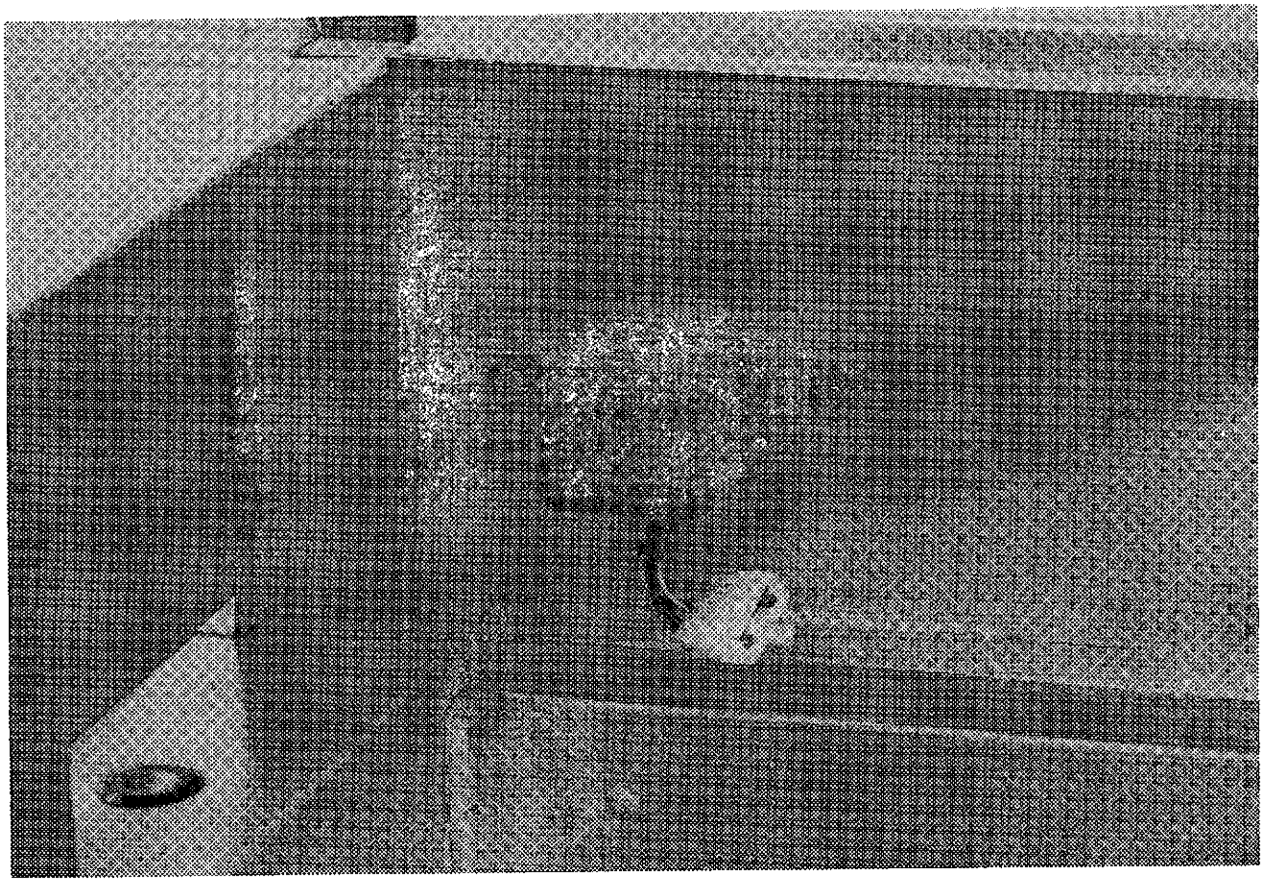


FIGURE 4-12. BUMPER SENSOR MOUNTED ON THE REPLACEABLE NOSE

3. Does not diagnose a shorted squib. Such diagnosis would not be practical, because the squibs have very low resistance (compared to the resistance of the rest of the circuit).

Figure 4-13 is a simplified schematic of the passive restraint system. The voltage at the junction of the "B" switches and the parallel squibs is fed into two comparator circuits. One comparator has a "high" (and the other a "low") reference applied potential. Almost any fault in the passive restraint circuit will cause one of the comparator circuits to trigger, and this output will operate both the warning light and the alarm buzzer through a solid-state power amplifier. The circuit will detect open or shorted resistors, shorted switches, open or shorted wiring, etc.

4.4.2 Driver Restraint Performance in Sled Tests

Sled tests 1326, 1329, 1332 and 1333 show the performance of the finalized RSV driver restraint system for 5th percentile females and 50th and 95th percentile males. Table 4-2 summarizes the sled test results; they show that the system is capable of protecting 50th percentile male drivers to speeds above 50 mph (80 km/h) delta-V and 5th percentile female and 95th percentile male drivers to approximately 45 mph (72 km/h) delta-V.

Three of the six Phase III crash tests are considered to be representative of the RSV's driver protection capabilities. These three tests are discussed in Section 4.7.

4.5 PHASE III PASSENGER RESTRAINT SYSTEM

Subsection 4.5.1 describes the passenger restraint system and focuses on the items that have been significantly changed or refined since Phase II. Subsection 4.5.2 discusses those Phase III test results which are indicative of the performance capabilities of the system.

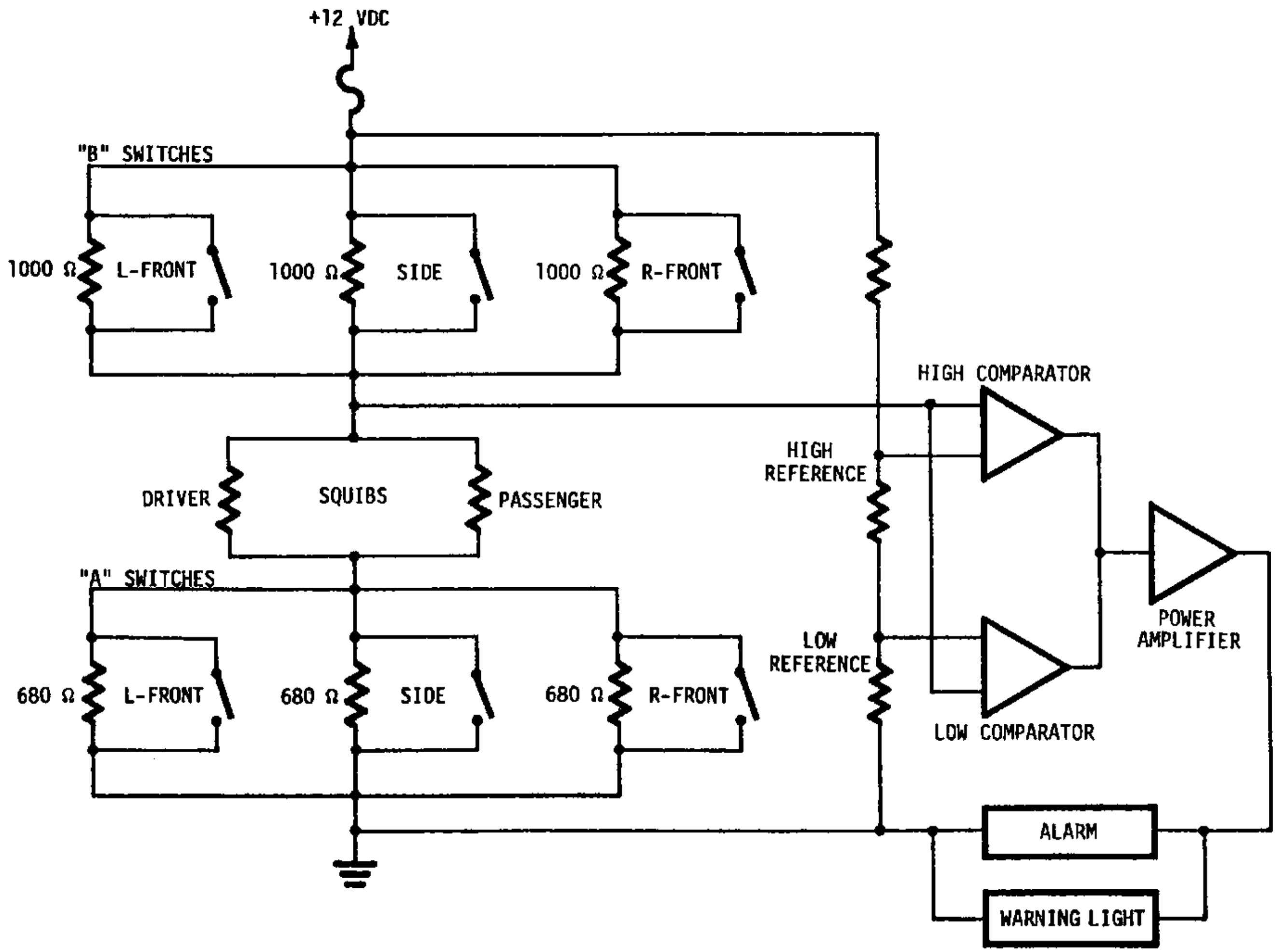


FIGURE 4-13. SIMPLIFIED ACRS CIRCUIT DIAGRAM

TABLE 4-2. SUMMARY OF REPRESENTATIVE DRIVER SLED TESTS

Test	Dummy Size Used	Velocity (mph)	Dummy Injury Measures: HIC	Peak Chest Acceleration (Gs)	Femur Loads (lbs) Left	Femur Loads (lbs) Right	Column Stroke (inches)
1326	50M	50.7	560	44	1350	1450	4-1/2
1329	50M	50.0	521	47	1600	1300	5-7/8*
1332	5F	45.5	528	55	900	800	1/2
1333	95M	44.8	615	60	1700	2000	5-7/8

*The sled pulse in this test was more severe than intended.

4.5.1 Passenger System Description

Figure 4-14 shows the passenger air cushion system. This system is composed of an air cushion module, knee restraint, passenger seat, and sensor/diagnostic system.

The seat and the sensor/diagnostic system have essentially identical functions and forms as parts of the driver restraint system; hence their descriptions will not be repeated here.

The most significant Phase III change in the passenger restraint system was the elimination of the stroking dash. The stroking dash was instituted in Phase II in order to place a force-limiting device in the system. But in the later portions of Phase II it became clear that the RSV frontal collapse characteristics were evolving better than anticipated — that is, the compartment stroking distances and acceleration levels in severe front impacts were being shown to be more innocuous than those being used in the preliminary sled tests. The demands on the passenger restraint system were reduced to the point that, in the frontal crash tests, dash stroking was neither achieved nor required. Thus one of the tasks established for Phase III was the elimination of the stroking dash (in the interest of reducing the overall system's cost and complexity).

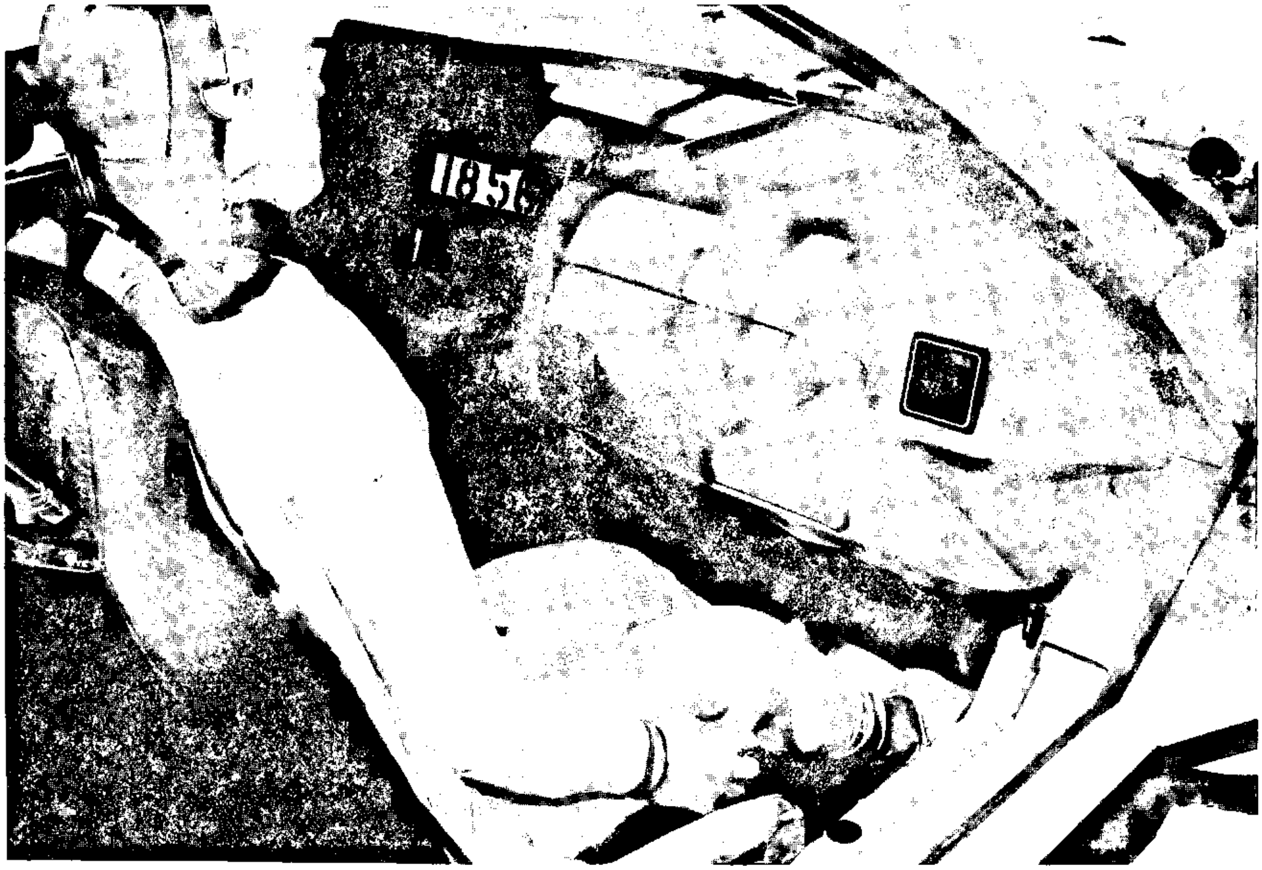


FIGURE 4-14. PASSENGER AIR CUSHION RESTRAINT SYSTEM

Air Cushion Module

The passenger air cushion module is made up of a bag assembly, inflator, associated bracketry and airbag cover. The elimination of the stroking dash, together with the introduction of a dashboard and cover, required a number of minor revisions to the restraint assembly. The final RSV airbag is a so-called "Number 12" configuration, which has upper and lower chamber volumes of 3.00 ft^3 (85 dm^3) and 2.75 ft^3 (78 dm^3), respectively. The torso chamber is designed to be coated with neoprene in much the same manner as was the driver airbag in the GM ACRS. But difficulties in obtaining such production-coated material forced us to simulate this part of the design by hand coating the bags with latex (and using talc for a limited stowage life). The final bag has a 3-3/4 inch (9.5 cm) diameter vent in the partition separating the torso and head chambers, two 3-3/4 inch (9.5 cm) vents in the side panels of the torso chamber, and two 2-3/4 inch (7 cm) vents in the side panels of the head chamber.

The brackets were completely redesigned to the configuration shown in Figure 4-15. The inflator brackets are two arms that extend from the cowl toward the passenger compartment. The outboard arm has a split ring assembly to clamp the cylindrical diffuser/inflator; a locking pin prevents the inflator from rotating during bag deployment. The inboard arm picks up the bolt stud provided in one end of the inflator. The RSV bag is "socked"* to the inflator. Therefore, a pad (the rubber gasket shown in Figure 4-16) is necessary at the inboard bracket arm (between the bag and the arm) to distribute clamping pressure to the bag as the mounting nut is tightened on the bolt stud.

The passenger air cushion cover (Figure 4-17) was also completely redesigned in Phase III. The new design has a rectangular cut-out in the ABS dash. A pre-slit polyethylene sheet, secured around its perimeter to the inner surface of the dash, covers this opening. A decorative fabric outer cover is lightly glued around its perimeter to the inner surface of the ABS dash. In a deployment, the polyethylene inner cover petals open and the outer fabric cover detaches.

*The term "socked" refers to a bag fabrication and assembly technique in which the bag is provided with a collared orifice in its side panel. A cylindrical inflator can thus be inserted into this orifice and a circular clamp used to attach these elements together.

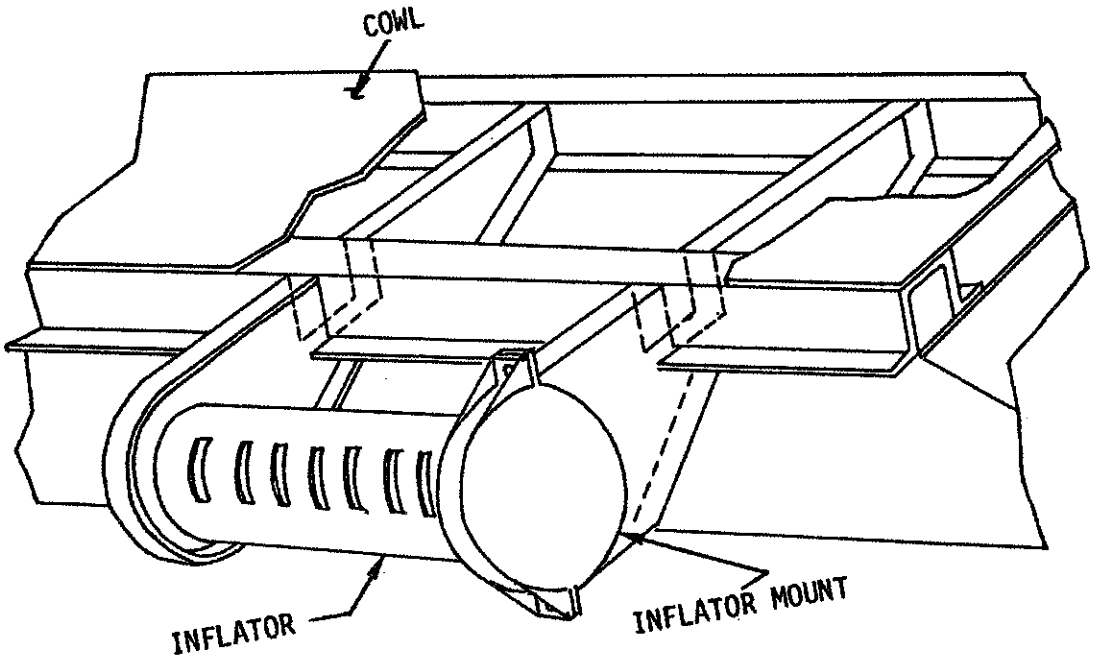


FIGURE 4-15. PASSENGER RESTRAINT BRACKETS

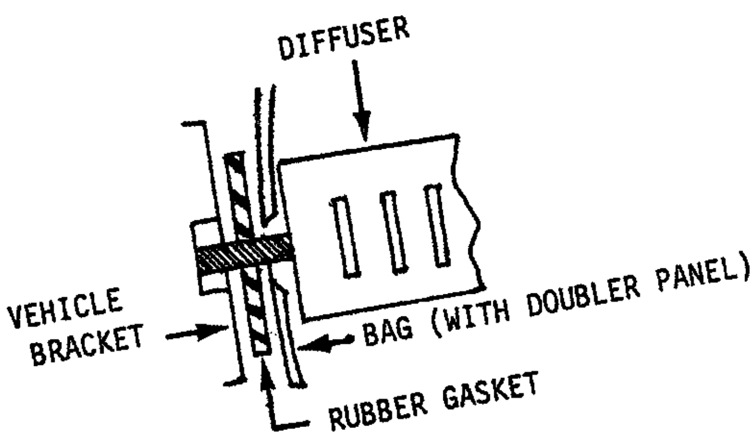
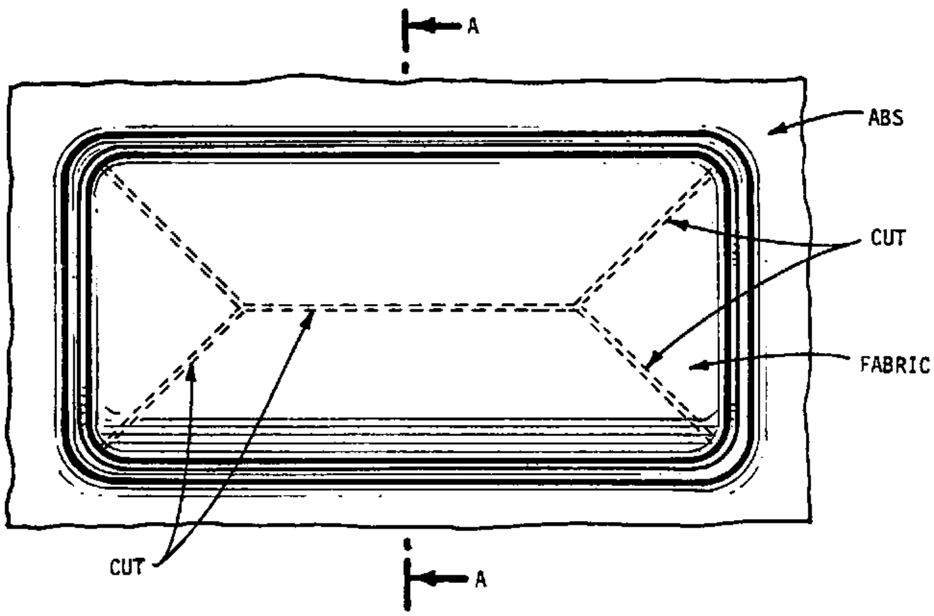


FIGURE 4-16. AIRBAG CLAMPING CONFIGURATION



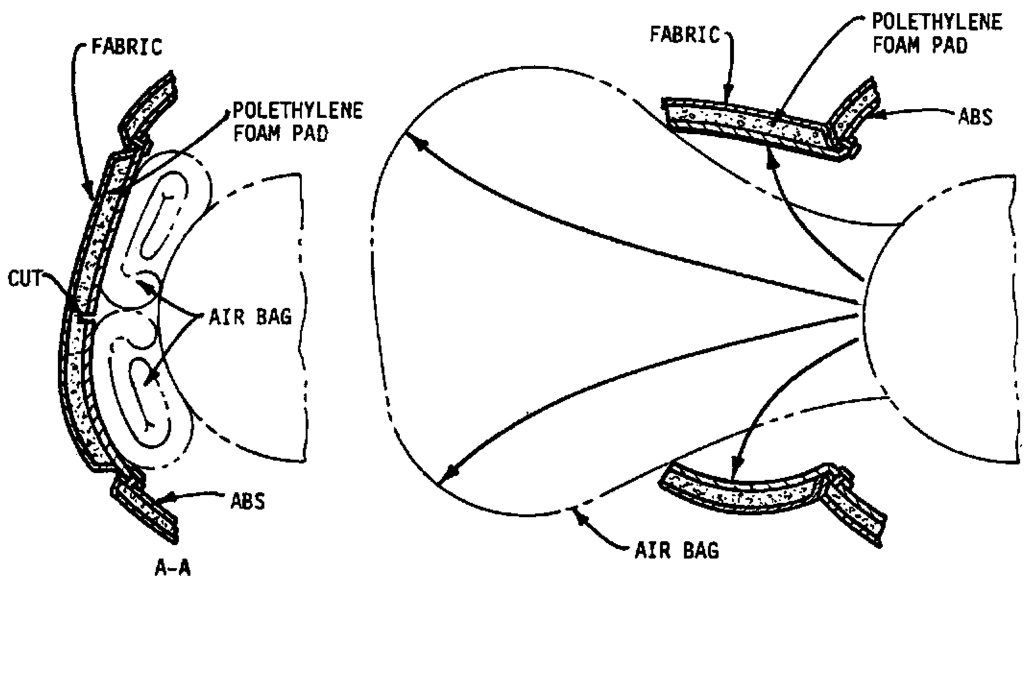


FIGURE 4-17. PASSENGER ACRS COVER AND OPENING SEQUENCE

Knee Restraint

In the Phase II passenger restraint system the extensive forward displacement of the (controlled) submarining passenger's lower body was accommodated by a combination of knee restraint penetration and dash displacement. With the elimination of the stroking dash, the knee restraint system had to be redesigned. In the system's current form, knee stroking is achieved by a combination of the penetration of a deeper foam element and the deflection of its sheetmetal reaction surface.

The reaction surface, a sheetmetal plate extending from the air cushion module downward, is designed to deform in a severe front impact, effectively adding 5 inches (13 cm) to the available knee stroke. This function is important to the maintenance of the controlled submarine trajectory – which is essential for the low injury measures achieved by the system in front impacts of up to 50 mph delta-V.

A 5 inch thick, 2 lb/ft^3 cored polyurethane foam billet is installed between the reaction plate and the ABS lower dash. The objective of the coring (see Figure 4-18) is to lower the knee restraint forces to about 500 to 600 pounds (225 to 275 kg) per knee (50th percentile male passenger), which is the force appropriate to the desired passenger trajectory. This objective could also have been reached by using a solid foam with a lower crush strength, but the program's timing and limited scope did not allow its development.

To facilitate knee penetration, a tear pattern was put in the ABS dash. This was accomplished in the same manner as the tear pattern for the driver knee restraint.

4.5.2 Passenger System Performance

In Phase III, 33 sled tests and 6 crash tests of the passenger restraint system were conducted. This subsection discusses the sled tests that are representative

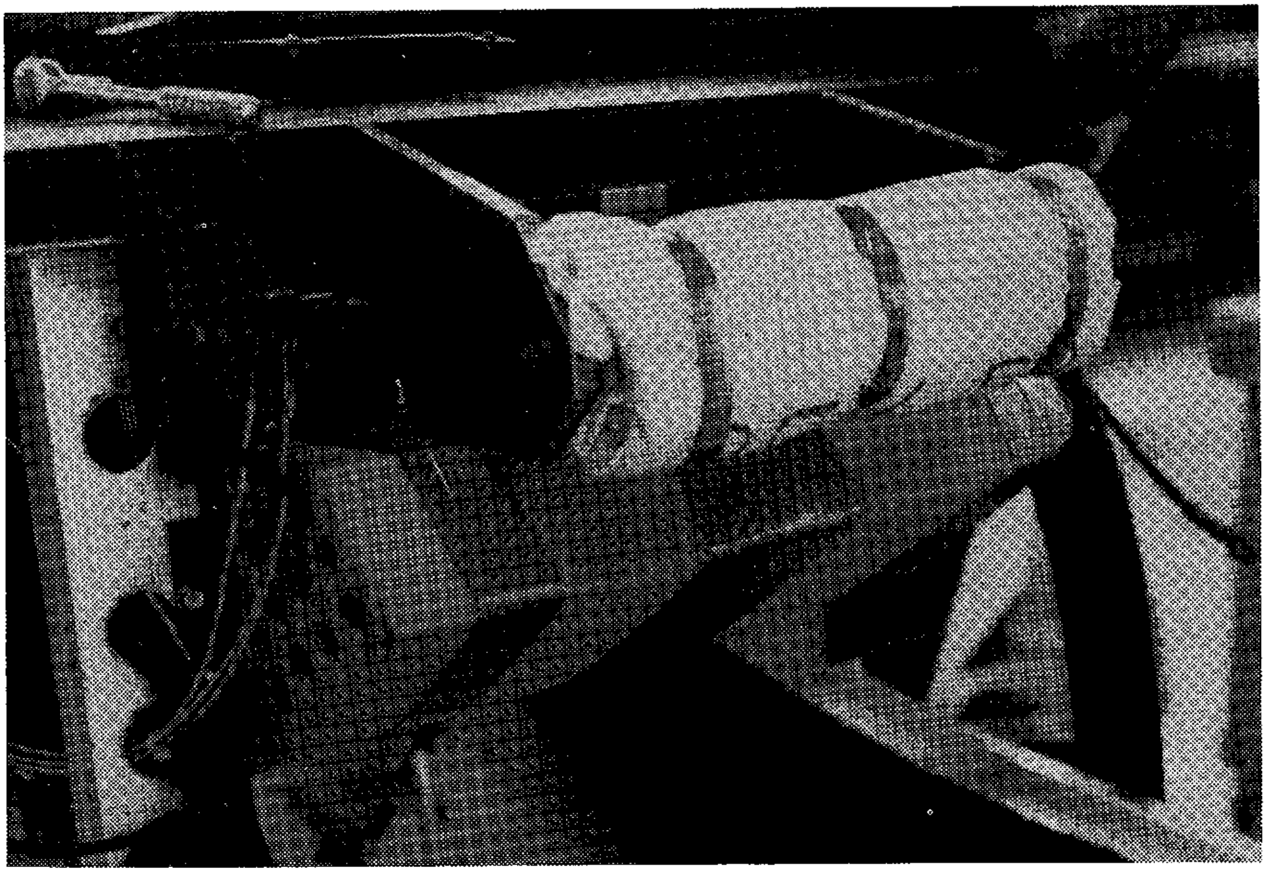


FIGURE 4-18. PASSENGER RESTRAINT SYSTEM

of the final configuration of the system. The crash test results are summarized in Section 4.7.

Sled Tests 1328, 1330, 1331 and 1334 best indicate the repeatability of the system and its expected performance limits for the 50th percentile male, 5th percentile female and 95th percentile male. The results of these sled tests are summarized in Table 4-3.

TABLE 4-3. SUMMARY OF REPRESENTATIVE PASSENGER SLED TESTS

			Dummy Injury Measures			
					Femur Loads (lbs)	
Test	Dummy Size Used	Velocity (mph)	HIC	Peak Chest Acceleration (Gs)	Left	Right
1328	50M	51.1	773	54	800	600
1334	50M	51.1	595	50	700	400
1330	5F	47.0	710	49	100	200
1331	95M	41.6	700	49	400	700

For the 50th percentile male dummy, the air cushion prevented both head and chest contact with the windshield and dash. However, the proximity of the chest deceleration peaks to the 60 G criterion of FMVSS 208 indicates that the 51 mph (82 km/h) sled velocity was very close to the limit of the system's performance. For the 5th percentile female, the data indicate a limit around the 47 to 50 mph (76 to 80 km/h) range. The 95th percentile dummy, on the other hand, suffered (in Test 1331) a head strike on the thick Lexan windshield used in the sled buck. Thus, if lack of windshield contact is one of the success criteria, then the limit of performance is about 40 mph (64 km/h) for the 95th percentile male passenger. On the other hand, if only the FMVSS 208 criteria are used, the limit of performance is in the 42 to 45 mph (68 to 72 km/h) range. This conclusion is based both on the HIC sustained in Test 1331 and on the fact that the RSV windshield is more compliant than the Lexan surrogate in the sled buck.

4.6 SIDE IMPACT, REAR IMPACT AND ROLLOVER PROTECTION

For side impact and rollover protection, we improved the Phase II configuration of the interior door pad, substituted a more appropriate side glazing, and redefined the emergency egress path. For rear impact protection we redesigned the seat (as described in Subsection 4.4.1) and refined the attachment of the seat back to the roof.

4.6.1 Side Impact and Rollover Protection Improvements

The door interior and the side door glazing are the two primary impact surfaces encountered in lateral and rollover collisions. Both were extensively redesigned in Phase III.

Door Pad Refinement

One of the major Phase III tasks was to productionize the RSV door interior. This task required the

- Choice of the technique to be used to protect the shoulder and hip pads during normal vehicle use
- Identification of suitable foams for the shoulder and hip targets
- Integration of the door latch mechanism with the hip pad.

The last item became an issue when the door latch mechanism was redesigned during Phase III, the latch being relocated to the lower center of the interior door panel — precisely the location of the typical hip strike.

Figure 4-19 shows the interior surface of the door. To give this surface a decorative and protective outer contour, we developed a 1/16 inch (1.6 mm) thick molded shell of FRP. Upholstered Ensolite pads are attached to this shell at the shoulder and hip impact areas in order both to distribute the impact forces and to attenuate the short-duration acceleration spikes that would otherwise occur just before shell breakup.

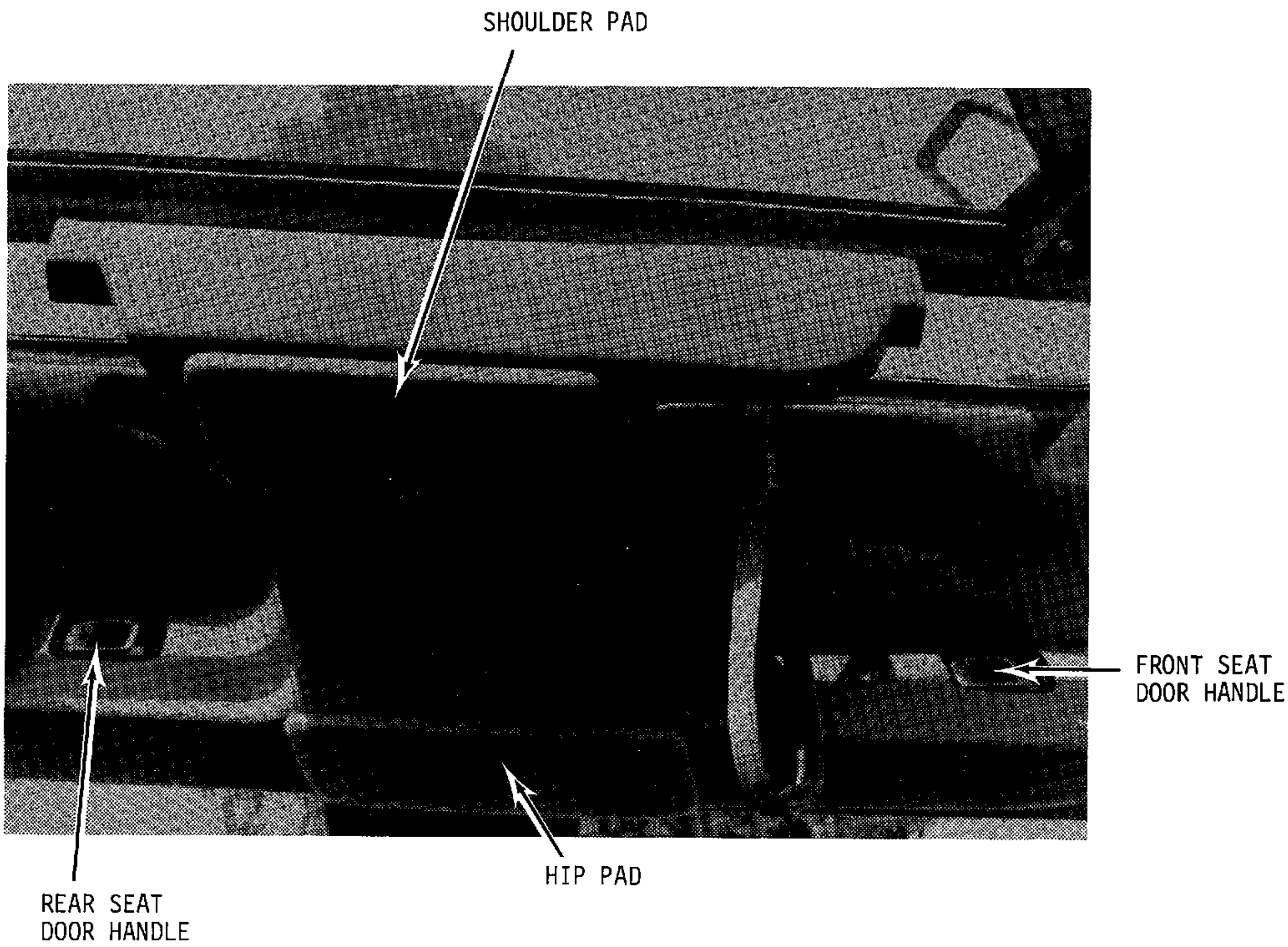


FIGURE 4-19. FINISHED DOOR INTERIOR

The shoulder and hip cavities of the shell are filled with 1.8 lb/ft^3 (29 kg/m^3) rigid polyurethane foam. This density would create too rigid a hip target, were it not for the removal of portions of this foam to clear the door latch mechanism. The removal of foam in the hip area produces a lower pad that crushes optimally (at about one-half of the crush force of the shoulder target).

The development of the Phase III door pad involved a series of sled tests in which a dummy was launched into a stationary door mock-up. The pad was then evaluated in a lateral collision, Test 1466, which is described in Section 4.7.

Side Glazing

The refinement of the side door glazing had as its objective a substitution for the Sierracin/Sylmar Phase II glazing, since a satisfactory abrasion-preventive coating for the Mylar inner layer could not be develped during the time frame required. The final RSV side glazing has a windshield-type configuration, consisting of outer layers of 0.125 inch (3.2 mm) thick annealed glass and a 0.031 inch (0.79 mm) thick PVB inner layer. It is bonded to the window frame with urethane adhesive, a standard windshield retention material. This securement technique was rendered viable only because the emergency egress strategy was revised.

During Phase III we considered a number of strategies for removing the side door glazing in an emergency. A few of these were found promising enough to bench-test. Of the side glazing retention techniques permitting ready removal in an emergency, however, none secured the glazing well enough in normal operation to make the glazing an integral part of the door structure. (Our testing indicated that the rigidity of the door frame was marginal without a contribution from the glazing.) Compensating for the loss of rigidity by further stiffening the frame would have added yet more weight to the door. In view of these considerations, the egress path was redefined to be through the rear hatch. This was accomplished by modifying the latch to permit opening the hatch from inside the compartment.

4.6.2 Rear Impact Protection

In a rear impact the basic restraint system is the seat – primarily the seat back and head restraint. As previously mentioned, the RSV front seats were completely redesigned during Phase III; the new front seats are modified Dodge van seats. For rear impact protection, a panel is welded across the lower vertical frame rails of the seat back. This prevents the knees of the rear seat occupants from bearing directly on the backs of the front seat occupants in rear impacts.

The final seat back and head restraint assembly is illustrated in Figure 4-20. Figure 4-21 shows the details of the seat-back-to-roof attachment. Mounted on the roof is an angle member – a curved beam with a Z-shaped cross-section – to which is attached a similarly curved bow angle section. The angle section mates with a third bow angle section (as shown in Figure 4-21) to clamp, via an array of attachment bolts, to the upper perimeter of the head restraint. This portion of the head restraint is comprised of two pieces of 0.02 inch (0.5 mm) thick sheetmetal. The sheetmetal subassembly is necessary in order to impart a more even distribution of tensile forces into the weaker Lexan. The Lexan panel is attached to the sheetmetal, via two clamping strips, by both pop rivets and an adhesive (Scotch-weld structural adhesive 2216). The bottom edge of the Lexan is secured to a second piece of sheetmetal in essentially the same manner. The lower sheetmetal piece is formed into an inverted-U shape, the arms of which are used as energy-absorbing tapes (Figure 4-22). These tapes are woven through a series of three pins provided by a pair of pin assemblies attached to the top horizontal member of the seat back frame. The middle "pin" is, in fact, the member itself. During a severe rear impact the seat back flexes rearward, causing the tape arms to be pulled through the pin assemblies. Each tape generates a force of about 350 pounds (160 kg), to limit the tensile force in the head restraint to around 700 pounds (320 kg).

The performance of the seat back/head restraint system was verified in Sled Test 1175. This test was a simulation of Test 7.11B, a Phase II test in which the RSV was struck in the rear by a Volvo traveling at 40 mph (64 km/h), producing a 21.6 mph (34.7 km/h) delta-V. In Test 1175 a 50th percentile male

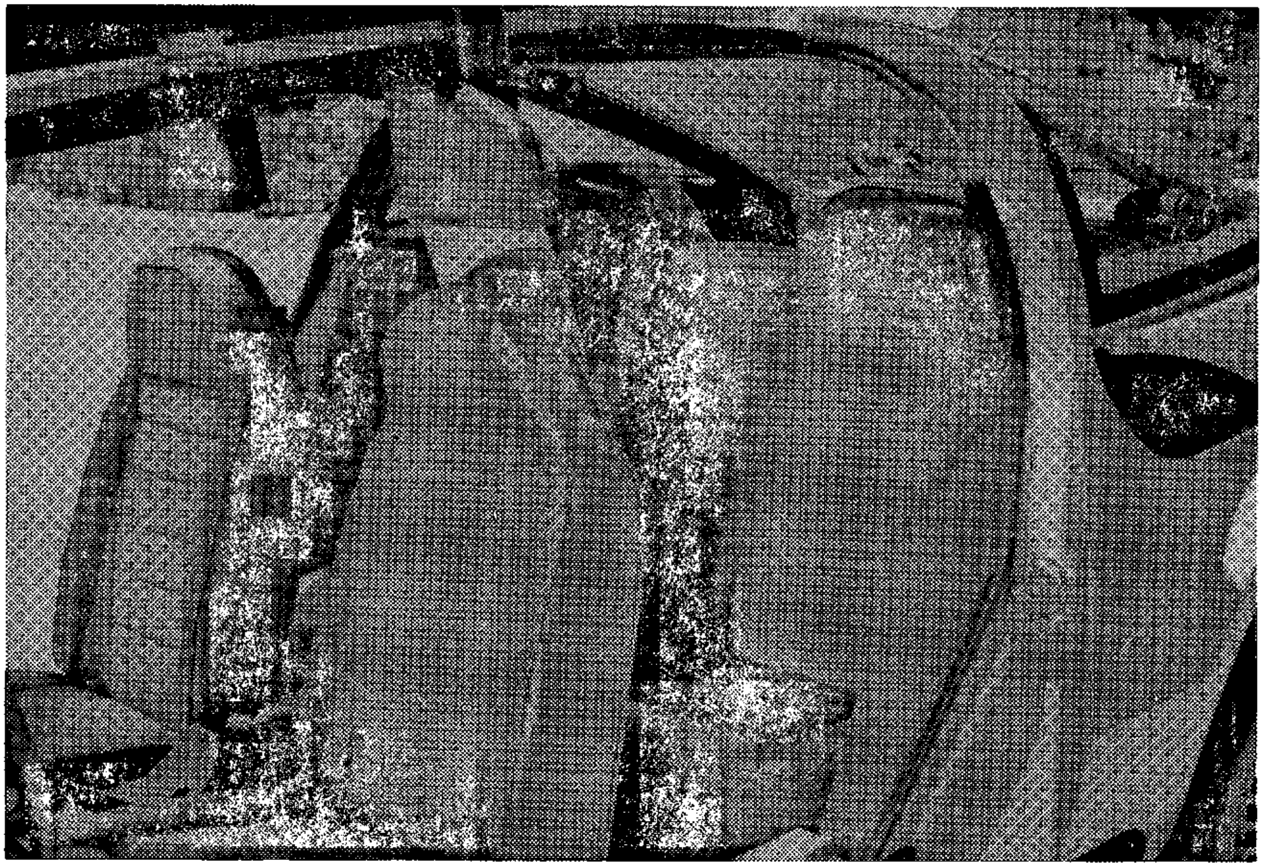


FIGURE 4-20. CLEAR LEXAN FRONT HEAD RESTRAINTS

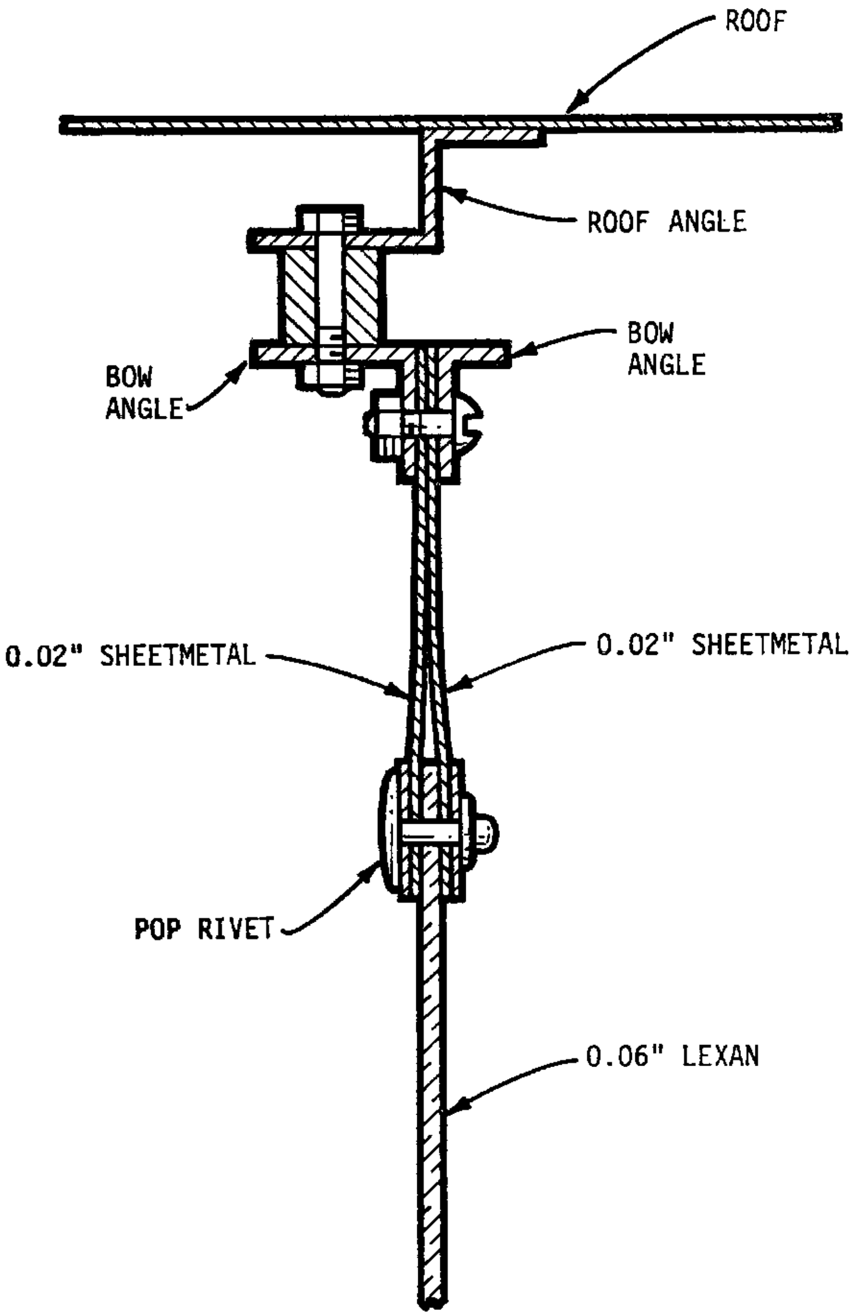


FIGURE 4-21. FRONT SEAT/ROOF ATTACHMENT ASSEMBLY

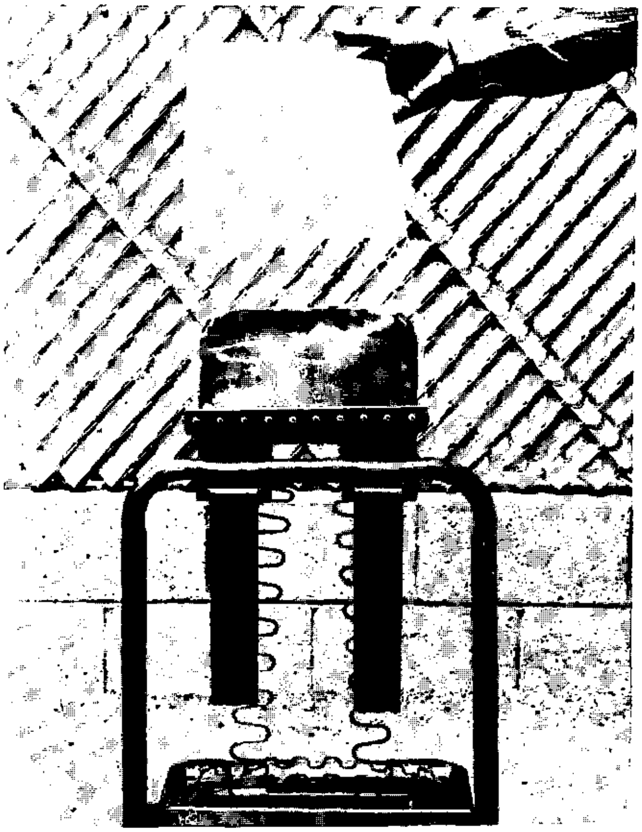


FIGURE 4-22. FRONT SEAT UPPER FRAME ASSEMBLY

dummy was located in the passenger seat, and the seat was adjusted to its middle position. The results are summarized below:

Sled velocity (mph)	22.5
Dynamic crush (inches)	22.75
Dummy response:	
HIC	108
Chest acceleration (Gs)	25
Head restraint band stroke (inches)	3

It should be noted that, as expected, the Volvo seat track latch mechanism did not hold (i.e., there is no device in the Volvo latch mechanism for retaining the seat at its adjusted position during impact). The seat moved rearward 2-1/2 inches (6.4 cm), where the stops (welded in for just such a purpose) prevented further seat translation and kept the seat on its tracks.

4.7 SUMMARY OF CRASH TEST RESULTS

In all, 18 high speed crash tests of RSVs were conducted in Phase II, and 7 in Phase III. A total of 10 more tests (including 8 crashes in Japan, Germany, England and France) were planned for Phase IV. In this section we will discuss the most recent Phase II or Phase III test conducted in each crash mode. The modes are: aligned frontal barrier, aligned frontal vehicle-to-vehicle, offset frontal vehicle-to-vehicle, side, rear, and rollover.

Table 4-4 summarizes the six pertinent crash tests. It lists the three dummy injury measures (head injury criterion, chest acceleration and femur loads) relevant to FMVSS 208 frontal compliance testing. It also includes Minicars' best engineering estimate of the maximum speed at which the occupants (Part 572 dummies) could still "survive" under otherwise identical test conditions. "Survival" is defined as a HIC that is less than 1000 and a peak (3 msec) chest acceleration less than 60 Gs. The Phase IV test results, to the extent that they were available to us, were also used to develop the maximum speed estimates.

4.7.1 Aligned Frontal Barrier Impact (Test 1346)

One measure of a vehicle's safety in front impacts is the maximum (aligned frontal) barrier impact speed at which the vehicle meets the FMVSS 208 criteria. The NHTSA recently tested several production cars at 35 mph (the compliance test speed is 30 mph) and found that the majority of them could not meet the head and chest injury criteria for both front occupants, even though the occupants were restrained. The best performance to date in such a barrier impact was achieved by the Chevrolet Citation (a GM X-body), which easily passed the criteria at 35 mph (56 km/h) and barely failed at 40 mph (64 km/h).

Judged by this standard, the RSV's performance in Test 1346 was an unqualified success. In this test an RSV struck a rigid flat barrier perpendicularly at 47.6 mph (76.6 km/h). The driver air cushion was deployed at 9 msec into the event by the GM BID sensors installed near the bumper. (Analysis and subsequent crash test results indicate that essentially this same sensing time would have been achieved by the Technar Curve 3 sensors of the final design.) The crash

TABLE 4-4. RSV CRASH TEST SUMMARY

Test	Description	Phase	Occupants	HIC	Peak Chest Acceleration (Gs for 3 msec)	L/R Femur Loads (pounds)	Vehicle Crush (inches)	Estimated Maximum FMVSS 208 Survival Speed* (mph)
1346	Aligned frontal barrier impact (delta-V = 47.6 mph)	III	LF	304	45	1250/1575	45	delta-V = 50+
			RF	554	48	700/890		
1856**	Aligned frontal impact with Impala (delta-V = 45 mph)	III	LF	807	45	1000/1100	40.3	delta-V = 45
			RF	1259	49	750/1000		
1529	Offset frontal impact with Impala (delta-V = 44.6 mph)	III	LF	183	35	1300/1600	40	delta-V = 50
			RF	261	25	800/700		
1466***	Impala (V = 34.9 mph) into RSV (V = 34.9 mph) side at 90°	III	RF	574	34	500/450	N/A	Impala V = 45****
			RR	244	65	200/150		
7.11R***	Volvo (V = 39.7 mph) into RSV (V = 0) rear	II	LF	185	50	N/A	N/A	Volvo V = 45+
			LR	104	40	N/A		
7.8	Rollover, 3 rolls (V = 30.5 mph)	II	LF	100	7	N/A	N/A	Not estimated
			LR	100	6	N/A		

*The maximum FMVSS 208 survival speed is the maximum estimated crash speed at which the same test could be run and the same two RSV occupants would sustain a HIC less than 1000 and 3 msec peak chest accelerations less than 60 Gs.

**The passenger airbag inflator used in this test was defective.

***These tests uncovered deficiencies in the structural design (which were subsequently corrected).

****This survival speed is estimated for the front passenger only.

test sequence was exactly as would have been predicted on the basis of the sled test results: the steering column stroked about 2 inches, and the windshield was left undamaged (and fully retained). Figure 4-23 shows the RSV during the impact. The crash pulse is shown in Figure 3-5 and the data traces are contained in Reference 27. As Table 4-4 shows, all injury measures were well below the criteria. The results indicate that the RSV crash management systems were not used to their full capabilities at the test speed — the steering column still had over 3 inches (7.5 cm) of stroke remaining and the front structure had about 6 inches (15 cm) of additional crush space. Most important, the toeboard had only intruded about 1 inch into the passenger compartment. Of course, if the test speed were increased, we would see more intrusion, which would probably result in higher femur loads and changes in dummy trajectories.

We therefore estimate that the RSV can protect its front occupants at speeds up to, and possibly in excess of, 50 mph (80 km/h). This estimate is also based on a Japanese frontal barrier test (conducted in Phase IV) in which the dummies just survived at 50 mph, despite what appeared to be a faulty passenger airbag inflator. Such performance at 50 mph means that the RSV can successfully manage 56 percent more crash energy than a Citation and at least 104 percent more energy than most of the cars on the road today (under the test conditions).

Even these numbers are underestimates. The RSV restraints are passive, while the Citation's are not, and, as is well known, the vast majority of active restraints are not used. Obviously, unrestrained Citation occupants would not do so well as their belted counterparts. We also have not taken into account the differences between the force-loading characteristics of airbags and those of belts. A 60 G acceleration applied by a lap and shoulder belt is almost certainly more traumatic than a similar acceleration applied by an air cushion.

4.7.2 Aligned Frontal Vehicle-to-Vehicle Impact (Test 1856)

While aligned frontal barrier impacts are a good way to compare frontal crashworthiness of different cars, such impacts occur very infrequently in the real world. Therefore, we also tested the RSV in various vehicle-to-vehicle modes: one of these was the aligned front impact. The 1977 Chevrolet Impala was

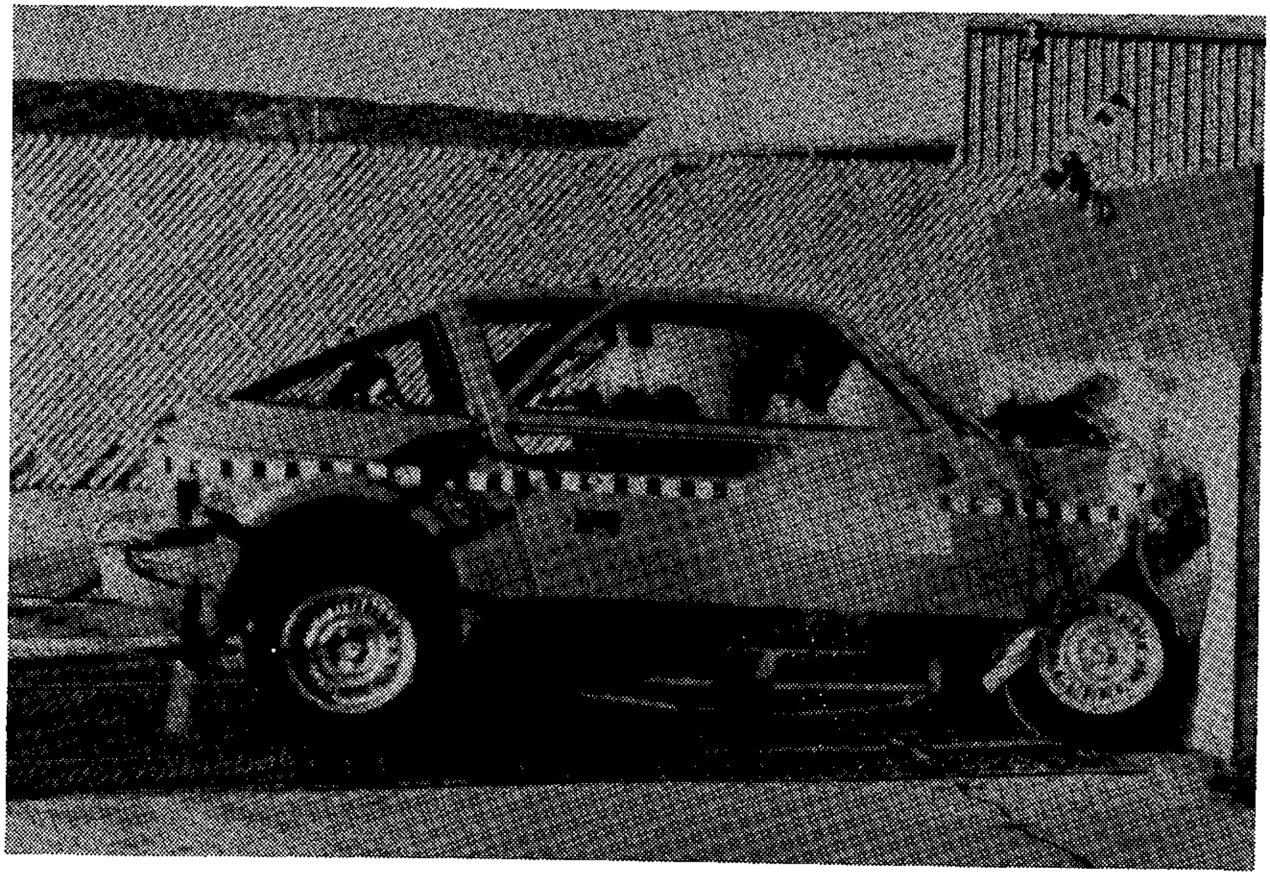


FIGURE 4-23. ALIGNED FRONTAL BARRIER IMPACT AT 47.6 MPH

selected as the target vehicle. This full size automobile is probably representative of the heaviest cars that will be found in the 1985 accident environment.

Test 1856, the last RSV/Impala impact, was run at a closing speed of 78.5 mph, which produced a 47 mph (76 km/h) delta-V (including rebound) in the RSV. Structurally, the test was a success; Figure 4-24 shows the passenger compartment longitudinal accelerations (at mid-compartment) for both cars. Unfortunately, the passenger airbag inflator did not operate properly (the mass flow characteristics did not meet specifications) and the passenger HIC was 1259. However, in a Phase IV Dynamic Science (Phoenix, Arizona) RSV/Dodge Challenger test (the RSV delta-V was 43.3 mph), both of the RSV's occupants had HICs under 700 and chest accelerations under 40 Gs. We believe that the Challenger is somewhat more aggressive than the Impala (Reference 9), and our conservative estimates are that the RSV can successfully protect its occupants in a 45 mph (72 km/h) delta-V impact with an Impala.

The Chevrolet Impala, with its subframe design, is not truly representative of the 1985 accident environment. From that standpoint, the Citation would have been a better choice, but it was not yet available when the test program began. If the RSV were crashed with a Citation, we expect that the RSV's performance could be diminished to some extent, since the Impala and Challenger may not be as aggressive as the Citation.

These tests emphasize that, for severe delta-Vs, the RSV performs better in barrier impacts than in vehicle-to-vehicle impacts. Barrier impacts insure that all load paths are adequately engaged and remove the uncertainties of pitching, override and underride, etc. We learned from the RSV/Impala test series (see Subsection 3.3) that override and underride, in particular, are difficult to predict, in that subtle changes in vehicle front structure can dramatically affect the way it interacts with the other car. Hence, caution must be exercised before extrapolating test results from one model of target vehicle to another.

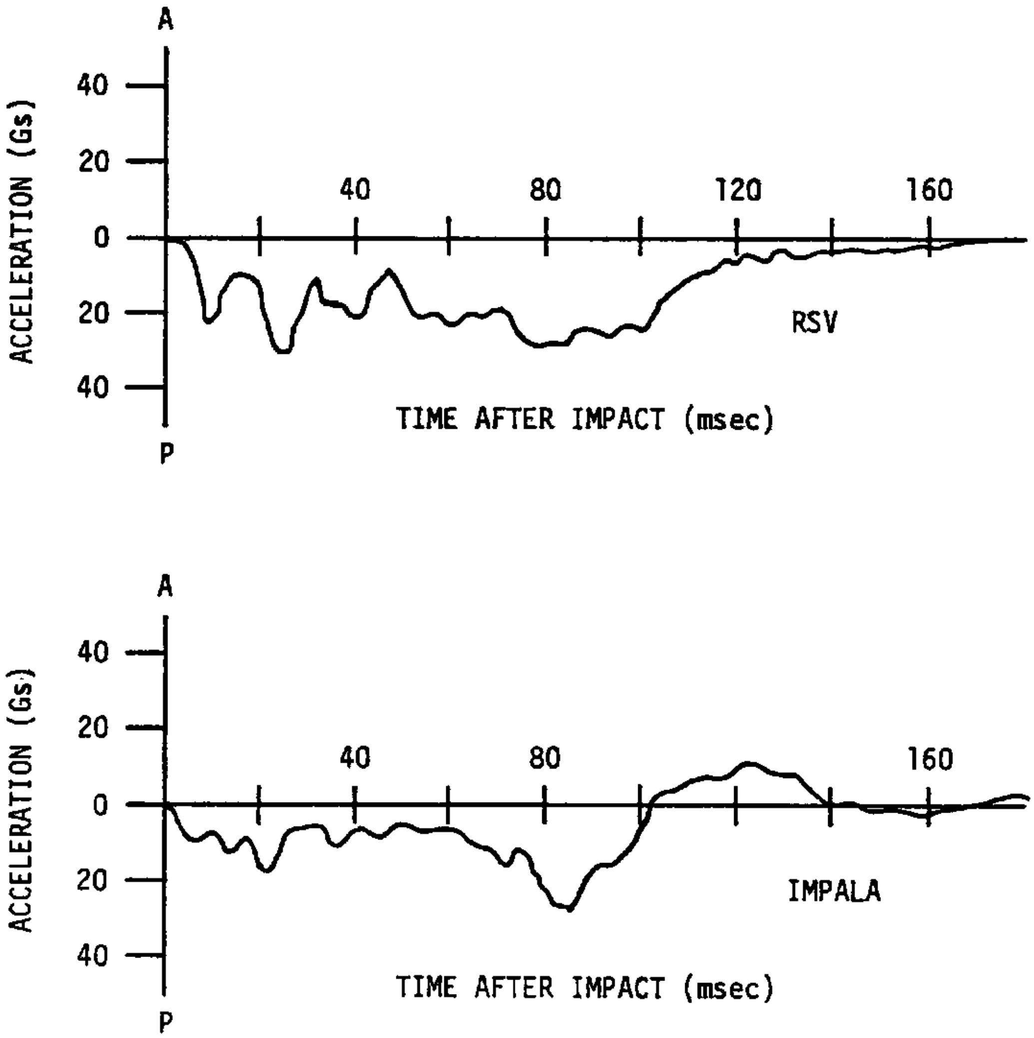


FIGURE 4-24. LONGITUDINAL MIDCOMPARTMENT ACCELERATIONS IN 78.5 MPH RSV/IMPALA ALIGNED FRONT IMPACT

4.7.3 Offset Frontal Vehicle-to-Vehicle Impact (Test 1529)

According to data from the National Crash Severity Study, the aligned frontal and offset frontal modes are two of the largest contributors to fatalities and overall societal loss. Because only part of the front structure is engaged, an offset collision will usually have a softer crash pulse (in general benefiting both occupants). Intrusion, however, will be greater on the struck side, increasing the threat to the occupant on that side.

In Test 1529 an Impala traveling at 36.5 mph (58.7 km/h) struck an RSV traveling at the same speed. The left side of the Impala was aligned with the RSV centerline, so that both driver sides were engaged. This crash had a soft crash pulse, which helped to produce very low injury measures (considering the high crash severity - the RSV's delta-V was 44.6 mph). The most severe problem was compartment intrusion on the driver's side. If the crash severity were significantly increased, the steering column stroke would be exhausted and the column would be pushed back into the compartment, subjecting the driver to unacceptable chest Gs. Based on the limited compartment deformation observed in this test and the additional stroke remaining in the steering column, we estimate that the driver could survive a similar impact at a delta-V of 50 mph (closing velocity of 82 mph with the Impala). The front passenger could survive at even higher speeds.

4.7.4 Side Impact (Test 1466)

In Test 1466, the only Phase III side impact, an Impala struck the RSV at 90 degrees, dead center on the RSV's A-pillar. Both vehicles were traveling at 34.9 mph (56.2 km/h), which produced a 20.5 mph (33.0 km/h) lateral velocity change* on the RSV compartment. The RSV door panel sustained a 28 mph (45 km/h) peak inboard velocity. Despite the presence of compartment intrusion, the near side front passenger easily met all injury criteria**, and had a peak (3 msec) pelvic acceleration of only 27.5 Gs. Considering that the side structure was

*Calculated by integrating the lateral acceleration of the compartment.

**For the purposes of this study, the FMVSS 208 injury criteria were supplemented with a 80 G limit on lateral pelvic accelerations.

modified after this test to better resist intrusion, we estimate that the Impala and RSV speeds could be as high as 45 mph and the front passenger would still pass the injury criteria.

Our estimate is also based on preliminary results from the Phase IV test in France in which a Renault 20 traveling at 40.8 mph (65.7 km/h) struck the RSV on the right door, just missing the A-post. The Renault was oriented at 70 degrees (approximately two o'clock) with respect to the RSV. Although the Renault weighed less than the Impala, its comparatively narrow and very aggressive front structure actually has the potential to cause more intrusion. In the Phase IV test the right front RSV passenger just passed the criteria*, but the far side driver failed the chest acceleration criterion, apparently due to an impact between the two occupants. It must be remembered, however, that the ability of Part 572 dummies to model human injury mechanisms in occupant-to-occupant interactions is unknown and probably poor.

The near side rear passenger did not pass the criteria in either test, because the RSV has only a nominal degree of lateral padding (3/4 inch thick Ensolite) for rear seat occupants. This design is based on two factors: first, the provision of high-speed rear occupant lateral protection is not cost-effective, because of the (current) low rear seat occupancy of automobiles; second, the addition of several inches of padding in the rear would greatly complicate rear seat entry and egress, as well as seriously compromise rear shoulder room. For these reasons, no remedial action was taken.

4.7.5 Rear Impact (Test 7.11B)

At this writing, only one RSV has ever been subjected to a high speed rear impact. In that test, which was conducted in Phase II, a Volvo traveling at 39.7 mph (63.9 km/h) struck a stationary RSV, causing a 21.6 mph (34.7 km/h) delta-V. In addition to the results shown in Table 4-4, there was 8.5 inches (22 cm) of intrusion into the rear seat and the front and rear passengers

*These are preliminary results.

received 79 and 80 peak pelvic Gs, respectively. We evaluated the various injury measures, and the mechanisms through which they were inflicted, and found none of them to be life-threatening.

Due to the substantial Phase III refinements in rear impact crashworthiness, we estimate that the speed of the Volvo could have been increased by at least 5 mph (8 km/h) without exceeding the injury criteria. However, this estimate is quite speculative, and a good measurement of rear impact performance will have to await a planned Phase IV test.

4.7.6 Rollover (Test 7.8)

The integrity of the RSV upper structure was evaluated in Test 7.8 of the Phase II program. The vehicle was placed sideways on an inclined rollover dolly, which was accelerated to 30.5 mph (49.1 km/h) and then stopped. The RSV slid off the dolly, rolled three times, and ended in an upright position. Both the right and left B-pillars received structural damage and the left sill and both left suspension systems were severely damaged by the initial impact. However, the greatest amount of intrusion occurred on the right side. Overall, the intrusion was within acceptable limits, and the indications from dummy accelerations are that the occupants would have received only minor injuries. In Phase III we evaluated the possibility that the structural changes made since that test would affect the upper structure performance, and came to the conclusion that no significant effects would be seen. Therefore, no further tests were conducted.

SECTION 5
BRAKING AND HANDLING

5.1 INTRODUCTION

This section describes the RSV dynamic systems that influence its ride, handling and braking performance. These systems are the front suspension, rear suspension, steering, tires and wheels, and brakes. By the beginning of Phase III of the RSV Program these systems had been selected and their preliminary integration into a running vehicle was complete. The objectives of the Phase III braking and handling efforts were to

- Upgrade the dynamic systems, as necessary, to accommodate structural and other changes in the RSV
- Integrate the dynamic systems into the RSV and demonstrate that the RSV exceeds the minimum requirements of the braking and handling performance specifications.

5.1.1 System Upgrade

The central reason for the upgrading of the dynamic systems was the RSV's weight growth. Most of the upgrading was minor and was implemented chiefly to ensure the car's ride and handling performance. The most important alteration was a change of the front and rear springs. The addition of fins to the brake back plates to provide proper brake rotor cooling was a typical minor change. Sections 5.3 through 5.7 describe the specific changes made.

5.1.2 Systems Integration

Two series of ride and handling tests were conducted during the Phase III effort. The test results indicate that the RSV meets the braking and handling performance specifications set for the program.

We reported in the RSV Phase I Final Report that it is difficult to quantify the societal benefits of improved ride, handling and braking performance. For the RSV ride and handling testing, therefore, we selected only those specifications that would be representative of comparable production cars. These specifications were chosen from the Intermediate Experimental Safety Vehicle (IESV) Crash Avoidance Performance Specifications.

5.2 RATIONALE BEHIND THE SELECTION OF THE DYNAMIC SYSTEMS

The RSV dynamic systems were designed and their components determined during Phase II of the RSV Program. The subsystems were selected to

- Meet or exceed all Statement of Work performance requirements
- Be of simple and straightforward design
- Maximize the use of standard components (which kept the modifications of components and fabrication of hardware to a minimum and gave us performance and integrity at minimum cost)
- Derive from a vehicle (the Fiat X1/9) which both has superior handling and is close to the RSV's curb weight and load capacity
- Retain (where the use of standard parts is not possible) the functional kinematics of the Fiat X1/9 configuration (to ensure the known performance of the subsystems).

It is appropriate here to again note that a production version of the RSV would have a substantially lower curb weight than that of the Phase III prototypes.

5.3 FRONT SUSPENSION (Figure 5-1)

Because the RSV has greater front wheel loading than does the Fiat X1/9, its front suspension uses modified X1/9 rear struts and springs. The suspension's forward stabilizer struts are mounted on a channel transverse crossmember just behind the bolt-on nose, and its rearward control arms are mounted on extension plates attached to the sill in the kick-up area. The attachment points were

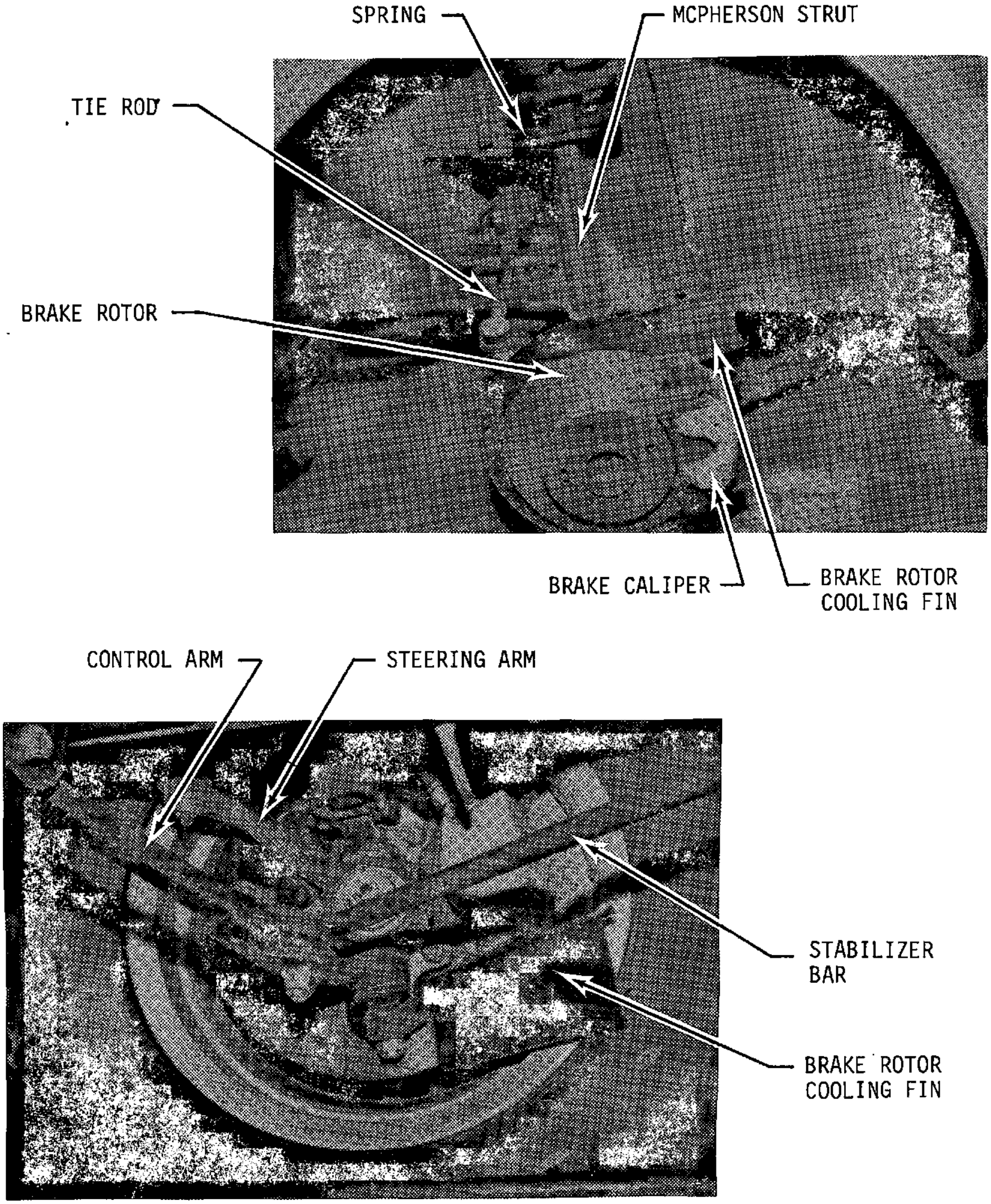


FIGURE 5-1. FRONT SUSPENSION, STEERING AND BRAKES

designed to retain the X1/9 suspension kinematics, even though the RSV has a wider track than the Fiat. Table 5-1 outlines the front suspension.

TABLE 5-1. FRONT SUSPENSION

Parameter	Remarks
1. Type	McPherson strut, independent
2. Strut	Fiat X1/9 rear strut, modified (spring seat relocated)
3. Spring	Fiat X1/9 rear spring
4. Control arm	Fiat X1/9, unmodified
5. Forward strut	Fiat X1/9, unmodified
6. Suspension kinematics	Basic Fiat X1/9 attachments and kinematics
7. Alignment	Limited camber and caster and full toe-in adjustments

5.3.1 Front Suspension Alignment

The Fiat X1/9 front suspension does not provide for camber adjustment, but it does allow full toe-in and limited caster adjustments. During the Phase III fabrication and testing we found that the RSV suspension systems needed camber and (more extensive) caster adjustment. We therefore built these capabilities into the front suspension by redesigning the McPherson strut mounts in the shock towers. In the new design three enlarged attachment holes may be used to adjust the strut's upper end laterally and longitudinally to provide caster and camber correction. These adjustments must be regarded as limited, however, because they still do not give the full range available in most cars that do have such adjustments.

5.4 REAR SUSPENSION (Figure 5-2)

The rear suspension is the basic Fiat X1/9 assembly (Table 5-2). It is a fully independent Chapman strut with wide base lower A-arms. This assembly was selected because it is reasonably lightweight and its hubs are attached to its lower A-arms with a toe-in adjustment. The lower A-arms are fabricated from folded channel stock, allowing them to be easily modified. The only modification actually made to the A-arms was the addition of a crossbrace for rear impact crashworthiness (see Section 3). The A-arm attachment brackets were designed to retain the basic Fiat X1/9 rear suspension kinematics.

5.4.1 Rear Suspension Alignment

As with the front suspension, the RSV rear suspension was upgraded to provide limited camber and more extensive caster adjustments. The necessary modifications were similar to those made in the front suspension, and the resulting adjustments are relatively simple. During the RSV's handling, braking and shakedown tests the suspension settings were checked to assure that the settings held firm and were not disturbed by high cornering and/or braking loads. No loosening was detected.

During Phase III, the rear springs were changed to accommodate the RSV's weight growth. The springs selected (from the Chevrolet Chevette rear suspension) provide a progressive spring rate (a result of variable wire diameter).

5.5 STEERING

The RSV uses a Fiat X1/9 rack and pinion steering system. Only two modifications were made to the X1/9 system:

- The end of the rack was extended to allow for the RSV's wider track.
- The geometry and configuration of the steering linkage were altered (between the steering column lower end and the pinion shaft) to suit the RSV steering column.

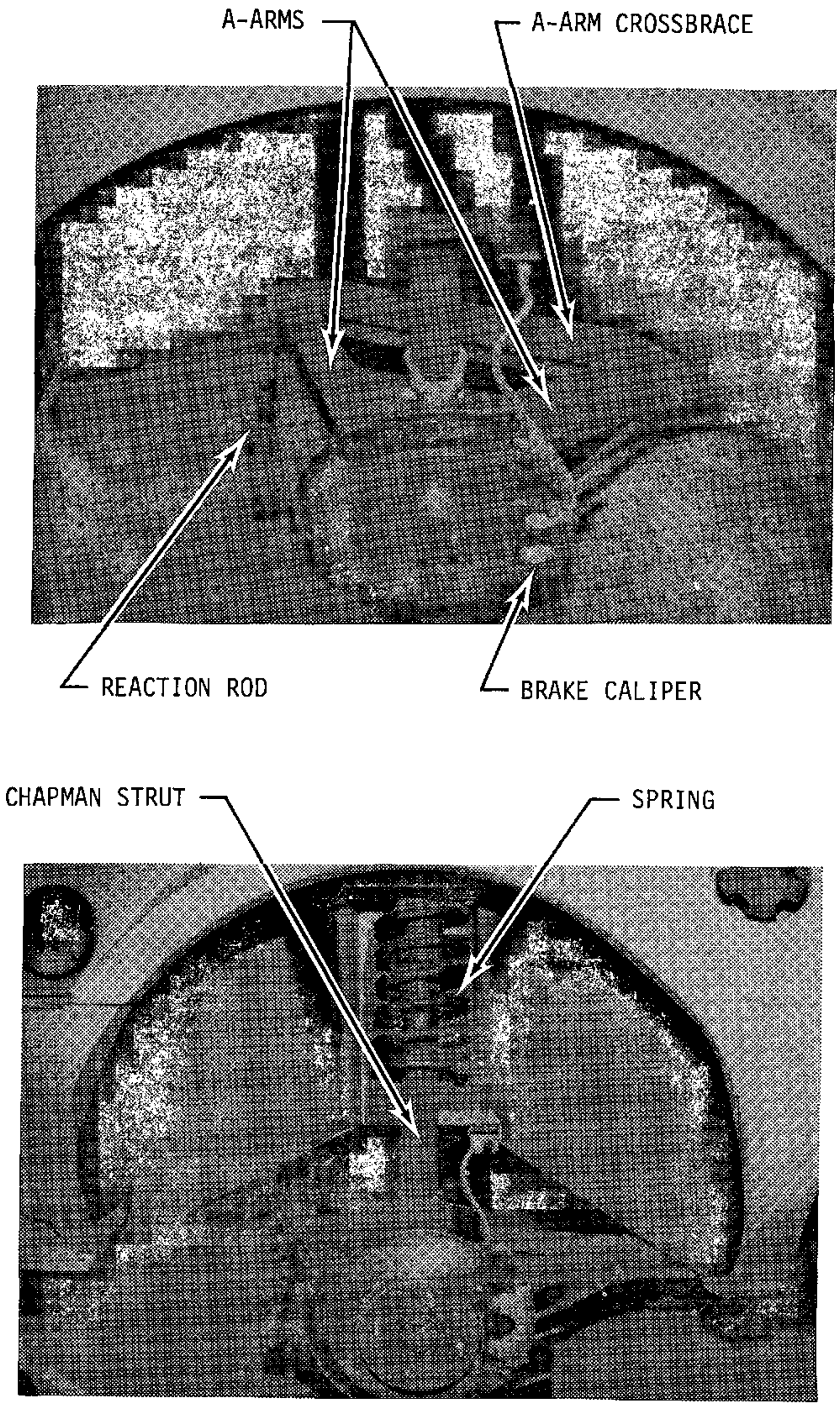


FIGURE 5-2. REAR SUSPENSION AND BRAKES

TABLE 5-2. REAR SUSPENSION

Parameter	Remarks
1. Type	Chapman strut type, independent
2. Chapman strut	Fiat X1/9 rear strut, unmodified
3. Spring	Chevrolet Chevette rear spring
4. A-arm	Fiat X1/9 A-arm with a cross brace added
5. Suspension kinematics	Basic Fiat X1/9 attachments and kinematics
6. Alignment	Full camber and caster adjustments

The basic attachment points of the rack and the lengths of the tie rods were left unchanged (with respect to the front suspension attachment). This retained the X1/9's front suspension and steering system kinematics. The steering system characteristics are outlined in Table 5-3.

TABLE 5-3. STEERING SYSTEM

Parameter	Remarks
1. Type	Rack and pinion, Fiat X1/9
2. Rack	Extension added to the right end of the rack to accommodate the RSV track width
3. Tie rods	Fiat X1/9, unmodified
4. Rack mounts	Fiat X1/9, modified to prevent rack rotation and lateral rocking
5. Steering linkage kinematics	• Rack mount retained unchanged with respect to the front suspension. • Linkage altered between the steering column and the pinion shaft to include two splined joints, and geometry altered to accommodate the RSV components.

The Phase III ride and handling tests disclosed two steering system problems: returnability and freeplay.

5.5.1 Returnability

The RSV's steering returnability was marginal in the ride and handling tests. A careful analysis of the vehicle's behavior revealed possible friction in the system and misalignment of the U-joints in the steering linkage. The rack was also observed to rotate in its mounts and to rock laterally under driver applied torque. The reduced returnability was the cumulative effect of all of these factors.

We were able to improve the returnability by

- Reinforcing the steering mounts to eliminate lateral rocking
- Reducing the rack rotation by adding a steel plate over the rubber D-ring in the two rack mounts
- Placing the U-joints in phase and realigning them so that the input and output shafts are parallel (and therefore the cyclic variations of rotation between the shafts is reduced)
- Replacing a Delrin bushing at the bottom of the steering column with a needle bearing (to eliminate possible friction).

These four corrective measures made a marked improvement in the RSV's returnability.

5.5.2 Freeplay

During the final ride and handling tests conducted at Minicars' test facilities, it was found that a significant amount of freeplay existed in the steering system. A study of the system indicated that the problem was in the steering linkage connecting the steering column to the pinion shaft. The freeplay was a result of looseness both in the U-joints and in the two splined shafts (one at the intermediate shaft and the other at the pinion shaft). Unfortunately, this discovery was made too late in the program to take corrective measures. However, it is our recommendation that the spline machining tolerances be made closer in the future; this should reduce the overall freeplay to an acceptable level.

Looseness in the U-joints can be explained in terms of the specific components (from a Fiat X1/9) and the angular excursions through which they work (greater than in the X1/9, but apparently less than in the GM X-body cars). A selection of different components would probably mitigate this deficiency.

Freeplay adversely affected the RSV's handling performance. In the steady-state tests, the results were found to vary between the clockwise and counterclockwise runs. The test drivers also found it difficult to maintain a steady, fixed control steering input during the transient tests. Tighter spline interfaces will certainly help to correct these problems.

5.6 TIRES AND WHEELS (Figure 5-3)

The RSV's tires are run-flat "Denovo 2" tires manufactured by the Dunlop Tire Company. The preferred size was 190/65 HR370. However, size 200/65 HR370 are production tires already in use in Europe and are readily available; hence they were used on the RSV.

Denovo 2 tires are 65 series radial construction tires. Their run-flat capability is provided by five features:

- Bead Location
  Denovo 2s use special single piece rims that incorporate a patented bead locking concept called "Denloc." A groove in the wheel rim engages with an enlarged, reinforced bead toe; this system provides positive bead location, even under extreme maneuvers while fully deflated.

- Lubrication
  The Denovo 2 tires are coated inside with a combination lubricant/sealant gel. The gel seals small punctures and lubricates the inside surfaces of

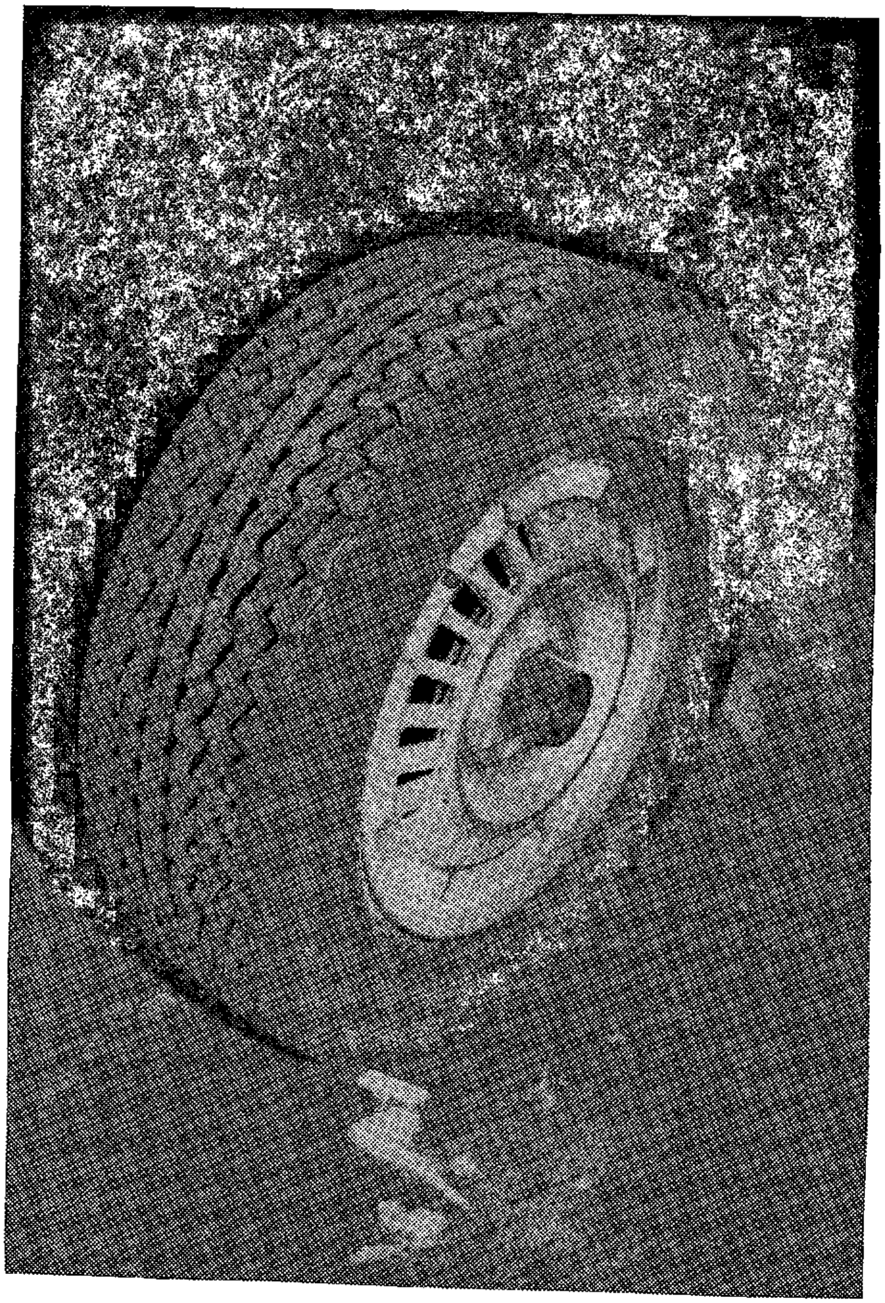


FIGURE 5-3. DUNLOP DENOVO 2 RUN-FLAT TIRE DENLOC WHEEL

the tire when it is running under run-flat or partially inflated conditions. The lubrication also reduces the interior heat buildup.

- Low Pressure Reinflation
  As the temperature in the tire rises, the sealant vaporizes, so a tire which has low pressure at ambient temperature will partially reinflate when it is run on the road.

- Sidewalls
  The sidewalls are reinforced with high resilience rubber. This enables the Denovo 2s to run flat with minimum heat generation and without excessive buckling.

- Geometry
  A low profile radial tire fitted on a narrow rim is beneficial for smooth performance — both run-flat and regular.

5.7 BRAKES

The RSV brakes are based on the Fiat X1/9 four wheel disc system. During Phase III on the RSV Program we added a vacuum power boost to the standard RSVs, and a Bendix four wheel anti-skid system and a collision mitigation system (CMS) to the high technology RSV. The brake systems are outlined in Table 5-4.

The basic brake system is a dual (front-rear split) arrangement. The front of the master cylinder feeds to the front brakes: one line runs directly to the right front brake; another passes through a pressure differential switch on its way to the left front brake. The single line from the rear of the master cylinder also passes through the pressure differential switch, then down the center spine of the car to a T-junction which branches to the rear wheels.

During the ride and handling tests we discovered that the stopping performance of the test car had deteriorated and the brake pedal felt very "mushy". We determined that the deterioration could be caused by even small quantities of air in the brake fluid. This problem was corrected by revising the brake bleeding

TABLE 5-4. BRAKE SYSTEM

Parameter	Remarks
<u>Service Brakes</u>	
1. Type	Fiat X1/9 4-wheel disc
2. Master cylinder	Fiat Spyder 2000 (dimensionally the same as the Fiat X1/9 master cylinder)
3. Vacuum boost	Fiat Spyder 2000 (bolts to the master cylinder)
4. Linkage between brake pedal and vacuum boost	Bell crank lever
5. Brake rotors	Fiat X1/9 (stock, 227 mm diameter)
6. Front calipers	Fiat 124 (dimensionally same as Fiat X1/9)
7. Rear calipers	Fiat X1/9
8. Additional cooling	Air scoop extensions
<u>Parking Brake</u>	
1. Type	Hand actuated
2. Rear hardware	Fiat X1/9
3. Lever and linkage	Fiat X1/9 lever with modified linkage
<u>Anti-skid System</u>	
1. Type	4-wheel hydraulic
2. Manufacturer	Bendix Corporation
<u>Collision Mitigation System</u>	
1. Accumulator	Greer Hydraulics, bladder-type, 2000 psi
2. Solenoid valves	Circle Seal, 3-way, 12 V dc, rated at 3000 psi
3. Pump	Electric operated piston type
4. Filters	Circle Seal, 5 micron
5. Check valves	Circle Seal

procedure to include pressure bleeding. The mushy feel was found to be due to the flexing of the calipers and a possible dilation of the brake hoses. The Fiat X1/9 hoses were replaced with stainless steel braided flexible hose. These changes improved the pedal feel.

The brakes also showed a tendency toward overheating. Part of this problem was, certainly, the weight growth of the RSV during Phase III. Another part was the fact that the Denovo 2 tires and Denloc rims tended to shroud the cooling scoop on the brake back plate. This was corrected by adding extensions to the air scoops to allow more cooling air flow (see Figure 5-1) and by using DOT 4 brake fluid in the brake system instead of regular DOT 3 brake fluid. DOT 4 is a heavier duty brake fluid which can withstand higher operating temperatures than can the DOT 3. Both corrections improved the RSV's braking.

Vacuum Boost

Relatively late in the program, we found that the brake pedal effort required to achieve straight line stops on dry surfaces was in excess of the performance specifications. The situation was corrected by adding a Fiat Spyder 2000 vacuum boost and a Fiat Spyder 2000 master cylinder to the brake system. The vacuum boost brought the pedal effort within the specification limits.

Figure 5-4 shows the location of the vacuum boost and master cylinder in the front luggage compartment. The pedal travel is transferred to master cylinder piston stroke through a bellcrank lever located just forward of the firewall. This particular placement of the master cylinder and vacuum boost robs the trunk of storage space. In production the vacuum boost/master cylinder system, if it were still required, could be more efficiently packaged along the firewall, either in the trunk or in the passenger compartment.

Figure 5-4 also shows the front support bracket, which attaches the front of the master cylinder to the trunk floor. The front support bracket is designed to push the master cylinder upward during a severe front impact. This reduces the chances of the master cylinder/vacuum booster deforming the firewall and

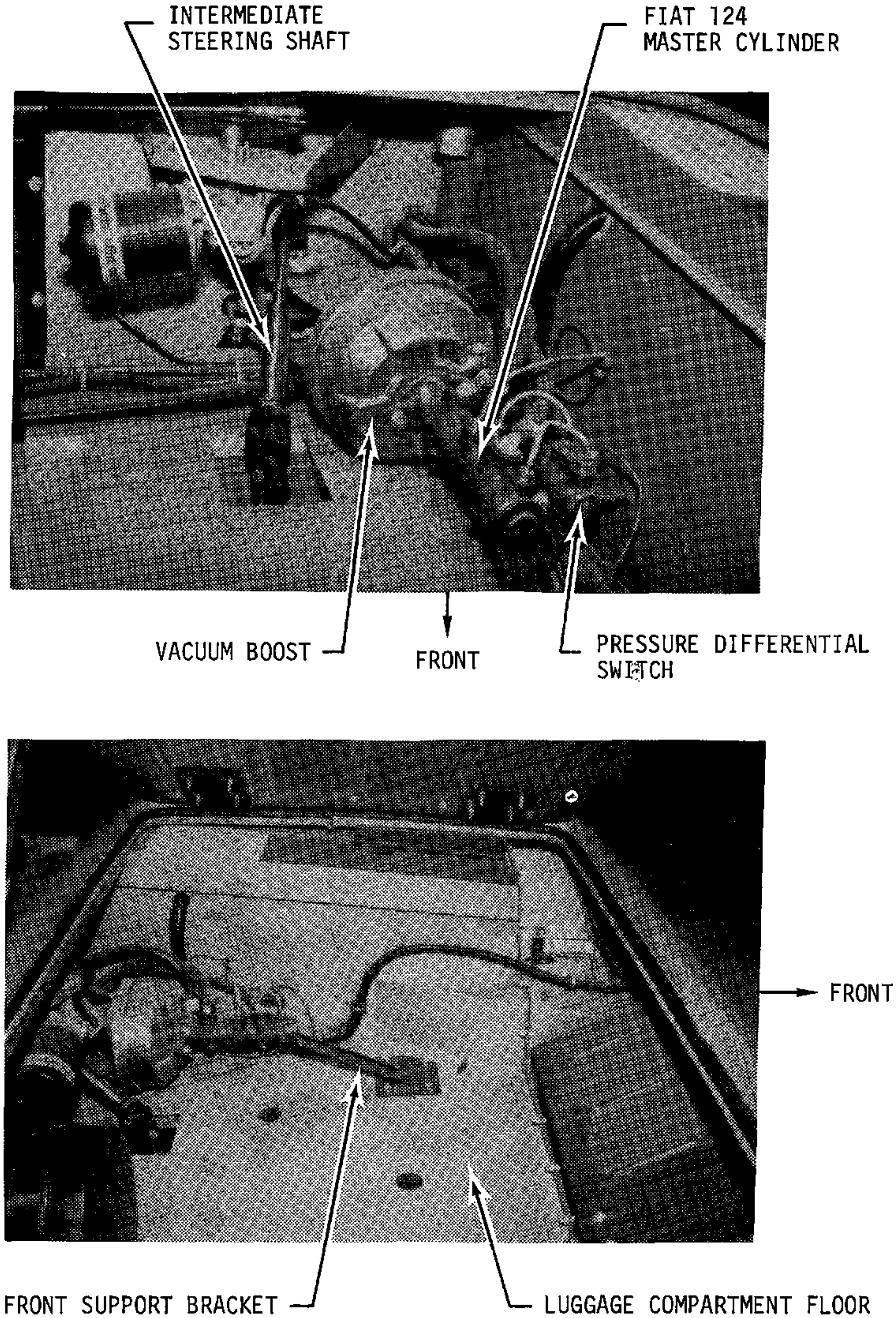


FIGURE 5-4. VACUUM BOOST/MASTER CYLINDER SYSTEM

influencing the restraint performance of the steering column and the driver airbag.

Bendix Four-Wheel Anti-skid Braking System

During Phase III the high technology RSV was equipped with a Bendix* anti-skid brake system designed to prevent wheel locking on any of the four wheels. The system reduces the skid potential of each wheel while maintaining adequate brake pressure (to produce the maximum stopping effort for the existing tire and road conditions). The result is an improvement in the RSV's directional control and steerability in extreme circumstances - and, in many cases, a reduction of its stopping distance. The retention of directional control during braking is especially important because the high technology RSV is also equipped with a collision mitigation system that has the capability of automatically applying the brakes.

Figures 5-5 and 5-6 are electrical and hydraulic schematics of the Bendix system. Its major components are an electronic control unit (ECU), a speed sensor at each wheel, an electric brake fluid pump, two accumulators, two regulators and three pressure modulators. Each wheel speed sensor consists of a variable reluctance pickup and a rotating toothed wheel (actually a modified brake rotor). The ECU is a microprocessor-based computer system which contains three channels (one for each pressure modulator), signal processors and failure detection circuitry.

The two accumulators are spring loaded containers which store pressurized brake fluid, so that the calipers will be replenished during the cyclic braking associated with skid prevention. To preserve the hydraulically split system, separate accumulators are mounted in the front and rear lines. Each accumulator is maintained at 1700 psi (11,700 kPa) by a single piston pump (driven by an electric motor) and has a relief valve that vents to the reservoir if the accumulator's internal pressure exceeds 2700 psi (18,600 kPa). Front and rear

*Bendix Automotive Control Systems Group (ACSG), South Bend, Indiana

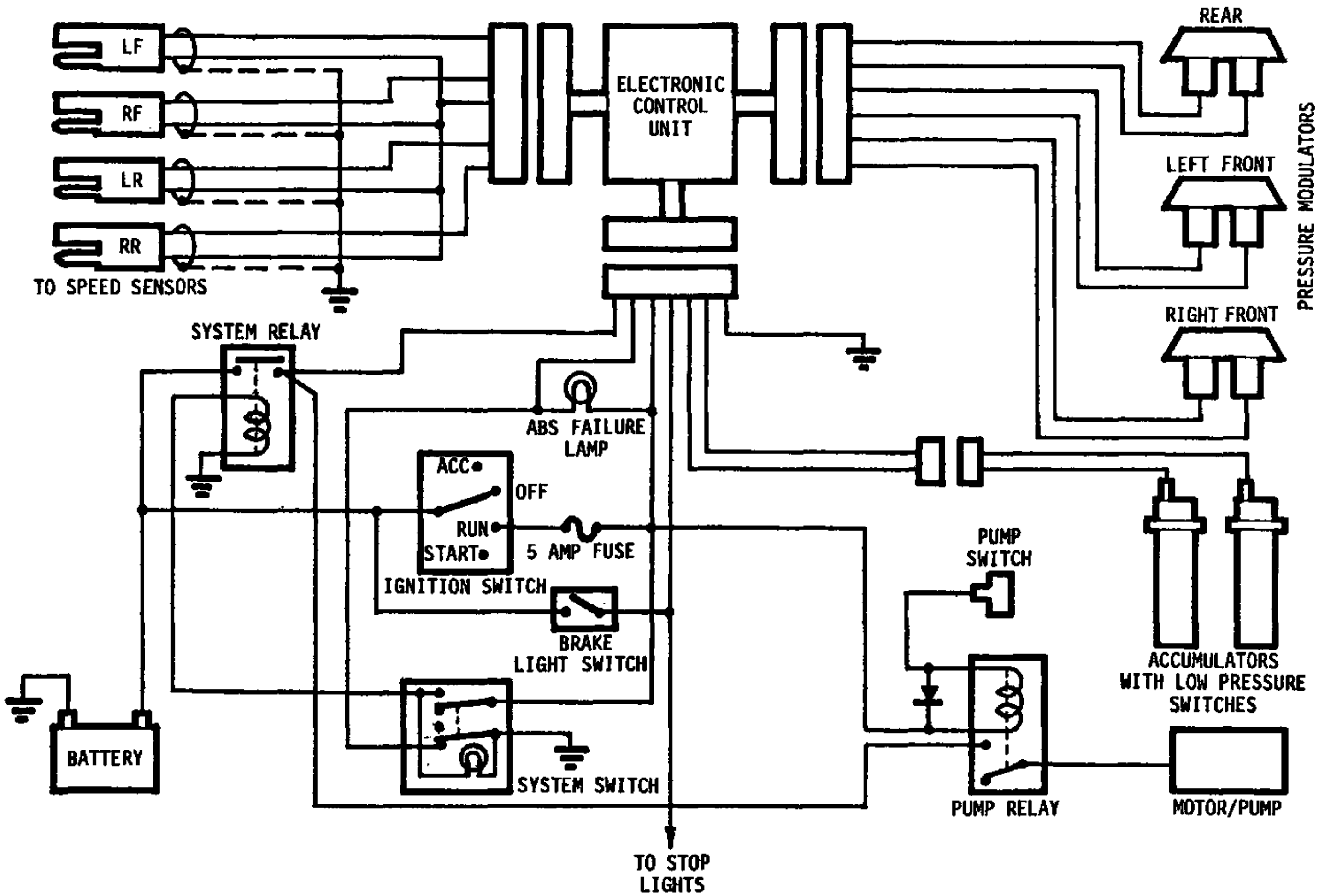


FIGURE 5-5. ELECTRICAL SCHEMATIC OF THE BENDIX ANTI-SKID BRAKE SYSTEM

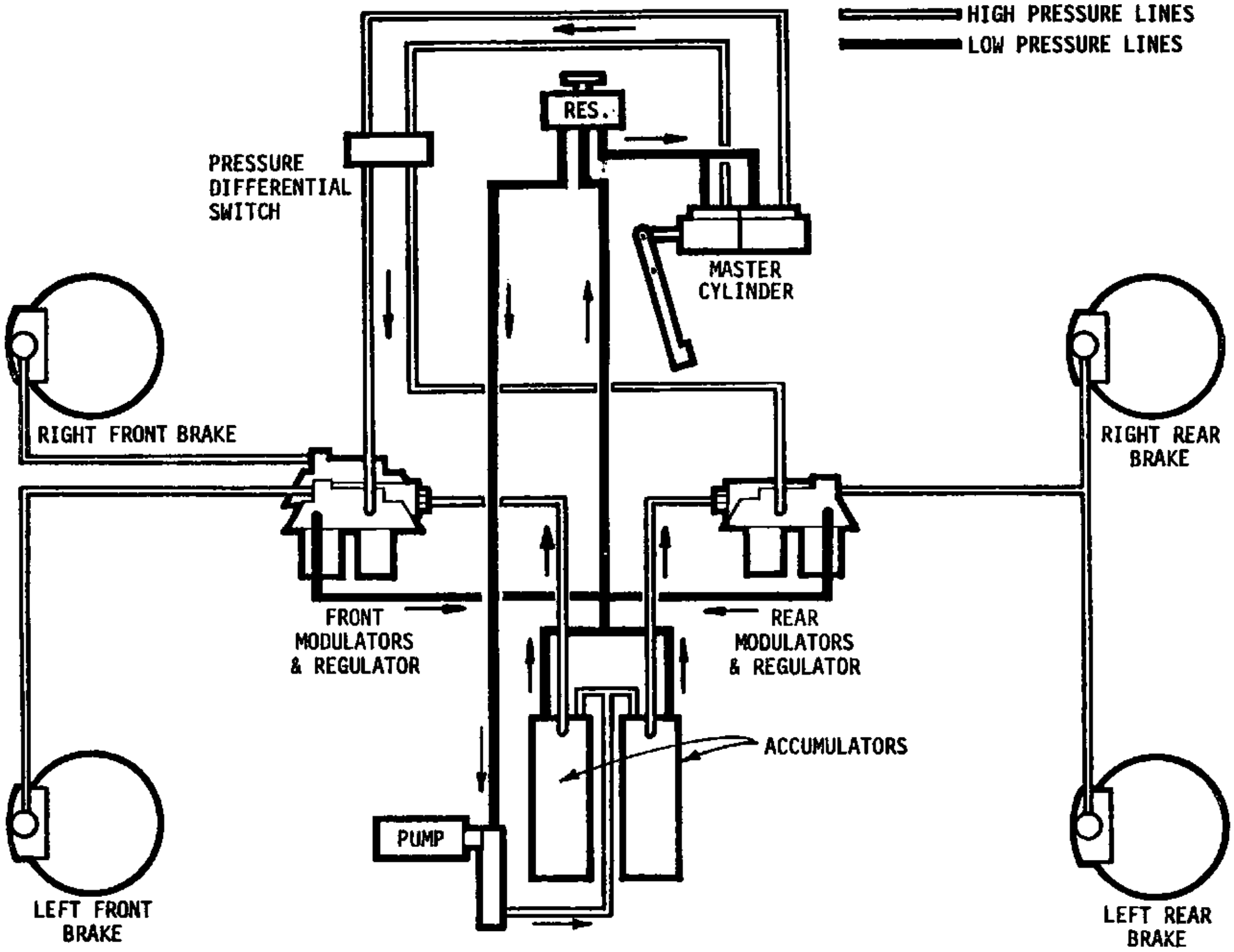


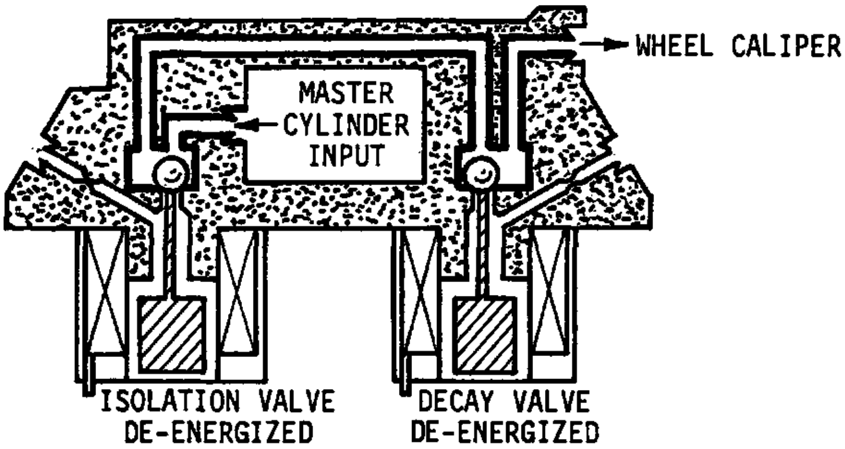
FIGURE 5-6. HYDRAULIC SCHEMATIC OF THE BENDIX ANTI-SKID BRAKE SYSTEM

regulators receive fluid from the accumulators and provide the modulators with a fluid pressure source equivalent to the pressure in the master cylinder.

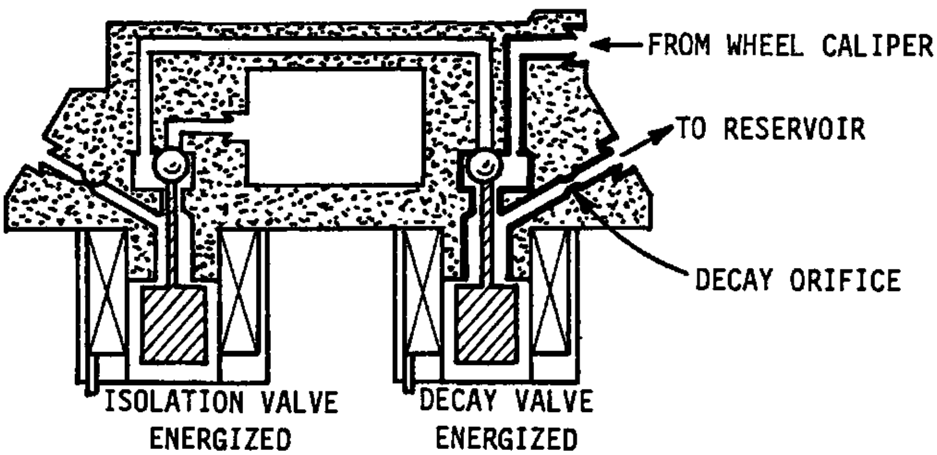
The system has three pressure modulators, one for each front brake and one for the two rear brakes. (The ECU logic only considers the lower of the two rear wheel speeds and modulates the pressure to both rear brakes accordingly.) Figure 5-7 shows a cross section of a modulator in each of its three permissible states of operation. The unregulated, or inoperative, state (Figure 5-7a) is assumed when the brakes are not applied or are not applied hard enough to cause wheel lockup. In this state, both valves – isolation and decay – are de-energized, the anti-skid system is effectively bypassed, and the pressure from the master cylinder is applied directly to the caliper. A failure in the ECU or the power supply will almost always cause the modulator to revert to this state.

When wheel lockup is sensed (the speed of one wheel being significantly less than that of the other wheels), the ECU energizes both valves, which isolates the caliper from the master cylinder and starts bleeding caliper fluid through the decay orifice to the reservoir (Figure 5-7b). The rate of decrease in caliper pressure is a function of the diameter of the decay orifice. As the caliper pressure decreases, the brake torque decreases and the wheel speed begins to increase. When the wheel speed reaches an appropriate level, the ECU de-energizes the decay valve (Figure 5-7c). This connects the caliper to the regulator supply, which is at the same pressure (approximately) as the master cylinder. The caliper pressure subsequently increases at a rate determined by the diameter of the build-up orifice. The pressure modulators are independently controlled and typically cycle between states at a frequency of 10-15 Hz during hard braking.

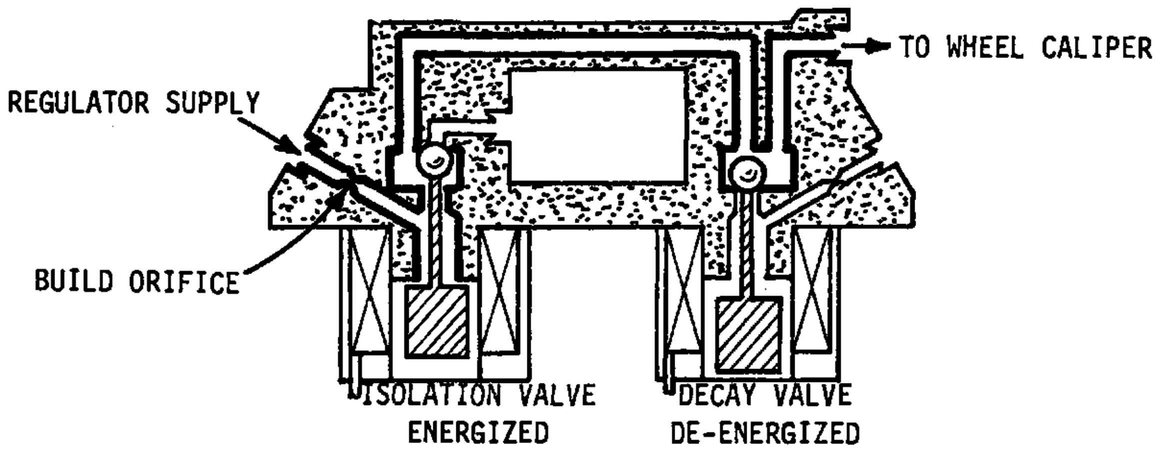
The logic is designed to make the system inoperable and to flash a warning to the driver if the fuse is blown, the pressure in either accumulator drops below 1500 psi (10,300 kPa), any modulator valve remains energized for more than 7 seconds, an open solenoid circuit is detected, or any processed wheel speed remains 15 mph (24 km/h) or more below the other wheel speeds for more than 7 seconds.



(a) Unregulated Pressure Build-up



(b) Regulated Pressure Decay



(c) Regulated Pressure Build-up

FIGURE 5-7. BRAKE MODULATOR OPERATION

Collision Mitigation System

The high technology RSV's radar (discussed in Section 9) provides the vehicle a unique function, a Collision Mitigation System (CMS). The principle behind this system is that the radar will detect an object in front of the RSV, and, based on other inputs (especially vehicle speed, distance of the object and braking/steering action on the part of the driver), the computer will decide if a severe accident is unavoidable. If so, the CMS applies full braking torque to the RSV brakes (which have, of course, the benefit of the anti-skid system). We expect that the CMS will either completely avoid, or substantially reduce the impact speeds of, many otherwise unavoidable accidents.

The hydraulic portion of the CMS, shown in Figure 5-8, was developed at Minicars. This subsystem is based on a hydraulic accumulator, which is kept charged to a working pressure of about 2000 psi (13,800 kPa) by an electrically driven hydraulic pump. (The CMS pump and accumulator are separate from the anti-skid pump and accumulators.) The CMS accumulator is connected to two solenoid valves (one each in the front and rear brake circuits) at which pressurized fluid can enter the anti-skid brake system. The valves are located between the pressure differential switch and the pressure modulators (see Figure 5-6). During normal vehicle operation, the normally open (N.O.) port provides an unhindered path between the master cylinder and the wheel cylinders. But, during CMS operation, the N.O. port is closed, shutting off the master cylinder, and the normally closed (N.C.) port is opened. This allows the high pressure accumulator charge to directly apply the brakes with minimal time delay and full brake torque. It must be noted here that the two pressure transducers shown in Figure 5-8 are not a permanent part of the CMS system. They were used only during the developmental effort.

Figure 5-9 shows the results of the tests conducted to establish the "lag time" between the receipt of the CMS signal and the pressure buildup in the brake system. As the figure shows, it takes 20 to 40 msec for the system to start building pressure; at about 60 msec there is 1500 psi (or 75 percent of full pressure); and within 90 msec full pressure is reached.

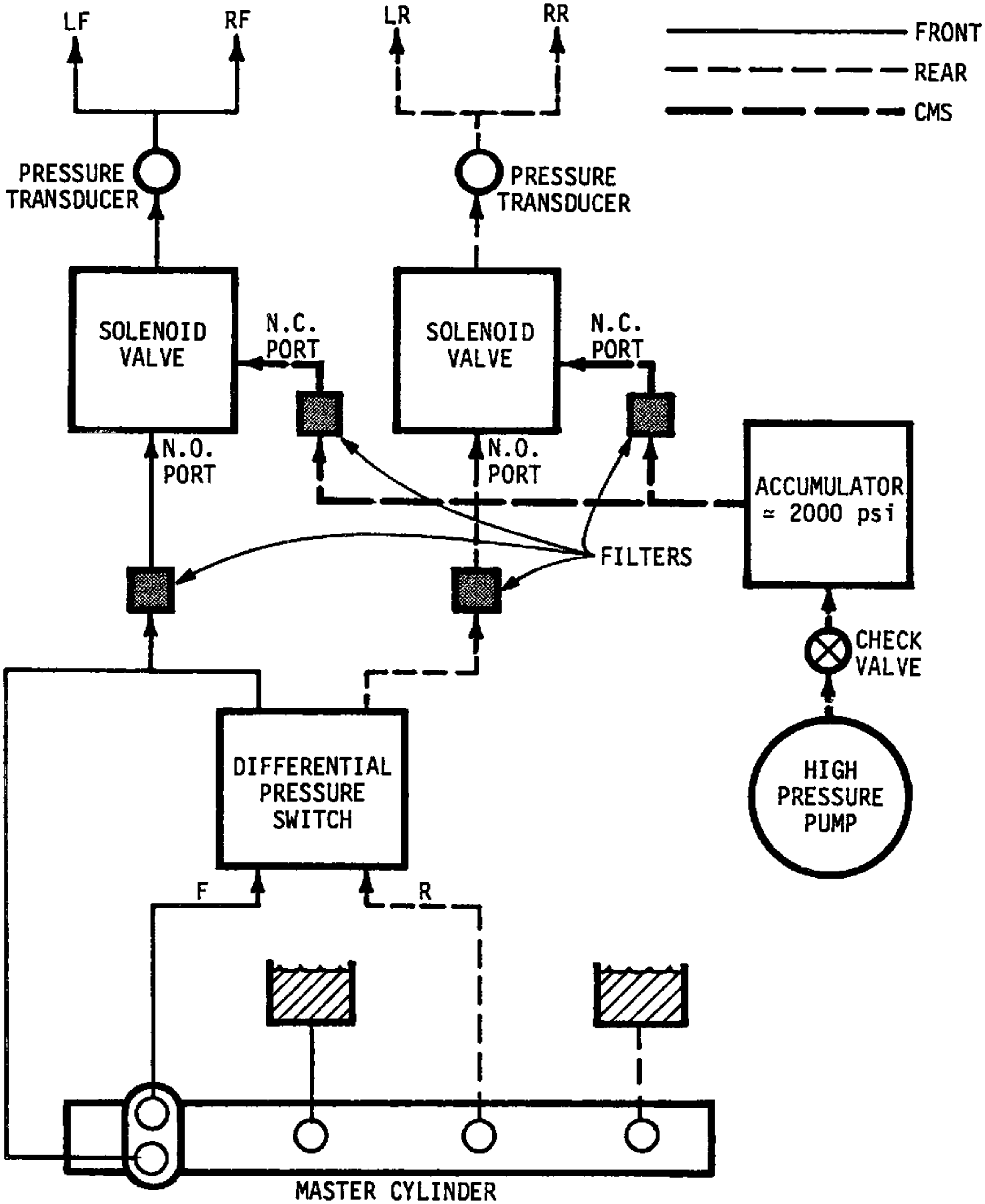
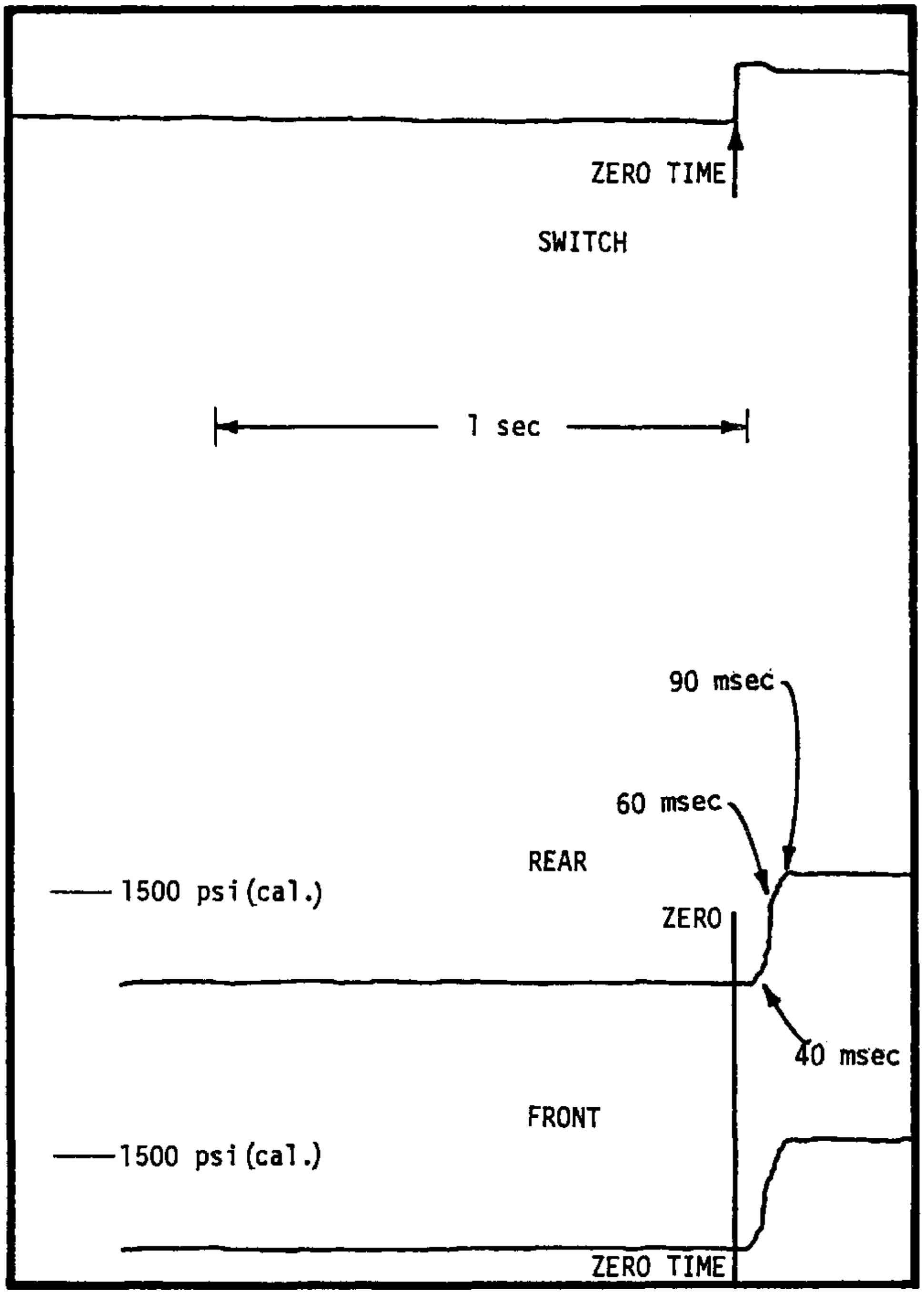


FIGURE 5-8. HYDRAULIC SCHEMATIC OF THE CMS



Note: "Zero time" refers to the time at which an electrical signal is sent to the CMS solenoids. The pressures shown here were measured just upstream of the anti-skid brake pressure modulators.

FIGURE 5-9. CMS BRAKE FLUID PRESSURE INCREASE

Parking Brakes

Because of space limitations, some parking brake components required special design. The most important is a pivoting equalizer assembly that connects the stock Fiat X1/9 brake lever and control cable to the brake actuator cable and stock Fiat rear wheel brakes. The brake actuator cable was also shortened (in order to retain the appropriate geometry for the equalizer).

5.8 TEST RESULTS*

During Phase III the RSV was subjected to two series of ride and handling tests. The first series was conducted in January and February 1978 (near the beginning of the program) and was described in Reference 5. Table 5-5 summarizes the tests conducted and the RSV's performance in them.

The second series of ride and handling tests was conducted in January and February 1980 (Reference 30). Table 5-6 summarizes these tests.

The Bendix Corporation also conducted braking tests during its development of the anti-skid brake system. The results (outlined in Table 5-7) show that the system substantially improves the RSV's braking performance on surfaces with low coefficients of friction (indicated by low skid numbers), at the cost of some loss of performance on high friction surfaces. On the latter a good driver is able to maintain a more optimal pressure at the caliper than the modulated pressure supplied by the anti-skid system. Nevertheless, the anti-skid system provides better controllability on any surface.

Finally, Minicars subjected two of the RSV prototypes to a few selected handling and braking tests. The tests were conducted with minimal instrumentation; the primary objective was to assure that the vehicles had no obvious deficiencies in their dynamic systems. Table 5-8 is a brief summary of these results.

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*CMS testing is discussed in Subsection 9.5.

TABLE 5-5. RIDE AND HANDLING PERFORMANCE (1978 TESTING)

No.	Test	Criteria	Specifications Met
RH1	Steady state yaw	Acceptability envelope	Yes
		Shape of curve	Yes
		Trend at higher and lower Gs	Yes
RH2	Transient yaw	25 mph lower limit	Yes
		70 mph upper limit	Test at nominal 65.4 mph
RH3	Returnability	Heading angle envelopes	24.5 mph – yes 50.0 mph – marginal
		Yaw rate at the end of 2 seconds	Yes
RH4	Maximum lateral acceleration	Maximum lateral acceleration achieved at various tire inflation pressure combinations	Yes
RH5	Slalom course	Minimum speed – 45 mph	Yes
		No overturning	Yes
RH6	J-turn	No overturning at 50 and 60 mph	Did not complete (structural failure)
RH7	Ride frequency	Front: 0.9 to 1.1 cps	No
		Rear: 1.2 to 1.4 cps	No

TABLE 5-6. RIDE AND HANDLING PERFORMANCE (1980 TESTING)

No.	Test	Criteria	Specifications Met
RH1	Steady state yaw	Acceptability envelope Shape of curve Trend at higher and lower Gs	Yes Yes Yes
RH2	Transient yaw	25 mph lower limit 70 mph upper limit	Yes Yes at 50 mph (test track limit)
RH3	Returnability	Heading angle envelopes Yaw rate at the end of 2 seconds	25.0 mph – yes 50.0 mph – yes
RH4	Maximum lateral acceleration	Maximum lateral acceleration achieved at various tire inflation pressure combinations	Yes
RH5	Slalom course	Minimum speed – 45 mph No overturning	Yes Yes
RH6	J-turn	No overturning at 50 and 60 mph	Yes
RH7	Control at breakaway	Regain control in less than 4 seconds	Yes
RH8	Roadway disturbance	Vehicle lateral deviation envelope	Yes
RH9	Straight line braking	Stopping distance less than 175 feet Pedal force envelope	Yes Yes*
RH10	Acceleration	30-70 mph in 18 seconds No loss of power around 100 foot radius circle	Yes** Yes
RH11	Ride frequency	Front 0.9 to 1.1 cps Rear 1.2 to 1.4 cps	No*** No***

*Test vehicle did not have vacuum assist during the tests. Pedal force tests were conducted later, after vacuum assist was incorporated.

**Test ran up to 64 mph (test rack limit). Based on extrapolation and theoretical prediction.

***Ride frequencies were not measured, but determined by calculation.

TABLE 5-7. BENDIX ANTI-SKID BRAKE PERFORMANCE

Surface (Skid Number Range)	Speed (mph)	Corrected Stopping Distance System ON (feet)	Corrected Stopping Distance System OFF (feet)	Improvement (percent)*
Wet X-10	30	76.1	92.6	+17.8
(18 to 35)	30	76.8	90.6	+15.2
	30	75.3	90.6	+16.9
Wet Jennite	30	73.5	90.0	+18.3
(28 to 48)	30	68.3	85.6	+20.2
	40	137.9	177.9	+22.5
	45	118.7	150.6	+21.2
Wet Asphalt (55 to 65)	30	52.0	49.4	- 5.3
Dry Asphalt**	30	41.0	38.5	- 6.5
(70 to 85)	60	159.9	156.0	- 2.5

*Percent improvement of system ON over system OFF.

**Locking of both front wheels sometimes erratic.

TABLE 5-8. "SPOT CHECK" TEST RESULTS

Parameter	Description
Vehicle number	M5-10
Test weight (lbs)	2,900
Steady state yaw	Tested at 25 and 50 mph clockwise and counterclockwise. Results were within the specification envelope.
Transient yaw at 25 and 50 mph	No indication of unusual behavior.
Returnability at 25 and 50 mph	Performance good at 25 mph and acceptable at 50 mph.
Maximum lateral acceleration on 100 foot radius circle	Lateral acceleration values were 0.64 to 0.74 Gs.
Straight line stopping from 30 and 60 mph and pedal force effort (full brake system only)	Pedal force within specification envelope. Stopping distance of 164 feet from 60 mph and 38 feet from 30 mph.
Pavement irregularity sensitivity	No measurable displacement in either direction at 40 mph.

Test Procedures

The test procedures in the braking and handling tests followed the guidelines given in the Intermediate Experimental Safety Vehicle Specifications. Most of the tests were repeated until three to five accurate data runs were obtained. A skilled test driver drove the car during the test maneuvers.

Test Instrumentation

Thirteen different transducers were used to obtain the measurements. Pre- and post-test calibration was carefully performed under the conventional standards. The data were recorded by an on-board 14 channel FM tape recorder (which was supplemented with 16 mm movie coverage in selected tests).

Data Reduction

Conventional manual data reduction techniques were used for the data reduction. The results were presented in the IESV Specification format.

Comments on the 1978 Series 1 Tests (Table 5-5)

The Series 1 tests were conducted at the Ventura County Airport. There were no instrumented braking tests and no pavement irregularity sensitivity and crosswind influence tests (the latter because of the lack of facilities). The transient and steady-state yaw response tests could not be performed at 70 mph (113 km/h) because of the lack of a large enough area to accommodate an 800 foot (244 meter) radius circle. Of the tests that were conducted, the car failed to meet the performance specifications for ride frequency and only marginally met the returnability specification. Although the RSV did not meet the ride frequency specifications, its ride frequencies are comparable with other production cars in that vehicle weight class. The returnability performance was improved later, as explained in Section 5.5.

Comments on the 1980 Series 2 Tests (Table 5-6)

The Series 2 tests were conducted at Minicars' Santa Maria test facility. The series included most of the Statement of Work tests. The tests not included were the

- Steady-state and transient yaw tests at 70 mph (because of the lack of area)
- Side wind disturbance (because of the lack of a wind machine)
- Brake pedal effort and failure mode tests (subsequently conducted with minimal instrumentation).

Among the tests that were conducted, only the ride frequency specifications were not met.

SECTION 6
PROPULSION

Emissions requirements for the RSV were 0.41 g/mile for hydrocarbons, 3.4 g/mile for carbon monoxide and and 1.3 g/mile for oxides of nitrogen. The fuel economy specification was 31 mpg (13.2 km/l) for the combined EPA driving cycles. The acceleration requirements were nominal, due to an allowance for the penalties expected for the high fuel economy goals. The initial goal for 0 to 30 mph (48.3 km/h) acceleration was 10 seconds and for 0 to 60 mph (96.5 km/h) acceleration was 22 seconds. The desired cruising range was set at 300 miles (483 km) under constant 55 mph (88 km/h) driving. Beyond all of these performance specifications, the propulsion system was to be producible or available at competitive prices to the consumer.

The powertrain activities had to take into account a number of trends in the automotive industry:

- Development of lighter, more compact, higher rpm – four- and six-cylinder gasoline engines
- Development of transverse mounted front wheel drive powertrains
- Development of three-way catalyst emission control systems
- Turbocharging of production gasoline engines
- Development of passenger car Diesel engines through redesign of production gasoline engines
- Turbocharging of passenger car Diesel engines
- Refinement of the three-valve, stratified gasoline engine
- Significant improvements in the fuel consumption of rotary engines using both the uniform and stratified-charge approaches
- Increased availability of four- and five-speed manual transmissions
- Introduction of automatic transmissions with torque converter lockup.

The RSV engine was selected late in Phase I (1976). At that time there were only two production engines that could be adapted to the RSV's rear engine/rear wheel drive configuration: the 1500 cc Honda Civic CVCC and the 1290 cc Fiat X1/9. We chose the Honda because it provided a better combination of fuel economy, emissions and acceleration in a simpler package. At that stage of its development, the RSV promised to have excellent fuel economy and low emissions relative to other cars, since the CVCC engine represented the state-of-the-art in small vehicle propulsion. The Phase III prototypes now use the 1978 Accord CVCC engine, a refined 1600 cc version of the earlier Civic design.

In the years since we selected the Honda engine, a number of advances in engine technology have resulted from increasingly stringent emissions standards and strong demand in the marketplace for better fuel economy. Significantly, in 1979 Honda, rather than modify the 1978 engine to meet the tougher 1979 and 1980 standards, replaced the Accord engine with a new design. As a result, the NHTSA awarded a separate contract to Western Washington University to upgrade the RSV's engine performance by using the new Honda Civic 1500 cc engine.

Today there are a number of other production engines that could be adapted to the RSV to enhance its overall performance. We are impressed with the Datsun 2000 cc NAPS-Z engine, although it might be too large for the RSV. Other possibilities include the Mitsubishi 1600 cc engine used in the Dodge Colt and Plymouth Champ and the 1600 cc engine used in the Ford Escort/Lynx.

A turbocharged version of the Honda engine was considered, but later dismissed because of difficulties in meeting the emission requirements and because of availability and producibility problems that would be encountered in mass production.

The basic characteristics of the Honda Accord engine used in the RSV are

Model year & Manufacturer	1978 Honda
Type	4 cylinder inline OHC stratified charge (CVCC)
Bore x Stroke	74.0 x 93.0 mm
Displacement	1599 cc
Compression ratio	8.0:1
Engine power	68 hp @ 5000 rpm
Engine torque	85 ft-lb @ 3500 rpm

The RSV transaxle went through a similar screening process; this resulted in the selection of the Honda five-speed transaxle. Its characteristics are

Manufacturer	Honda
Type	5-speed manual transaxle
Gear ratios	
5th	0.72
4th	0.85
3rd	1.18
2nd	1.82
1st	3.18
Reverse	2.92
Final drive	4.27

Again, continuing evolution made the choice in transmissions much wider at the end of the program than at the beginning. The newer transmissions have reduced weight, improved mechanical efficiency, and careful matching to engines to minimize brake specific fuel consumption.

6.1 AUTOMATED MANUAL TRANSMISSION

New car purchasers face a choice between manual transmissions (offering high efficiency) and automatic transmissions (offering convenience). Despite the upsurge in fuel prices, most people still seem to prefer the latter and over 80 percent of American-built cars in 1980 were equipped with automatics (Reference 11). In recent years the auto industry and others have addressed this tradeoff with considerable vigor; one potential solution is the automated manaul transmission developed for the high technology RSV.

Transmission speed ratio is a key factor for vehicle fuel economy. It is well known that the best speed ratios are those that optimize engine thermal efficiency. In the ideal case, an infinitely variable transmission can always yield optimum speed ratios; however, such transmissions have only recently demonstrated high mechanical efficiency and are still several years away from mass production.

The next best alternative is an ideal shift schedule (one in which the gears are shifted to maintain the best engine thermal efficiency). The most accurate way to achieve such a shift schedule is computer control. A computer that has stored in its memory the fuel consumption map of the vehicle's engine (such as that shown in Figure 6-1) can determine the optimum speed ratio for any given load and vehicle speed.

Minicars therefore modified the Honda five-speed manual transaxle for computer control and subcontracted to Dubner Compter Systems, Inc., Fort Lee, New Jersey the task of developing the computer hardware. The computer governs the throttle, the clutch and the gear changes of the Honda transmission.

Operation

The transmission is designed to be operated in almost the same way as an automatic. The vehicle has no clutch pedal or shift lever. One simply chooses any gear by pressing buttons labeled Reverse, Neutral, Drive, or First through Fifth. In Drive the forward gears are selected automatically by the computer; seleting the other positions causes the system to revert to manual control.

An important difference from most vehicles is that the accelerator pedal has no direct connection to the throttle. The only connection is through the computer. Under most conditions the throttle follows the accelerator pedal movements. The exception is during shifting, when the throttle is automatically closed, regardless of accelerator pedal position.

To start the car moving, the driver depresses the accelerator. This action is sensed by the computer, first gear is selected, and the clutch begins to engage. The clutch engagement pressure is regulated according to engine speed and accelerator position.

At small accelerator depressions the computer uses the clutch to keep the engine speed low. At larger accelerator depressions it increases the engine speed. If the actual engine speed is less than the demanded speed, the computer increases the clutch release actuator pressure to allow the clutch more slip. Conversely,

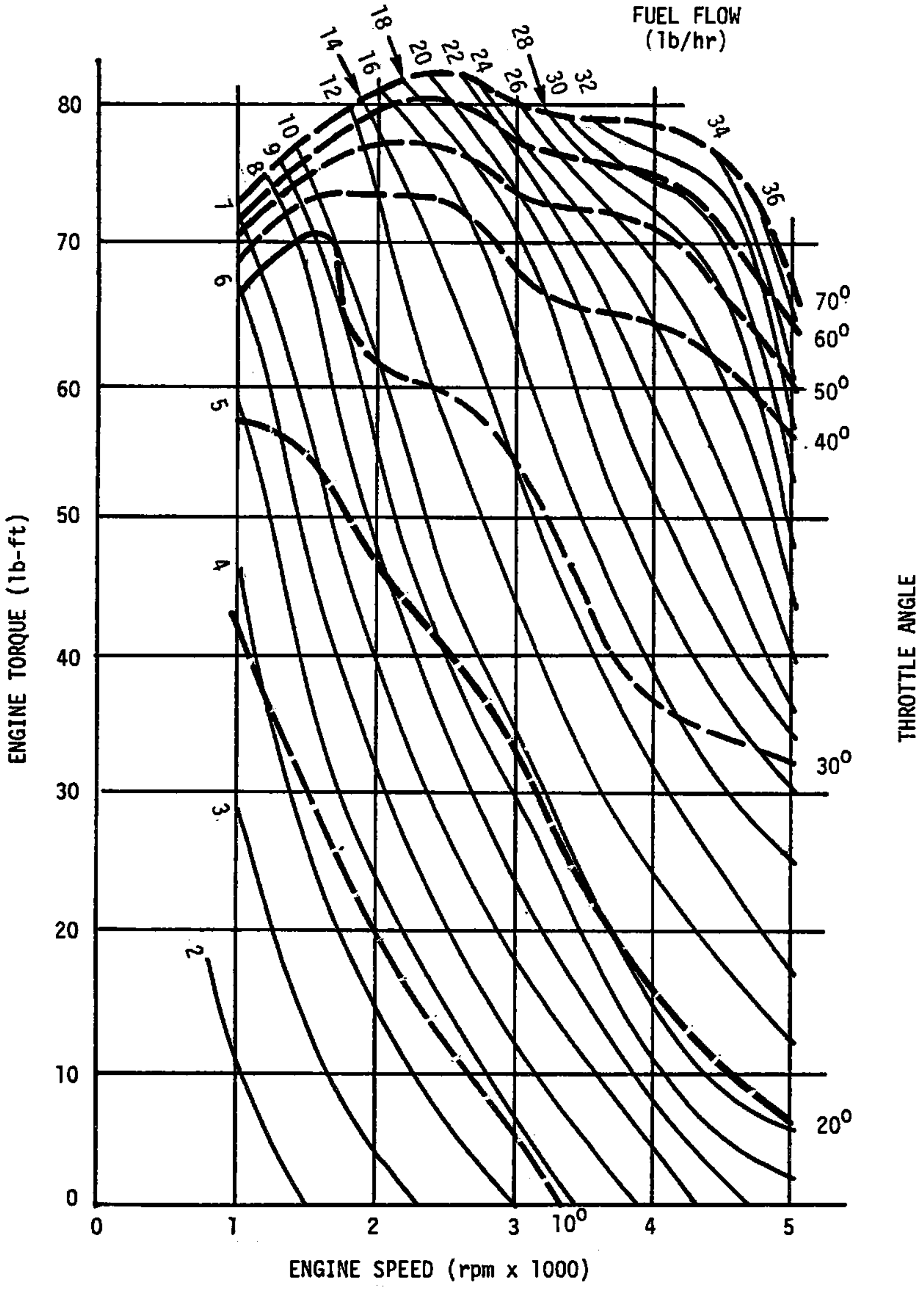

FIGURE 6-1. ENGINE FUEL CONSUMPTION MAP

if the engine speed is greater than the demanded speed, the clutch release actuator is vented, so that the clutch engagement is increased.

To prevent stalls, the computer also calculates engine acceleration. High engine acceleration (even when the speed is below the demanded speed) causes an increase in clutch engagement. High deceleration causes the clutch to release. Once clutch lockup is sensed (through a comparison of engine to vehicle speed), the clutch release actuator is fully vented. The computer constantly determines the optimum gear ratio for given accelerator pedal positions and vehicle speeds.

Figure 6-2 shows a flow diagram of the system logic. The main loop is executed at 50 msec intervals.

System Components

The system is controlled by pneumatic actuators that offer regulated pressure to the clutch, shifters and throttle. The pneumatic pressure is regulated by pulsing the solenoid valves and modulating their open times.

The components of the automated manual transmission are

- Digital microcomputer
- Honda Accord five-speed manual synchromesh (nonsynchromesh reverse) modified transaxle with three double acting air cylinders
- Honda Accord clutch and clutch release lever, pneumatic slave cylinder
- Monroe automatic 12 Volt air compressor
- Six solenoid activated valves controlling the shift cylinders
- Three solenoid activated valves controlling the clutch cylinders
- Air operated throttle actuator
- Two solenoid activated valves controlling throttle position
- Air pressure reservoir
- Air pressure regulator
- Sensors of
  - Engine rpm (magnetic)
  - Axle rpm (magnetic, bidirectional)

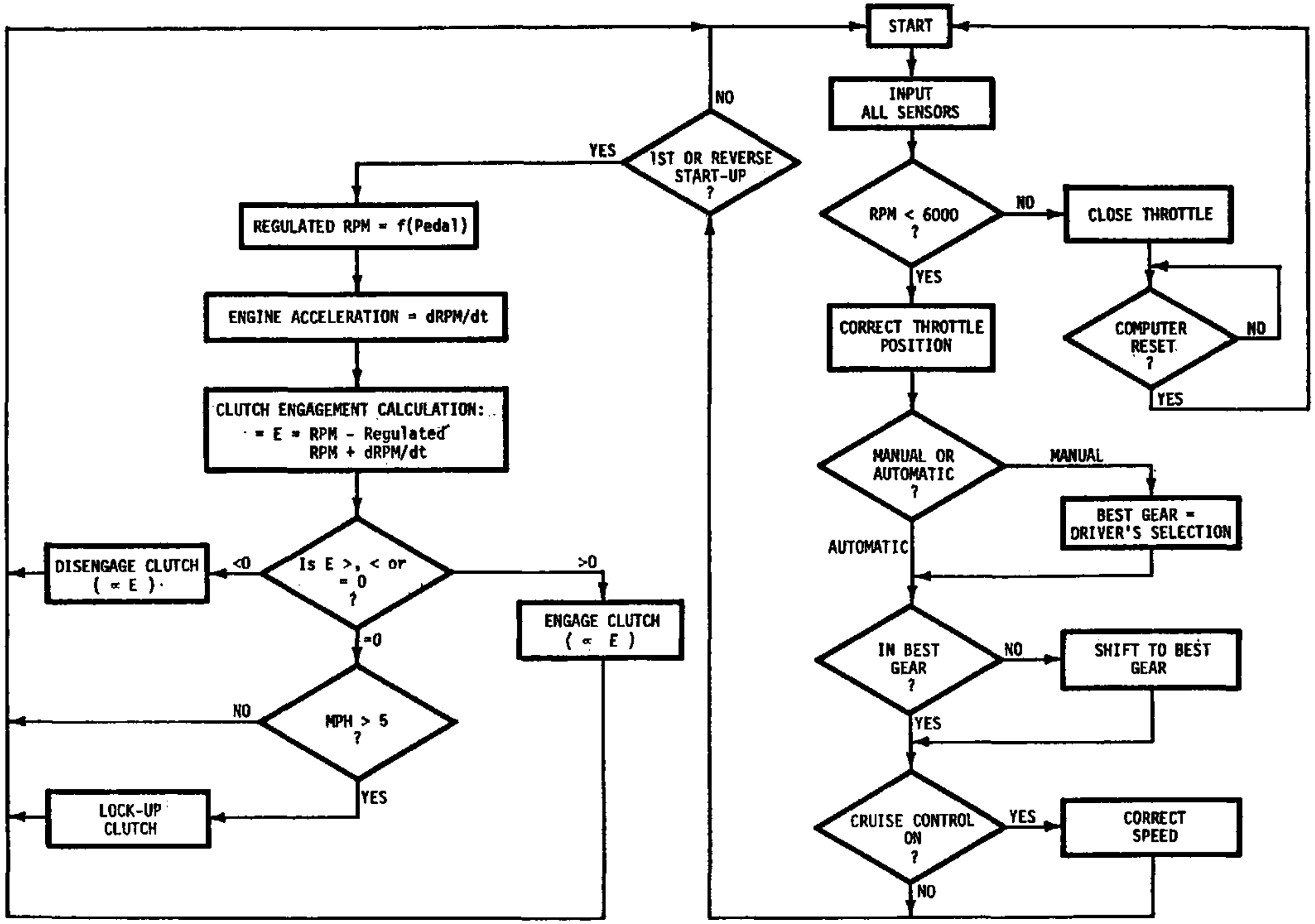

FIGURE 6-2. FLOW DIAGRAM OF THE AUTOMATED MANUAL TRANSMISSION

- Brake actuation (switch)
- Throttle position (potentiometer)
- Accelerator position (potentiometer)
- Drive range selection (pushbuttons).

A list of the sensors, actuators and control valves used in the automated manual transmission is given in Table 6-1. Subsection 9.3 describes the processing hardware.

TABLE 6-1. SENSORS, ACTUATORS AND CONTROL VALVES IN THE AUTOMATED MANUAL TRANSMISSION

Sensors	
Engine Speed	AIRPAX magnetic pickup (No. 11-0003)
Vehicle Speed	AIRPAX magnetic pickup (No. 14-0002)
Acceleration Position	0-10K linear potentiometer
Throttle Position	0-5K rotary potentiometer
Drive Selection	8 pushbuttons
Actuators	
Shifting	Three ARO 3/4" bore cylinders (No. 0176-1009-0)
Clutch	One ARO 1-1/2" bore cylinder (No. 0315-1009-01)
Throttle	One ARO 1-1/8" bore cylinder (No. 0118-1009-01)
Control Valves	
Shifting	Six 3-way Skinner (No. V53DA2050)
Throttle	Two 2-way Skinner (No. V52DA1100)
Clutch	One 3-way Skinner (No. V53DA2050)
	One 2-way Skinner (No. V52DA1100)

Shifting

Once the vehicle speed becomes too great for the particular gear and accelerator position, the computer shifts the transmission. Simultaneously, it disengages the clutch, releases the throttle and vents the transmission actuators (which puts the transmission in neutral). All of this occurs in approximately 100 msec. The new gear is then selected and the throttle is opened just enough to bring the engine to the proper speed for engagement. When this speed is attained, the clutch is re-engaged at a rate proportional to the accelerator position.

At low power demand (as sensed by low accelerator positions), the shift speeds are low. The shift speeds progressively increase as the accelerator is depressed. The shift speeds for maximum fuel economy are shown in Figure 6-3.

Starting the Vehicle

The automated transmission is operated with compressed air provided by two 12 Volt compressors (both installed in the engine compartment). When the ignition is on, the compressors maintain the air pressure of the system above 120 psi (827 kPa). Compressed air operates the clutch, the gear selectors and the throttle.

In starting the engine, it is necessary to first let the compressors bring the system up to pressure. To do this, the key must be turned to "crank" momentarily. After the engine is started, the driver simply pushes the button marked "D." Any accelerator pedal movement will then trigger the clutch to begin engaging. The best performance will occur if rapid pedal movements are avoided, since there is some delay in the system. If there is no accelerator response, tapping the brakes will reset the computer. There will be no accelerator response while the brake pedal is depressed.

6.2 ENGINE MODIFICATIONS

A few engine modifications were necessary to adapt the Honda/Accord CVCC to the RSV engine compartment. The most important is the carburetor wedge, which was installed so that the engine could be rotated 15 degrees aft of vertical (to permit access to the spark plugs, which are on the front of the engine). The wedge (mounted between the carburetor and the Honda intake manifold) maintains the carburetor's horizontal position.

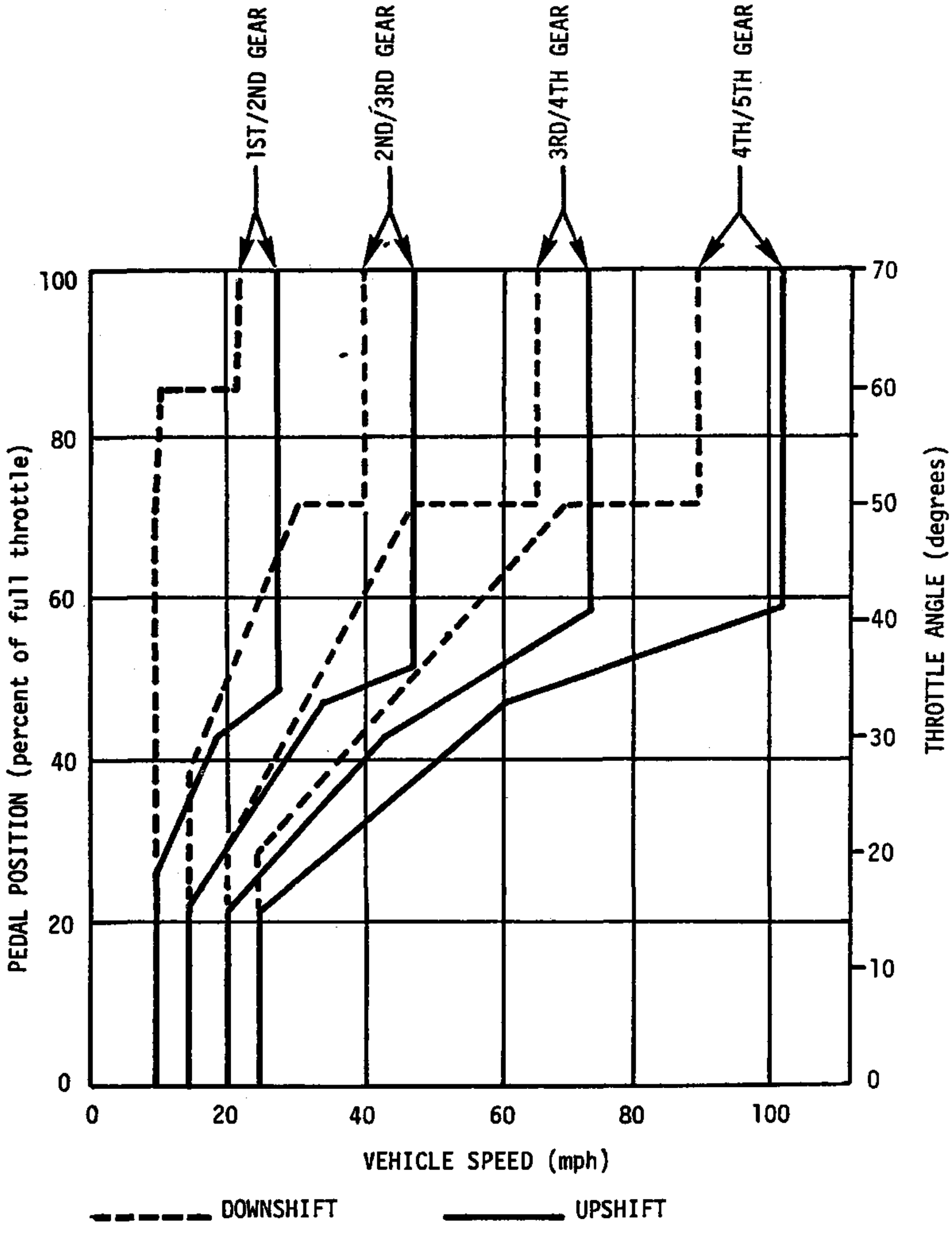

FIGURE 6-3. SHIFT SPEEDS FOR MAXIMUM FUEL ECONOMY

The other modifications included the rerouting of some oil passages and the installation of an adapter plate to rotate the transmission with respect to the engine.

6.3 OTHER PROPULSION SYSTEM COMPONENTS

Fuel Storage Cell

To improve fuel storage crashworthiness, the RSV was fitted with a fuel cell, rather than a conventional sheetmetal tank. The fuel cell, housed on the centerline of the RSV in a special compartment between the rear and mid-compartment crossmembers, was fabricated to Minicars' design specifications by Aero Tec Laboratories (ATL), Waldnick, New Jersey. It is similar to fuel cells used on some race cars. The outer skin is molded polyurethane and is filled with blocks of reticulated ultra-low density foam. The fuel cell has a 8.3 U.S. gallon (31.4 liter) capacity.

Cooling System

The Fiat X1/9 radiator was selected for its capacity, aspect ratio and integral motor-fan assembly. The aluminum coolant feed and return tubes are routed under the vehicle.

Axles

Completely new rear axle half-shafts were designed and fabricated to accept Fiat outboard and Honda inboard U-joints. These half-shafts are the only interfaces required between the Honda differential and the Fiat hubs.

Engine Cradle

The engine cradle is a simple tubing assembly which integrates the complete propulsion system, drive axles and rear suspension into a single element. One advantage of the engine cradle is that the entire assembly can be installed in, or removed from, an RSV with four rubber-mounted bolts. This allows the powertrain to be assembled and tested remotely from the vehicle structure during production.

Propulsion System Accessories

All propulsion system accessories for the RSV are standard Honda components. Accessories that are not directly mounted on the engine/transaxle are located on the inner panels of the engine compartment. The alternator, coil, condenser and clutch control are mounted on the engine/transaxle. The coolant surge tank, emissions control valves, voltage regulator, and fuel pump and filter are mounted in the engine compartment.

Exhaust System

The emissions control is furnished by "stratified charge" combustion, spark advance control, exhaust gas reaction and positive crankcase ventilation. Since the Honda engine is "clean burning," it requires no catalytic system. The RSV is fitted with an oval muffler and a short length of exhaust tubing. The muffler is mounted just forward of the engine.

6.4 EMISSIONS, FUEL ECONOMY AND ROAD PERFORMANCE TESTS

During the development of the automated manual transmission we conducted emissions and fuel economy tests in a test bed RSV and a Honda Civic. A new 1978 Honda Accord 1599 cc engine and transmission were installed in the Honda Civic and were broken in during 2,500 miles (4,000 km) on the road and on a chassis dynamometer. This mileage roughly approximates the 4,000 mile (6,437 km) breakin required of EPA certification emission and fuel economy vehicles. The engine and transmission were then transferred to our RSV driveline test buck, and the carburetor wedge was installed to maintain proper carburetor float bowl orientation. The engine was retuned to the manufacturer's specifications, its raw emissions were monitored, and preliminary fuel economy measurements were made.

At the time the engine development effort was conducted, the RSV had a curb weight of approximately 2,450 pounds (1,110 kg); thus it fell into the 2,750 pound (1,250 kg) inertia weight category. Therefore, for the emissions and fuel economy testing we specified a 2,750 pound inertia weight and an 8.5 hp (6.3 kW) absorber setting for the dynamometer. The latter was based on the results of the coast-down tests described in Subsection 7.2.

As originally tested at Automotive Environmental Systems, Inc., Westminister, California, the RSV buck had the following (approximate) emissions and fuel economy:

	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	Fuel Economy (mpg)
F.T.P.	1.6	15.0	1.9	23.9
Highway	0.2	3.9	2.0	37.1
Combined				28.5

Because these results were short of our goals, we installed a small catalytic converter (a quick start catalyst from a 1978 California version Dodge Omni) in the exhaust system. A retest showed a slight improvement:

	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	Fuel Economy (mpg)
F.T.P.	1.2	12.1	1.3	23.7
HOT 505 (BAG 3)	0.55	10.2	1.6	28.3

Finally, we advanced the ignition timing from the stock 5 degrees before top dead center (BTDC) to 11 degrees BTDC – and produced:

	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	Fuel Economy (mpg)
F.T.P.	1.18	10.7	1.1	27.8
Highway	0.08	0.9	1.8	42.3
Combined				32.9

While these data met the 1979 emission requirements of 1.5, 15 and 2 g/mi HC, CO and NO_x, and exceeded our fuel economy goal of 32 mpg (combined), it did not achieve the emissions goals of 0.41, 3.4 and 1.3 g/mi HC, CO and NO_x.

We also performed road performance tests with the Phase IIIb RSVs. The acceleration time for 0 to 30 mph was found to be 6 seconds and for 0 to 60 mph was 21 seconds.

SECTION 7
BODY EXTERIOR

The design of the RSV body exterior is based on a number of considerations — including aerodynamics, styling, pedestrian protection, weight and cost. This section describes the selection of materials for the external components (Subsection 7.1); the rationale behind the shape of the body exterior (Subsection 7.2); and how the exterior contributes to reducing pedestrian injuries and fatalities (Subsection 7.3).

7.1 MATERIALS

Virtually all current external automotive surfaces (except for glazing) are fabricated from steel, fiber-reinforced plastic (FRP) or reaction-injection molded (RIM) urethane. Steel is still the most popular choice, primarily because of its durability, surface finish and low unit cost in mass production. But the higher initial costs of FRP and RIM urethane are partially offset by their lower weight and their greater resistance to corrosion; in many cases, their use is now justifiable on the basis of life cycle cost.

Parts made from RIM urethane and FRP have similar weights and production costs, but urethane's flexibility gives it an additional advantage: it can sustain minor impacts without damage. Consequently, RIM urethane has recently found widespread use in bumper fascias (which must meet the Federal damageability standards). In fact, the 1981 Oldsmobile Sport Omega even has fenders made of RIM urethane.

Minicars selected RIM urethane for the exterior surfaces most prone to damage (see Figures 7-1 and 7-2). Consequently, much of the cosmetic damage on conventional vehicles would not be visible on the RSV, even if the underlying body-in-white suffered minor damage. The rear panel, hood panels and upper rear fenders (which are not so subject to damage) are fabricated from FRP (so as to reduce costs in limited production quantities). The hood surround is also FRP, because of the need to provide stiffness at the latch and hinges. In production,

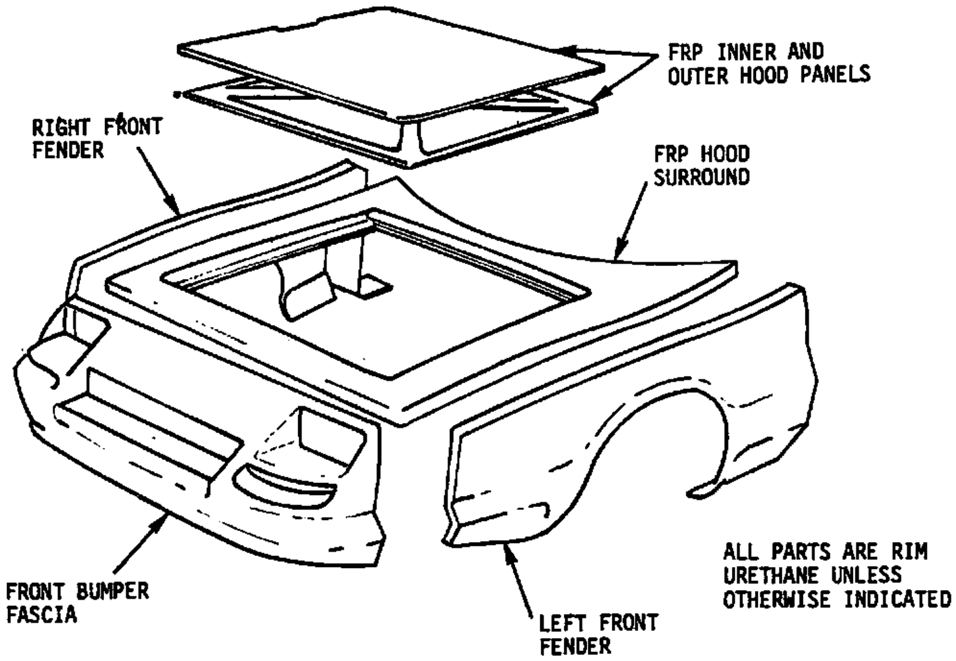

FIGURE 7-1. FRONT EXTERIOR PARTS

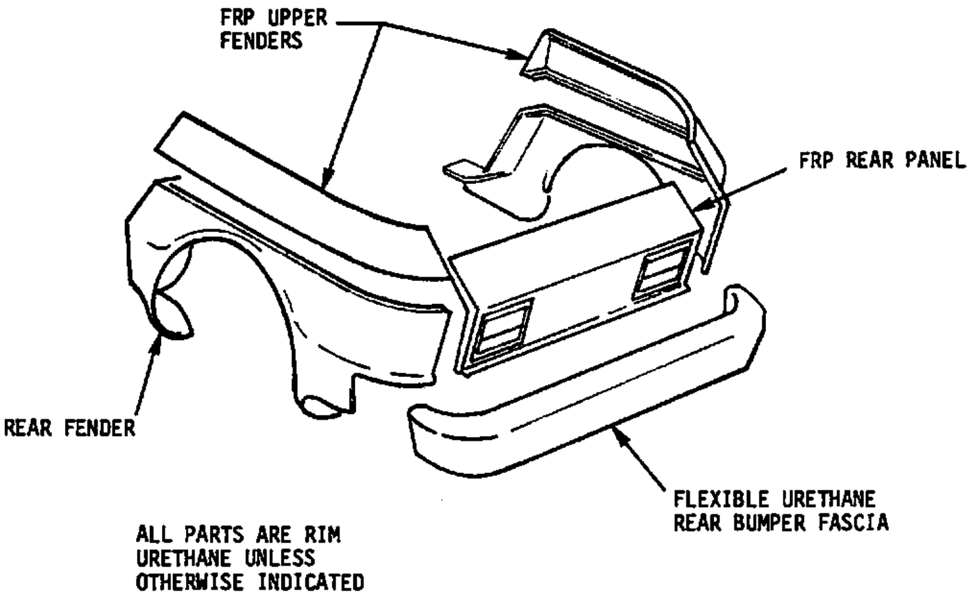

FIGURE 7-2. REAR EXTERIOR PARTS

the rear bumper fascia would be RIM, but, to reduce development costs during this program, we used a surrogate part made from a flexible urethane resin hand lay-up.

For the prototype RSV the RIM urethane parts are fabricated in cast kirksite molds by the Bailey Division of the Imhart Corporation (Seabrook, New Hampshire). The part thicknesses range from 0.125 inch (3.2 mm) to 0.198 inch (5.0 mm). The fenders have a flexure modulus between 80,000 and 100,000 psi (5620 and 7030 kg/cm^2). The fascias, which require more flexibility, have a flexure modulus between 22,000 and 25,000 psi (1550 and 1760 kg/cm^2).

Selecting the optimum flexure modulus involves a tradeoff between achieving sufficient flexibility at low temperatures and maintaining rigidity at high temperatures. We tested the latter by heating a front fascia to a mean surface temperature of 120°F (49°C) for 70 minutes with infrared lamps. The urethane exhibited no permanent deformation. However, evidence of "clotheslining" (indentations between supports) in the final RSV prototypes indicates that some increase in stiffness is warranted.

7.2 AERODYNAMICS AND STYLING

The RSV's safety requirements are not incompatible with an acceptable exterior styling treatment and excellent aerodynamics. Traditional automobile design completes the vehicle styling first and makes aerodynamic "fixes" later. In contrast, the RSV's basic shape was generated from forms which have both low drag characteristics and strong visual appeal. These forms include the semi-fastback roof line, the severe tumble home of the body sections, the flat sloping hood line, and the heavily rounded plan form of the body. The styling details, developed within the context of the basic form, included the large area of glass, the flared wheelhouses, and the planar lower body surfaces. The overall styling was influenced by the Mercedes C-111 rotary engine research car, the Lotus four seater coupe, the Lamborghini "Trapeze" and some of the Japanese safety cars.

One of the RSV design goals was to achieve a drag coefficient of 0.30, which would provide a significant improvement in fuel economy over conventional sedans at highway cruising speeds. During Phase II the California Institute of Technology conducted a wind tunnel test program using a 1/4 scale RSV. They were able to achieve a drag coefficient of less than 0.30 by making simple modifications to the test model, including the addition of a front air dam, a trailing edge spoiler, and a rear anti-flow-separation air foil on the rear fascia. The front air dam and the trailing edge spoiler were incorporated into the Phase III design.

Early in Phase III we conducted coastdown tests over two velocity ranges: 85 to 35 mph (135 to 55 km/h) and 50 to 0 mph (80 to 0 km/h). These tests were not performed under rigorous EPA procedures, and care must be exercised when comparing the results with those of other vehicles. However, the 0.39 drag coefficient which we calculated was lower than any four-seat automobile in production at the time (1977).

The Phase III styling changes were relatively minor. The body form and fender flairs were made more crisp, to enhance the appearance and to help stiffen the RIM urethane parts, and the parking lights and taillights were relocated, to permit the use of inexpensive production components.

7.3 PEDESTRIAN PROTECTION

By properly designing a vehicle's exterior surfaces, it is possible to significantly reduce the injuries and fatalities of pedestrians struck by the vehicle. The RSV design addresses the three principal injury mechanisms of pedestrian impacts: the impact of the leg by the bumper, the impact of the body and head with other vehicle surfaces (usually the hood), and the later impact of any part of the body or head with the ground. Most fatalities result from head strikes with the vehicle and with the ground.

Bumper Design

The Battelle leg impact simulations (described in Subsection 3.4), showed that both the bumper foam and the rubrics were too hard to satisfactorily cushion leg impacts. We therefore began experimenting with configurations in which the flexible RIM urethane fascia was located forward of the rubrics and foam.

It was found that moving the fascia 5 inches (12.7 cm) forward reduced the impactor's peak accelerations from 180 to 66 Gs, meeting our 70 G objective. When this configuration was tested, the 7.0 pound (3.2 kg) impactor (with an initial velocity of 25 mph) received an almost constant 47 G acceleration as it deformed the fascia, and then reached the 66 G peak while the foam was deforming.

Battelle then tested the displaced fascia concept in full scale tests; in these tests an RSV sled buck struck a 50th percentile adult male dummy in the side of one leg. The standard bumper and 5 inch displaced fascia configurations were both tested at 20 mph (32 km/h) and 25 mph (40 km/h). The results are given in Table 7-1. Not surprisingly, they show that small increases in impact speed may cause considerably higher acceleration levels. As expected, the displaced fascia significantly mitigated the foot and knee accelerations (even though it did increase pelvic accelerations to some extent). Perhaps more important were the indications that the displaced fascia could also mitigate life threatening injuries to the head and chest.

Displacing the fascia forward could, therefore, help reduce pedestrian injuries, at least in the 20 to 25 mph range. Moreover, an extended fascia could even enhance the car's appearance. Unfortunately, we were unable to add this modification to the Phase III prototypes, due both to time limitations and to the high costs required to modify tooling.

Hood

The RSV hood (Figure 7-3), is designed to cushion pedestrians in impacts and to prevent them from being thrown onto the pavement. By sandwiching a phenolic foam sheet between FRP inner and outer panels, we were able to make the hood buckle downward under pedestrian impact loads and absorb the impact energy. The phenolic foam absorbs most of the energy, while the FRP panels provide sufficient rigidity. In both of the 25 mph Battelle tests, the hood buckled and otherwise appeared to perform adequately (although our only quantitative measures of success were the dummy injury measures themselves).

TABLE 7-1. DUMMY INJURY MEASURES FROM BATTELLE PEDESTRIAN IMPACT TESTS

Velocity at Impact (mph)	Fascia Position	Peak Resultant Acceleration (Gs) at Time (msec) After Impact										Head Severity Index
		Head		Chest		Pelvis		Knee		Foot		
		(Gs)	(msec)	(Gs)	(msec)	(Gs)	(msec)	(Gs)	(msec)	(Gs)	(msec)	
20.0	Normal	94	(138)	25	(126)	29	(16)	198	(24)	200	(62)	661
25.0	Normal	133	(116)	34	(129)	48	(24)	364	(21)	330	(52)	1307
20.0	5" forward	63	(159)	29	(160)	33	(69)	50	(51)	39	(89)	258
25.0	5" forward	75	(130)	22	(78)	58	(46)	106	(37)	260	(56)	838

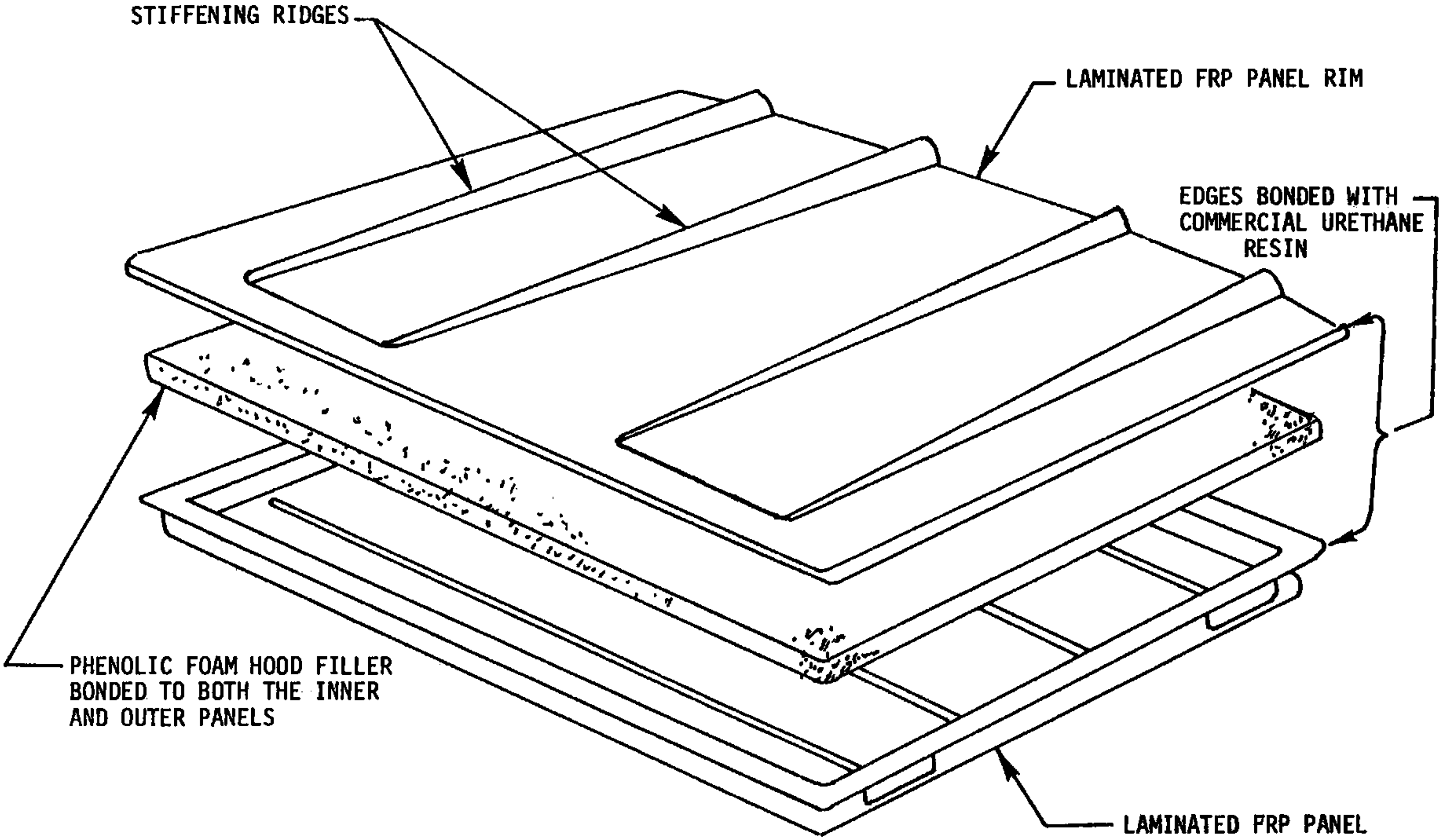

FIGURE 7-3. HOOD ASSEMBLY

SECTION 8
DRIVER CONTROLS AND ENVIRONMENT

8.1 DISPLAYS AND CONTROLS

In today's automotive industry there is a strong trend toward the digital display of information. Digital displays offer both a more stylish interior treatment and significantly greater flexibility than do conventional gauges. In addition, these displays are becoming less expensive – and are particularly attractive if the vehicle already has a microcomputer.

Unfortunately, development cost limitations precluded the installation of digital displays in all RSVs. Consequently, a conventional analog gauge display became the standard RSV instrument panel. The only exception was the high technology RSV, for which Minicars and a subcontractor, RCA of Princeton, New Jersey, selected a Burroughs self-scan alphanumeric gas plasma display. At the time of our selection, these units offered the most inexpensive means to display the necessary quantity of information in an acceptable automotive format. (However, recent cost reductions have probably made electroluminescent units the best choice today.) The integration of the Burroughs display with the dash can be seen in Figure 8-1, which shows how the controls and displays have been located at the periphery of the steering wheel, to avoid occlusion by the stowed airbag.

The Burroughs system operates on 12 Vdc and has a 32 character, single line capacity. A flexible display format allows the driver to select either of two modes (shown in Figure 8-2). The "status check" mode contains the trip odometer and displays the time, water temperature, oil pressure, fuel economy and battery condition. The "nominal" mode displays the fuel level, engine speed and vehicle speed. The speedometer and the fuel gauge are both analog because of driver familiarity with that format.

The digital display will, under certain conditions (Table 8-1), flash 3 second warning messages at 20 second intervals. The system will also continuously show "HI", "LO" or "OK" adjacent to the water temperature and oil pressure sections of

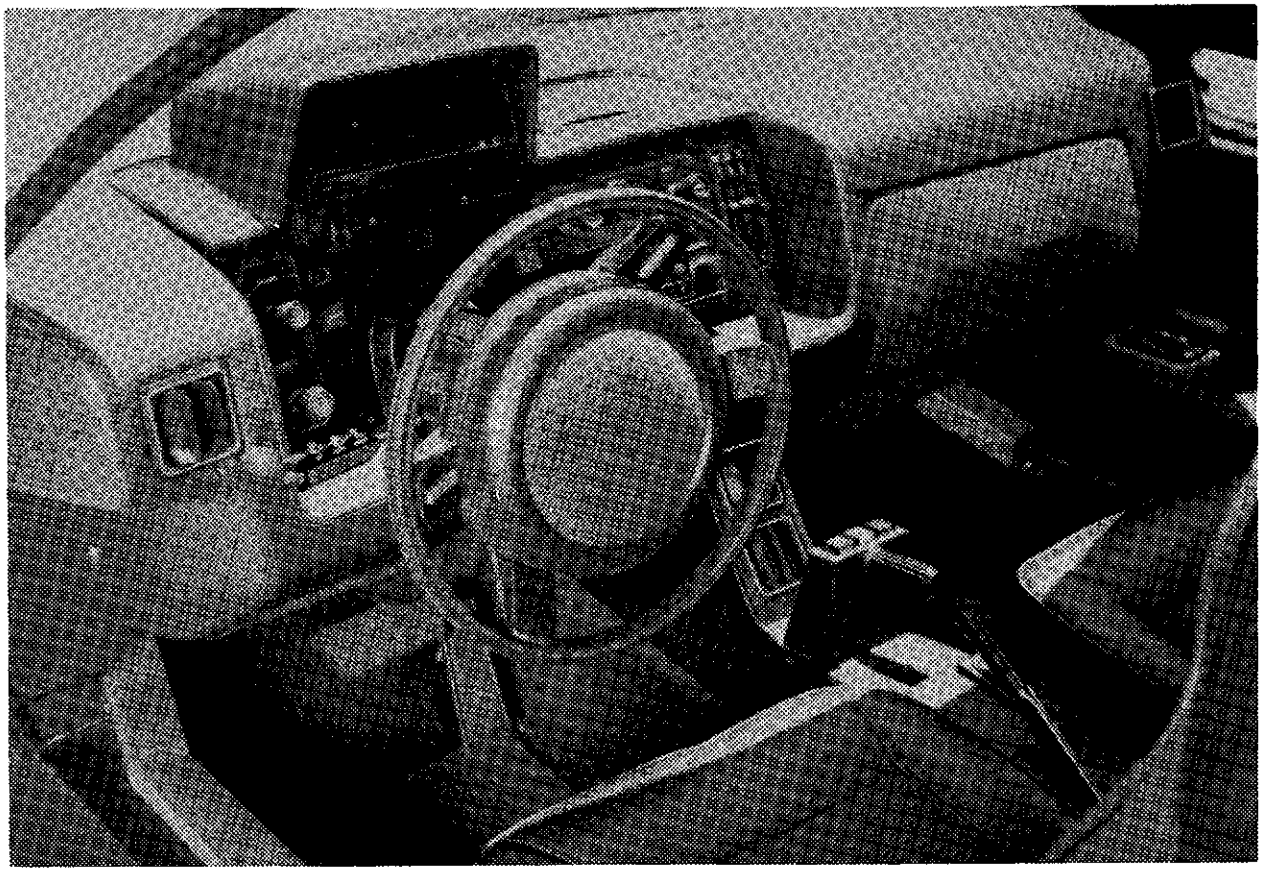

FIGURE 8-1. HIGH TECHNOLOGY RSV DRIVER STATION

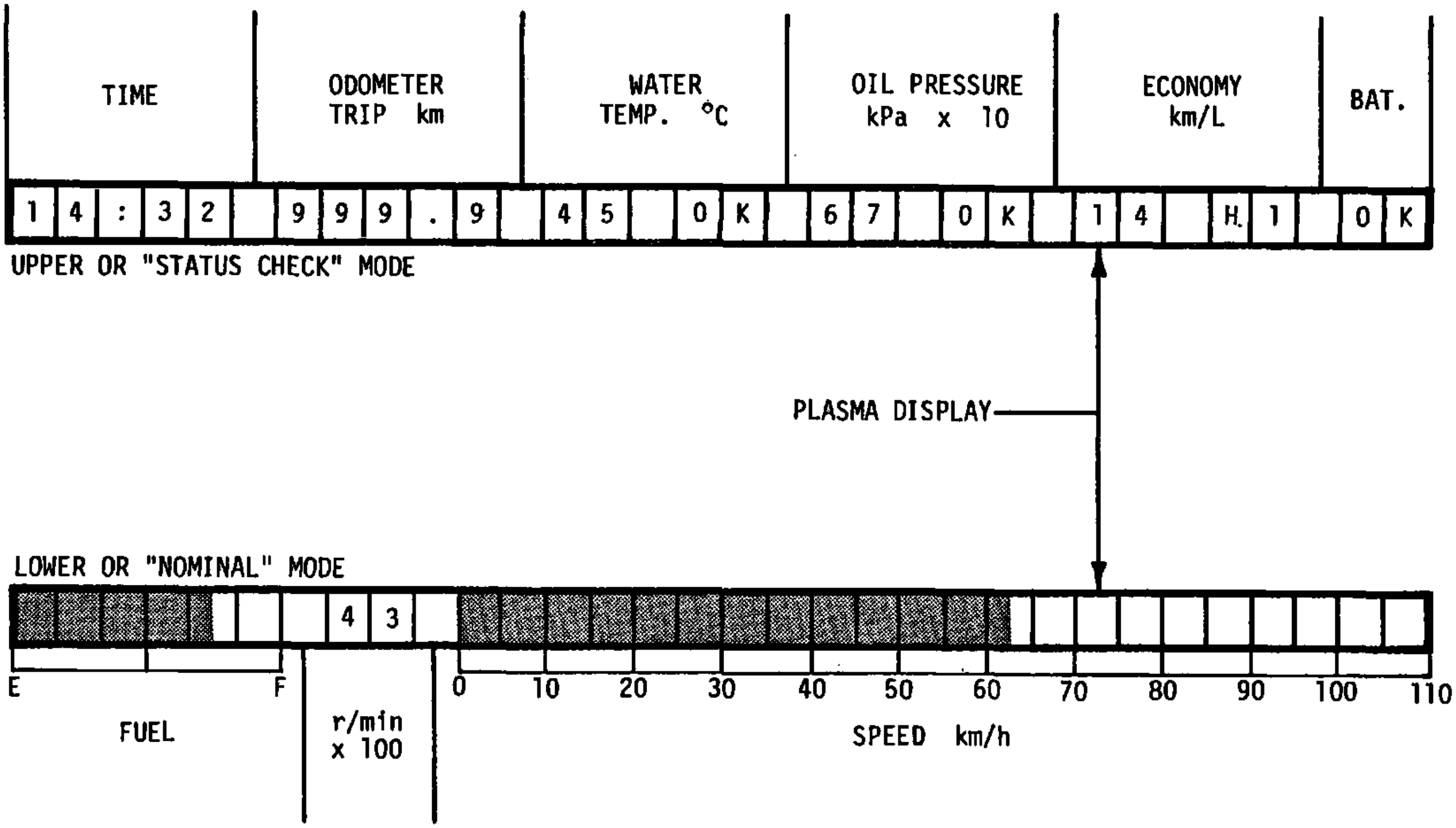

FIGURE 8-2. HIGH TECHNOLOGY DRIVER DISPLAY

the display (according to the criteria listed in Table 8-1). "LO" and "HI" are signaled for fuel economies below 9 km/1 (21.1 mpg) and above 13 km/1 (30.6 mpg). The words "OK" or "LO" appear beneath the "BATTERY" label for battery voltages above or below 5 Volts, respectively.

TABLE 8-1. DISPLAYED WARNING MESSAGES

Message	Activation Criteria
"WATER TEMPERATURE HIGH"	Water temperature >97°C
"OIL PRESSURE LOW"	Oil pressure <20 kPa
"RESTRAINT SYSTEMS OUT"	Squib-to-ground voltage <6 V or >10 V
"BRAKE FLUID LOW"	Signal from brake fluid container switch
"ANTISKID OUT"	Signal from brake system software
"SERVICE BRAKE ON"	Signal from hand brake switch
"DOOR OPEN"	Signal from switch on either door
"DANGER - SLOW DOWN"	Closing speed >3 m/sec or range <10 m (from headway control)

The RSV employs fully conventional foot controls. Hand controls follow standard human factors practices; all labels are illuminated and all controls are indicated by universal graphics. The transmissions, except for the automated transmission in the high technology RSV, are shifted via a conventional shift handle on the center spine. (Sections 6 and 9 describe the special controls for the high technology RSV's automated transmission and headway control system.)

8.2 VISIBILITY

Good visibility was achieved without incurring significant structural or aerodynamic penalties. This resulted from the car's extensive glass surface area and lack of a solid C-pillar. The only real drawback to the inclusion of so much glass is increased heat loading (see Section 8.4).

No standard visibility tests were run by Minicars, but the Japan Automobile Research Institute (Tsukuba, Japan) conducted visibility tests (as part of the RSV Phase IV Program) and was critical of vision impairment at the A-pillars. This problem was caused by the RSV prototype fabrication techniques, and we expect that production engineering efforts could reduce A-pillar/door pillar vision impairment angles to conventional values without a loss in strength.

8.3 ROOMINESS

Based on measurements made according to the Motor Vehicle Manufacturers Association (MVMA) standards (Figure 8-3), the RSV has an EPA Interior Volume Index of 97.7 cubic feet (2.77 cubic meters). Its cargo space (hatchback and luggage compartment) is 9.5 cubic feet (0.27 cubic meters), and the sum of these two volumes places the RSV in the EPA compact car size class.

Table 8-2 compares the RSV's interior volume index and cargo volume with those of other well-known cars. Obviously, the RSV provides ample room for its occupants, but relatively little space for their luggage. The initial specification called for 14 cubic feet (0.40 cubic meters) for cargo, but, as prototype development progressed, the provision of adequate trunk space received comparatively low priority, and several cubic feet were lost.

For instance, it was found that the air cushion and knee restraint systems, in order to provide high speed occupant protection, required more bulk than we had anticipated. These systems took up space that would normally have gone to the heating, ventilating and air conditioning (HVAC) systems, and, despite our concerted efforts to optimize packaging efficiency, we were forced to move some of the HVAC hardware forward of the the firewall, into the luggage compartment. This change alone reduced the cargo space by 2 to 3 cubic feet (0.06 to 0.08 cubic meters) – although these numbers may be somewhat exaggerated by the RSV's prototype status. We feel that the present HVAC systems design has excellent packaging efficiency, but there may still be room for improvement in a full production engineering treatment.

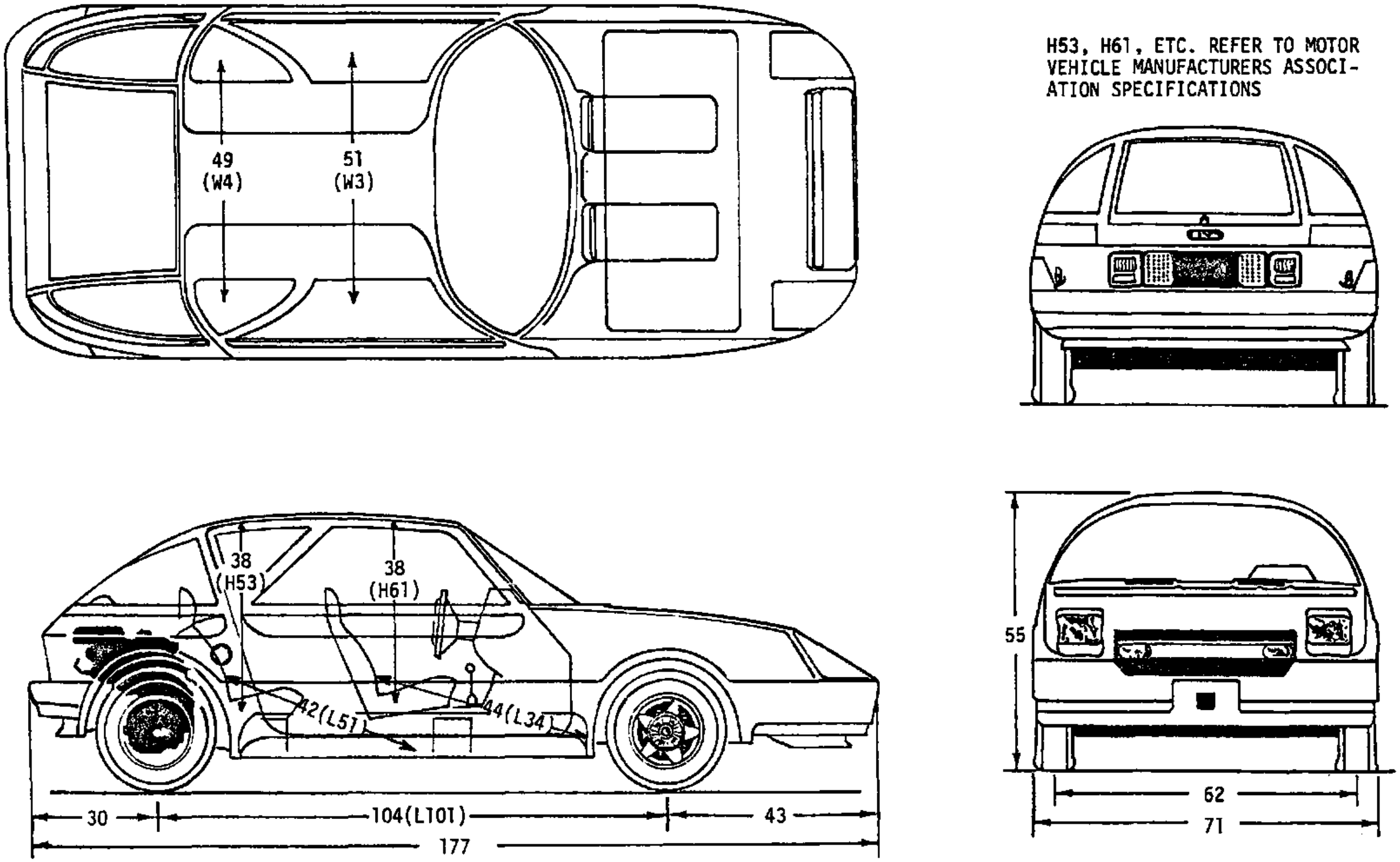

FIGURE 8-3. SIGNIFICANT RSV DIMENSIONS (IN INCHES)

TABLE 8-2. EPA VOLUME CALCULATIONS FOR 1980 PASSENGER CARS

Automobile	EPA Size Class	EPA Interior Volume Index (ft^3)	Cargo Volume (ft^3)
Ford Pinto	Minicompact	75	8
Chevrolet Chevette	Subcompact	79	10
Honda Accord	Subcompact	81	10
Volkswagen Rabbit	Subcompact	77	14
RSV	Compact	97.7	9.5
Volvo Sedan	Compact	89	14
Oldsmobile Omega	Compact	94	14
Pontiac Phoenix (hatchback with automatic transmission)	Mid-size	96	20
Chevrolet Malibu (two-door)	Mid-size	96	17
Chevrolet Malibu (four-door)	Mid-size	102	17

Note: Unless otherwise specified, all cars have standard engine and manual transmission.

The usable luggage compartment volume was further reduced by the addition of a vacuum boost on the brake system (described in Section 5). The vacuum boost hardware intrudes significantly into the trunk. Again, production engineering efforts would probably improve this situation.

8.4 HEATING, VENTILATION AND AIR CONDITIONING

The RSV HVAC systems are similar to those of conventional automobiles. In fact, the heating core, evaporator and plenums are all production automotive equipment. A distinguishing feature of the HVAC system is that it is possible to have warm defrost air while the air conditioner is operating (although, in that case, the defrost air passes through both the evaporator and the heater core).

The RSV's unique design affects the thermodynamic properties of the passenger compartment. The foam-filling provides excellent insulation, but the large glass surface areas admit more sunlight and add to the cooling requirements. (In a Phase II test the RSV's interior temperature averaged 3°F higher than that of a Pinto, when the two cars were placed side-by-side in direct sunlight with their windows closed.) It was also necessary to run the hot water hoses from the heater core back to the engine. We first connected the hoses directly to the radiator, a shorter distance, but found that the radiator required excessive time to warm up on cold days.

SECTION 9

RADAR AND ELECTRONICS
RADAR CONTROLLED COLLISION MITIGATION SYSTEM

9.1 INTRODUCTION

Beyond developing crash management systems, the RSV Program also investigated systems that could reduce societal cost by changing the pre-accident environment. These investigations led to the radar controlled Collision Mitigation System (CMS) installed in the high technology RSV. The radar development effort was performed by the RCA Corporation* at their David Sarnoff Research Center in Princeton, New Jersey.

There are two basic philosophies on the use of radar for accident avoidance and mitigation. One, which has been studied in three German programs (References 12, 13 and 14), employs radar to warn drivers of impending dangerous situations. The German efforts are directed toward improving safety on the autobahns, where both high speeds and large variations in speed are common. Because of the relatively long reaction time of the driver (between 0.6 and 1.0 second) at expressway speeds, the warning has to be based on long range information (typically 100 to 150 meters).

The traffic environment in the United States, which has a legal speed limit of 55 mph throughout, is substantially different. In this situation we try to mitigate a collision by automatically applying the brakes when the collision has become inevitable. The key considerations here are the accurate detection of all unavoidable collisions and the elimination of all false alarms. The effective range of the radar is limited to 80 to 100 feet (25 to 30 meters) because over longer distances the opportunities for false alarms increase rapidly – and, more importantly, a skilled driver might still perform an avoidance maneuver (one which could be hampered by automatic braking).

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*RCA's work is fully documented in their Phase III Final Report, reproduced as Appendix A. Much of Section 9 was condensed from this report.

In this program, therefore, the emphasis was on the automatic reaction of the system only when a high-speed collision is unavoidable. This does not exclude the use of longer range radar for warning systems; but such systems had been covered extensively by the German radar development efforts and thus were not addressed in this program.

The high technology RSV also has a radar headway control system which shares much of the CMS hardware and software. Headway control is a sophisticated "cruise control" that automatically operates the throttle to maintain a safe distance behind another vehicle. In a particular automobile the CMS would rarely, if ever, be used; but the headway control could improve driver convenience and might lend a strong sales appeal to the inclusion of radar in future cars.

A serious consequence of any automatic braking system is that it may actually cause some accidents, because of false alarms or other exceptional circumstances. Most importantly, the sudden, unexpected application of brakes could cause the driver to lose control of the vehicle. To reduce the likelihood of such a possibility, we have also incorporated a Bendix anti-skid brake system into the high technology RSV. (This system is described in Section 5.) Although the use of anti-skid devices in driver-activated braking systems is difficult to justify from a cost/benefit standpoint, we feel that they are essential in collision mitigation systems.

The RSV Program, by exploiting the recent emergence of low cost microprocessors, developed hardware that shows important possibilities for computer controlled systems. The high technology RSV employs digital processing subsystems that control the (subcontractors shown in parentheses)

- Collision mitigation braking (RCA)
- Anti-skid braking (Bendix)
- Headway control (RCA, Dubner)
- Automatic gear shifting (Dubner)
- Driver display operation (RCA).

Presently, each of these functions is controlled by a separate microprocessor, as Figure 9-1 shows; Table 9-1 lists the inputs to these subsystems. Further

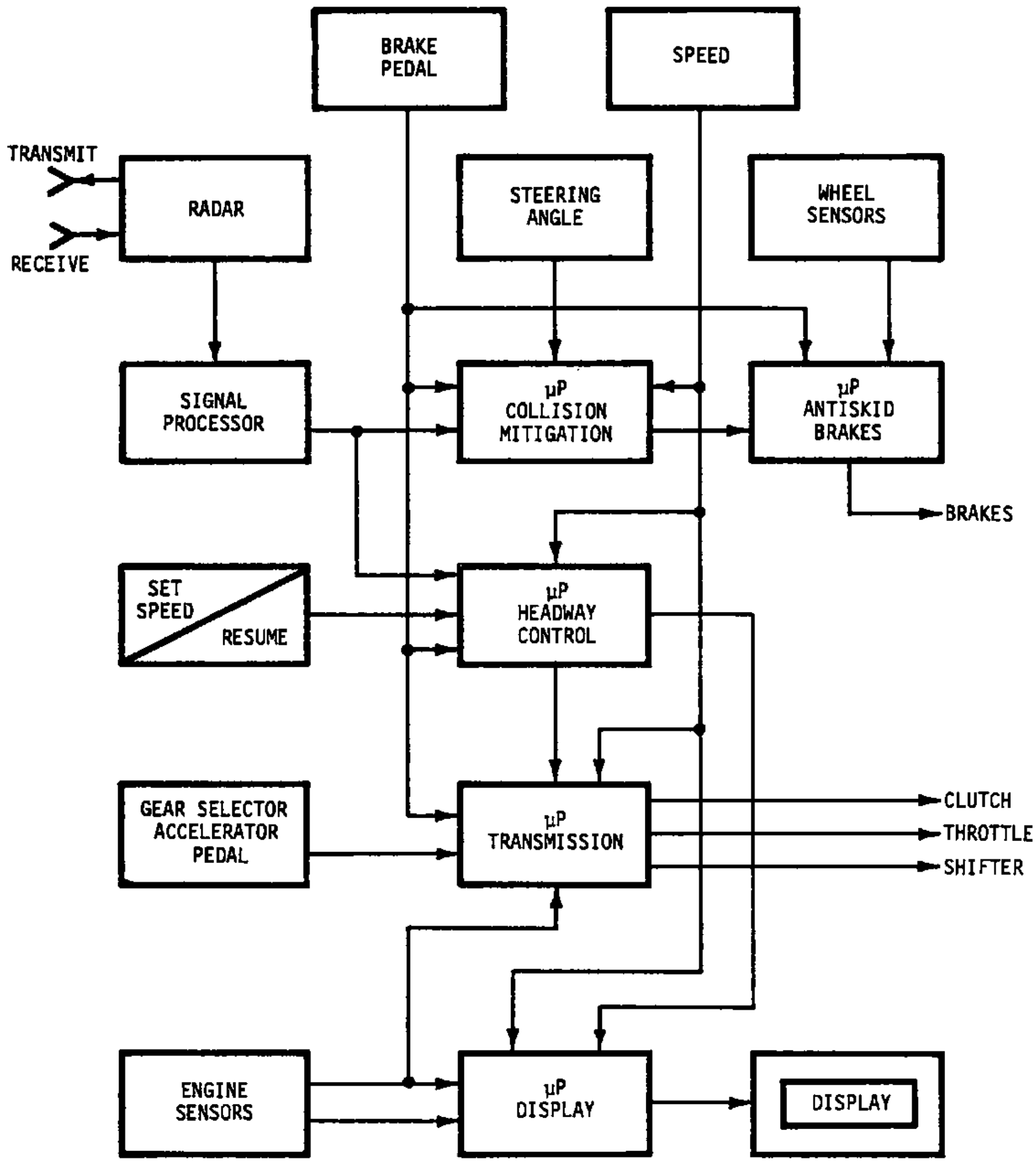

FIGURE 9-1. RSV ELECTRONIC FUNCTIONS

TABLE 9-1. RSV ELECTRONIC INPUTS

Input	Goes to*	Transducer
Range	C,H,D	Bistatic, noncooperative FMCW radar
Range Rate	C	Bistatic, noncooperative FMCW radar
Brake Pedal Position	C,H,B,T	On/off switch (also used to activate brake lights)
Steering Angle	C	Belt driven rotary potentiometer
Vehicle Speed	C,H,T,D	Magnetic pickup adjacent to transmission final reduction gear
Headway Control State	H	Momentary contact pushbuttons on turn signal stalk, labeled "ON," "OFF," "SET SPEED," "SET 55," and "RESUME"
Wheel Speeds	B	Magnetic pickup adjacent to toothed brake rotor in each wheel
Accelerator Pedal Position	T	Precision conductive film potentiometer
Carburetor Throttle Position	T	Precision conductive film potentiometer
Gear Selector	T	Momentary contact pushbuttons, labeled "D," "N," "R," and "1" through "5"
Engine Speed	T,D	Magnetic pickup adjacent to starter ring gear on flywheel
Transmission Shifter Position	T	Linear potentiometers on each shift rail (3 total)
Start Switch	T	Standard automotive ignition switch
Water Temperature	D	Thermocouple
Oil Pressure	D	Pressure transducer
Fuel Flow	D	Turbine-driven opto-electronic emitter-detector pair
Fuel Level	D	Float operated potentiometer
Battery Voltage	D	None required

*Microprocessors: C - collision mitigation system; H - headway control; B - anti-skid braking system; T - automated transmission; D - display refinement could reduce the number of microprocessors to two or three (one would function as a backup and provide a "limp home" capability). Questions of time sharing between microprocessors and interleaving of computer programs, however, were not addressed during the RSV Program.

9.2 RADAR RF DESIGN

Automotive radar systems may be either cooperative or noncooperative. In a cooperative system the targets are identified by a special tag (attached to the target vehicle) that affects the reflected radio frequency (RF) energy in a unique way. Previous RCA systems have used frequency doubling (Reference 15) and phase modulation (Reference 16) to distinguish the target return from regular backscatter clutter. Noncooperative systems simply process any reflections of their transmitted signal. In the Phase III program RCA first used a cooperative X-band system and later developed a noncooperative Ku-band system.

Cooperative X-Band Radar

Two major advantages of a cooperative system are the practical elimination of false alarms (only targets provided with a tag are recognized by the radar) and the ability to obtain an accurate, nonambiguous target location (the tag provides a single clean point of reflection). These characteristics were especially desirable for the development of the headway control algorithm. The use of a cooperative radar in the initial development phases eliminated a large number of possible problem areas and permitted more concentration on actual algorithm development. The cooperative system could then be exposed to a large variety of traffic conditions, so that its behavior could be conveniently evaluated and optimized. In this part of its development program, therefore, RCA modified the X-band (10.575 GHz), monostatic (single antenna) radar (used during the RSV Phase II Program) to cooperative operation under the phase modulated tag principle.

In the cooperative system, alarms are triggered only by "tagged" targets, so that false alarms from road signs, guard rails, and other reflecting objects in the radar beam are eliminated. Thus the useful warning range can be extended. Also, since the radar cross-section of the tag is constant, there is no problem with fluctuating returns and the dynamic range is reduced. A tag on a compact car will return as much signal as will a tag on a truck.

In practice, cooperative radar is not feasible for collision mitigation systems, at least in the near term, because all potential targets would have to be equipped with tags. Consequently, RCA only used cooperative systems for development work, and selected a Ku-band, noncooperative radar for the high technology RSV.

Noncooperative Ku-Band Radar

The Ku-band radar is a forward-looking, bistatic, noncooperative, frequency modulated/continuous wave (FMCW) system. A block diagram of the system is shown in Figure 9-2. The RF section of the radar is made up of a transmitter chain and a receiver chain, each with its own antenna. The transmitter chain consists of a varactor-tuned oscillator and modulator, power divider and printed circuit antenna. The receiver chain consists of a printed circuit antenna (identical to the transmitter antenna), isolator and mixer. The IF section has a shaped preamplifier and a shaped postamplifier. Voltage regulators and ignition noise filters are included in the amplifiers. Table 9-2 shows some of the performance characteristics of the system.

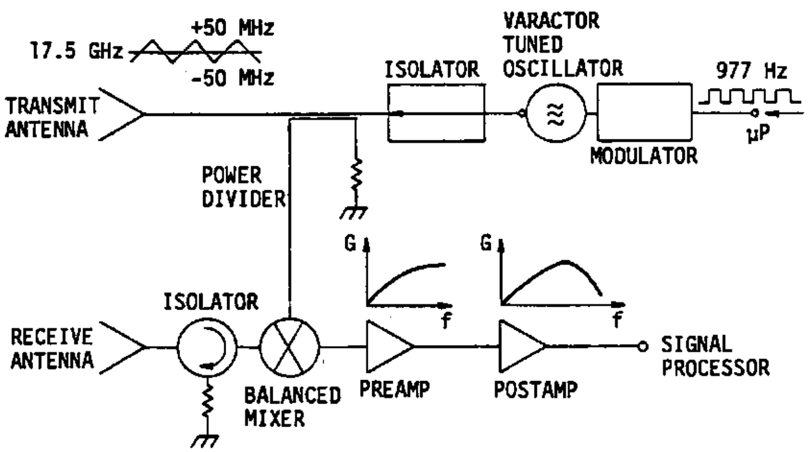

FIGURE 9-2. Ku-BAND FMCW RADAR

TABLE 9-2. PERFORMANCE CHARACTERISTICS OF THE Ku-BAND RADAR

Parameter	Value
Frequency, f_o	17.5 GHz
Power Output, P_o	10 mW
Frequency Deviation, Δf	± 50 MHz
Modulation Rate, f_m	977 Hz
Horizontal Beamwidth, θ_H	3 degrees
Vertical Beamwidth, θ_V	5 degrees
Antenna Gain, G	30 dB
Bistatic Antenna Assembly Size	30 x 8 x 1 inch (77 x 20.5 x 2.5 cm)
Range	23 to 100 feet (7 to 30 meters) collision mitigation 26 to 165 feet (8 to 50 meters) headway control
Range-Rate	0 to 200 ft/sec (0 to 60 m/sec)

The operation of the radar is straightforward: the varactor-tuned oscillator and modulator furnish a 15 mW frequency-modulated carrier to the power divider. The carrier frequency is 17.5 GHz and has triangular modulation of ± 50 MHz deviation. One output of the power divider (11 mW) is directed to the antenna, and the other (2.75 mW) enters the local oscillator port of the mixer via a rigid cable. (The power split is 6 dB, to compensate for the 1.6 dB loss in the cable.) The transmitted signal is reflected back to the radar from a target and is coupled to the signal port of the mixer through the antenna and isolator in the receiver chain.

Because of the time delay between transmission and reception, the frequency of the received signal will differ from the transmitted signal (local oscillator signal), and a beat frequency signal will be generated at the IF port of the mixer. The beat frequency (which is recovered in the processing circuitry) contains the desired range and range-rate information. The range and range-rate information, and the speed and steering angle of the radar-equipped vehicle, are processed further to determine if a vehicle control action is necessary.

To avoid false alarms from vehicles in adjacent lanes or from roadside objects, it is desirable to have a narrow beamwidth. Beamwidth is proportional to wavelength and inversely proportional to antenna size. Thus, to achieve a sufficiently narrow beamwidth, one can either use large antennas or go to high frequencies. Large antennas, of course, are more expensive and are ultimately constrained by physical size limitations. The availability and cost of RF components constrains the use of higher frequencies.

RCA selected the upper end of Ku-band (17.5 GHz) as a compromise frequency. At 17.5 GHz, transferred electron oscillators (TEOs) still give state-of-the-art performance, and microstrip technology can be applied cost effectively to the other microwave components. In addition, microwave absorption through the atmosphere is still small (0.02 dB/nautical mile for 1 percent water vapor and 6 dB/nautical mile for heavy rain). The actual Ku-band antenna is 13 x 7.5 inches (33 x 19 cm) – 19 x 11 wavelengths – and has a 3 degree beamwidth in azimuth and a 5 degree beamwidth in elevation.

A 3 degree azimuth beamwidth has been found to be a good compromise between beam confinement at far ranges and target acquisition at close range. For example, at 164 feet (50 meters) the beam coverage is ±51.6 inches (±1.31 meters). Although the possibility of missing a target off to the side exists at close range, the decreased probability of false alarms in the far field is of greater importance.

The Ku-band antenna (Figure 9-3) uses a construction similar to the Phase II X-band design. The antenna consists of 512 fan-shaped dipoles printed together with the feed structure on both sides of a Duroid circuit board. A ground plane is located, as a reflector, a quarter wavelength behind the printed board. This arrangement provides a high-gain antenna in compact form (13 x 7.5 x 0.8 inches; 33 x19 x 2 cm). Two identical printed circuit antennas, one for transmission and one for receiving, were used for the Ku-band bistatic radar.

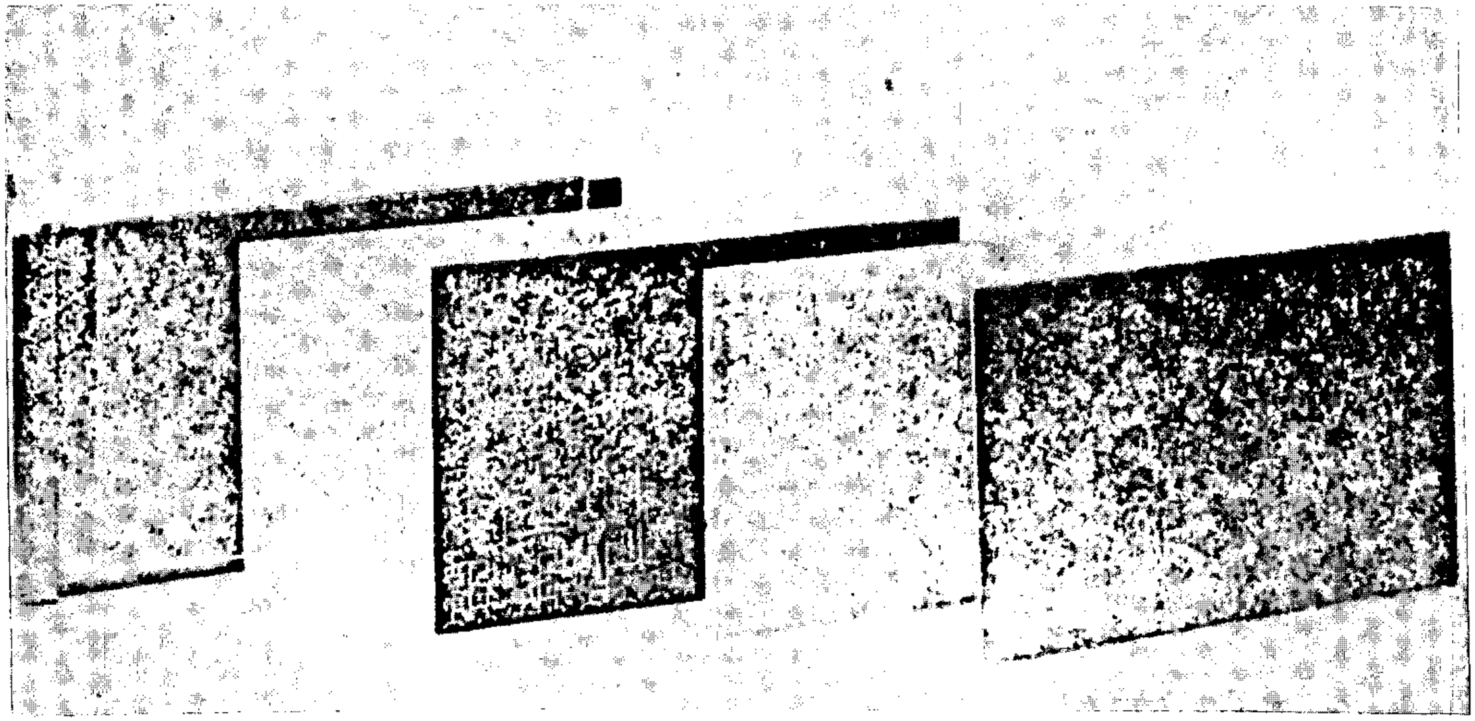

FIGURE 9-3. EXPLODED VIEW OF ANTENNA

The antennas' response was tested in a special anechoic chamber, using a 110 square foot (10 square meter) corner reflector mounted at the same height as the antennas. The measured beamwidth was found to be close to the 3 degree azimuth and 5 degree elevation objective values. Figure 9-4 shows a contour plot, in which the return was monitored at the output of the preamplifier (shown in Figure 9-2). To confine the return to approximately 100 feet (30 meters), as needed for CMS operation, a shaped postamplifier was designed with the aid of a computer program (discussed in Appendix A of Appendix A). Figure 9-5 shows the power contour at the output of the shaped postamplifier. An inspection of this figure shows that, when the threshold level of detection is set for 100 feet, the maximum coverage is within -3 feet (-1.0 meter) and +1.5 feet (0.5 meter) off axis (a sharply defined microwave beam).

Radome Design

The radome structure, located directly forward of the antennas, must meet a number of requirements, including:

- Same shape as the vehicle's exterior body
- Suitable electrical properties (low dielectric constant and low loss)
- Environmental soundness, (waterproof and solvent resistance).

First, the suitability of the standard RSV front structure was evaluated in the RCA anechoic chamber. An attempt was made to beam microwaves directly through the RIM outer skin and acrylonitrile-butadiene-styrene (ABS) air scoop. Because of the high dielectric loss factors of the two materials, and the difference in their dielectric constants, the microwave signal was severely degraded.

RCA therefore developed and fabricated a separate radome structure. Candidate materials considered for the structure are listed in Table 9-3. Foamed polystyrene seemed to be the best building block because of its extremely low dielectric constant and dissipation factor. A sheath of closed cell, cross-linked, expanded polyethylene was selected as a cover over the polystyrene. This material does not absorb moisture, is highly resistant to automotive solvents, and has acceptable electrical properties.

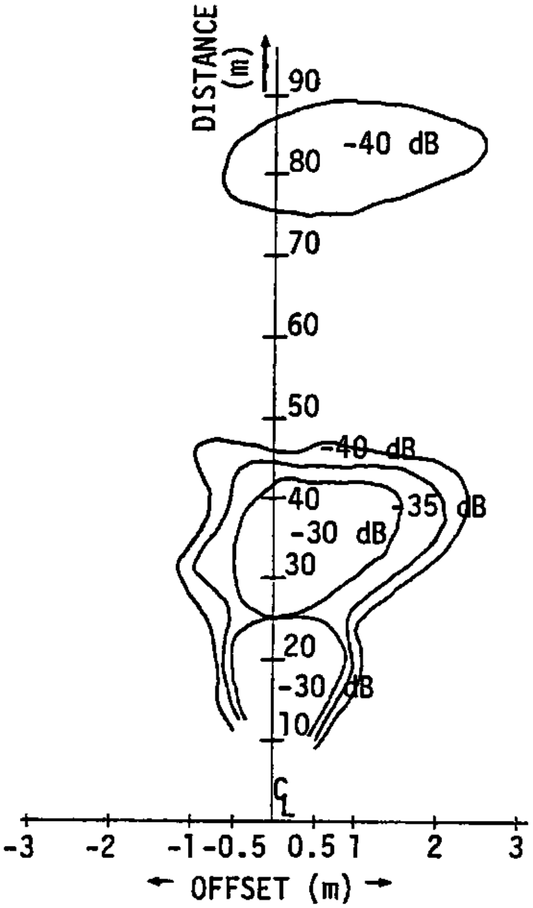

FIGURE 9-4. COVERAGE PATTERN Ku-BAND RADAR – OUTPUT OF PREAMPLIFIER

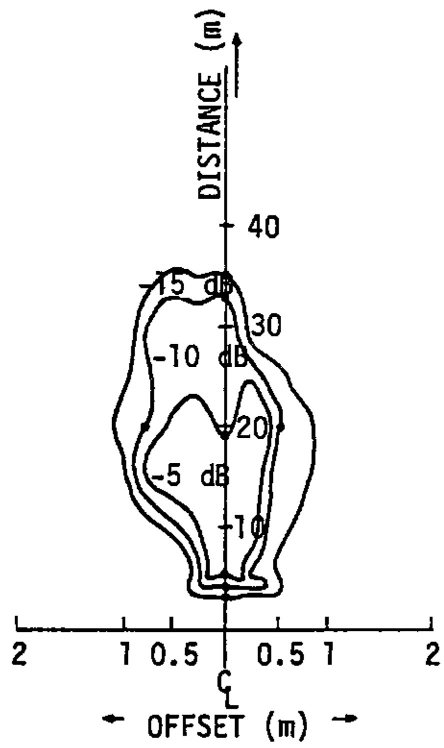

FIGURE 9-5. COVERAGE PATTERN Ku-BAND RADAR – OUTPUT OF POSTAMPLIFIER

TABLE 9-3. CHARACTERISTICS OF MATERIALS CONSIDERED FOR RADOME CONSTRUCTION

Material	Dielectric Constant	Dielectric Loss Factor	Comment
Hardman Epoweld 3672	3	0.021	Hard/brittle
Foamed Polystyrene	1.03	0.0001	Light/porous
Polyethylene*	2.26	0.0031	Flexible/nonporous
Eccofoam FPH	1.04/1.25	0.001/0.005	Hard to handle
Eccoseal High-Q	2.55	0.0004	Solvent attacks substrate
Eccocoat FP3	4.40	0.006	Too fluid/absorbed by substrate

*The polyethylene used is expanded approximately 4:1, which reduces the dielectric constant and dissipation factor.

Finally, a full scale radome (Figure 9-6) was constructed. The antenna and radome unit fits into a cutout in the RSV nose section. Figure 9-7 shows the high technology RSV with the radar and radome inserted (but with unfinished joining areas).

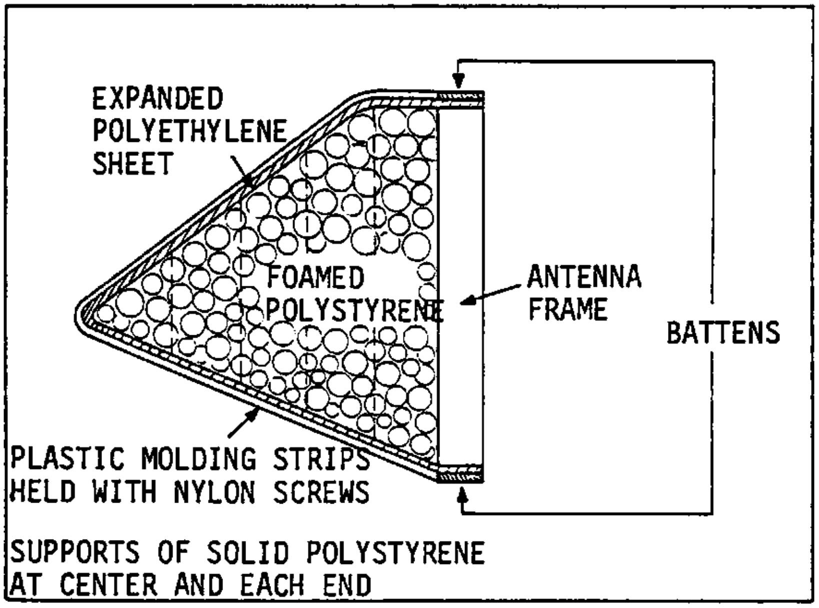

FIGURE 9-6. RADOME CONSTRUCTION

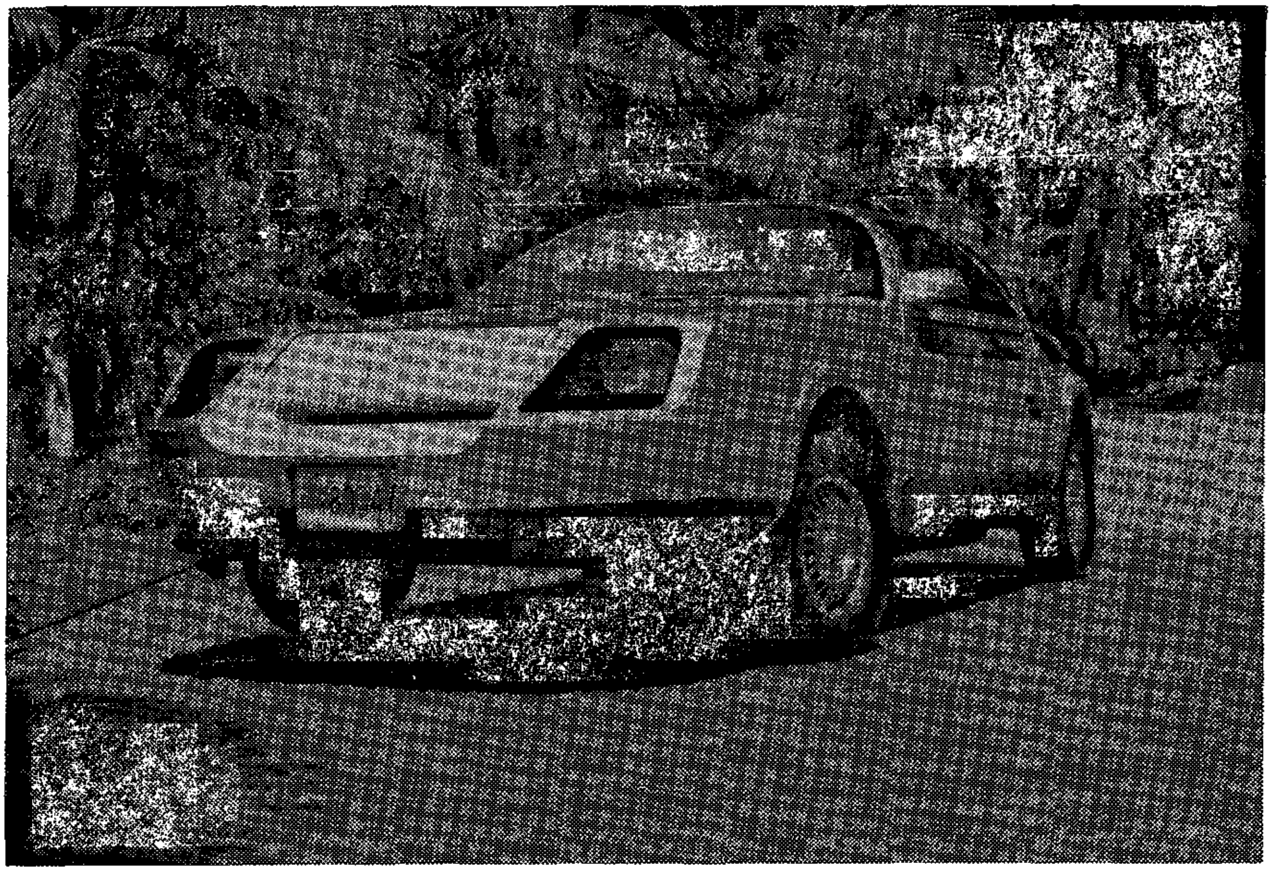

FIGURE 9-7. RSV WITH RADAR AND RADOME IN PLACE

9.3 PROCESSOR HARDWARE

Radar Signal

The radar signal processor converts the analog radar inputs into usable data for the microprocessor. During Phase III, RCA designed and fabricated a new radar card that reduces the high incidence of data rejection in the Phase II processor hardware and provides more accurate range and range-rate measurements (the latter are now calculated from doppler information). Moreover, the signal processor is now capable of furnishing range and range-rate information in much shorter time intervals — a real advantage for CMS operation. These improvements have placed the burden of detecting false alarms on the software, where the problem is more manageable.

CMS/Headway Control

The initial stages of hardware and software development almost always require a flexible microcomputer system for prototyping. The RCA COSMAC development system (CDS) had the necessary memory size required for a prototype system – in the form of random access memory (RAM) space – so that software could be easily loaded from another storage area or host computer. To aid in this storage and rewriting, a ROM (read only memory) chip containing a "utility" routine was also included. The utility software could enter and retrieve data from the RAM space and, when necessary, could be used to modify the data and then restore it to any selected location or address.

During Phase II, RCA used exclusively the COSMAC development system for prototyping both hardware and software. The CDS consisted of a card nest, central panel and basic set of plug-in modules. The card nest provided user space for the development of interface hardware between external hardware and the control processing unit (CPU) system. A large variety of interface cards was developed for the radar, display and various sensors on the RSV. Two major problems, however, were noted for the CDS. The plug-in modules that formed the basic microcomputer system were interconnected at the back plane by a printed circuit (PC) structure that connected each card of the module to other modules within the card rack. The continuous insertion and removal of cards during the development period and the vibrations from the test vehicle caused the printed circuit connections eventually to deteriorate to the point that some open- and short-circuits occurred. A second problem was the difficulty in using the system to debug the hardware. A hardware failure in an interface card usually caused one of the plug-in modules of the microcomputer system to fail.

During Phase III, therefore, RCA switched to the newly released RCA evaluation board, a single PC card (9.5 x 14 inches; 24 x 36 cm) that contains all of the necessary components for prototyping. The evaluation board was finally replaced by another standard PC board that fit in the normal card cage to form a compact, single-enclosure computing system.

The final RCA CMS/headway control processing hardware is contained in a single card cage and forms a stand-alone microcomputer. The cage has a CPU card, a CPU interface card, and three hardware interface cards – one each for the CMS, headway control and throttle controller interrupt. The CPU card consists of an RCA CDP 1802 microprocessor with a 2 MHz crystal for the system clock. Two CDP 1822 RAM chips provide 1/4K of memory space for available storage. Either 2758 or 2716 EPROMs (erasable programmable ROMs) can be used with the CPU card. The 2758 is a 1K EPROM and the 2716 is a 2K EPROM. From 1K to 8K of EPROM space is available on the CPU board. Both types of EPROMs are convenient to program and erase, and both operate from a single 5 volt supply. An 1852 chip is used as an address latch and a 4555 chip is used for address decoding. A CK4028 serves for input/output (I/O) decoding.

A production cost analysis of the CMS and headway control system was prepared using RCA's PRICE program (Reference 17). The system analyzed consists of an FMCW Ku-band bistatic radar and a 3-chip microprocessor controller set (since large production quantities were assumed, very large scale integration – VLSI – would be implemented in a metallized weather-tight plastic box. The cost of the velocity and steering wheel position sensors, the throttle controller for the cruise control, and the system integration and testing are included in the overall production cost figure. The complete CMS and radar cruise control system is estimated to have a production cost figure of $177 (based on 100,000 units, 1979 dollars and 1985 technology).

Automated Shifting

The Dubner processing hardware that controls the automated transmission consists primarily of a CPU card and an I/O card. The system is based on an Intel 8080 microprocessor and requires 4K total memory (of which less than 512 bytes are RAM). The I/O card includes an analog to digital (A/D) converter to read the analog pedal position and throttle feedback signals. Counters are provided to read pulse signals for the engine and vehicle speeds.

Sensor Interfacing and Display Control

The sensor interfacing and display control hardware, like the CMS/headway control hardware, forms a stand-alone microcomputer system (again developed by RCA using their COSMAC Development System). It also consists of a CPU card, a CPU interface card and three hardware interface cards, all mounted together in a single card cage. The system has special circuitry for controlling the Burroughs display, including the A/D converter, multiplier, counters and other circuitry required to monitor the various sensors.

9.4 SOFTWARE*

Collision Mitigation System

The two key features of the collision mitigation system are (1) the automatic application of anti-skid brakes when a high-speed collision is definitely unavoidable and (2) the complete elimination of false alarms (application of brakes when there is no collision imminent or when the driver could actually have avoided the collision). For a better understanding of the boundaries that guide automatic braking, we will present a simplified summary of braking dynamics.

The general situation of two vehicles moving toward each other, with one being braked, is illustrated by the time-distance relationship shown in Figure 9-8. In this figure:

*This section describes only the CMS and headway control software. Control algorithms for the anti-skid brakes and automated transmission are discussed in Sections 5 and 6, respectively.

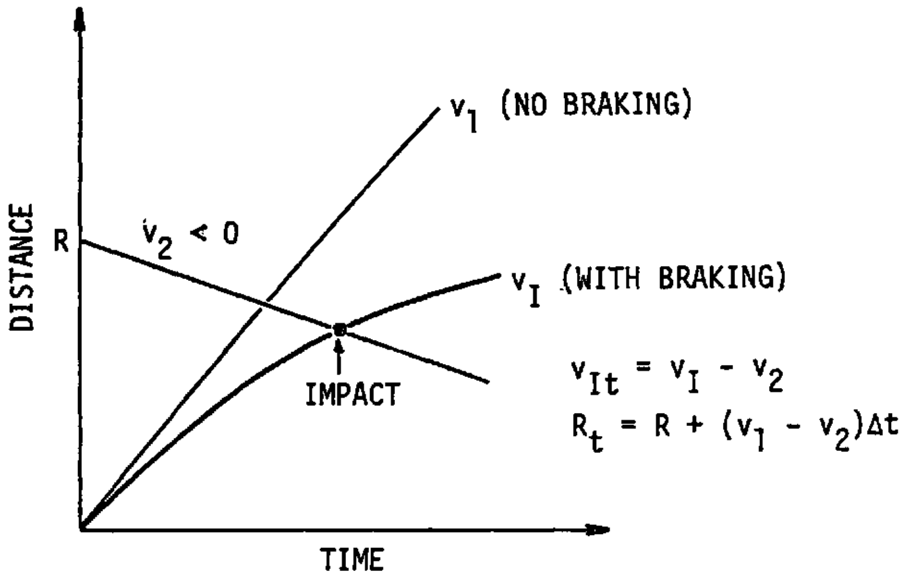

FIGURE 9-8. DISTANCE/TIME RELATION BETWEEN TWO VEHICLES, ONE OF WHICH IS BEING BRAKED

v_1 is the initial velocity of the radar-equipped car

v_2 is the initial velocity of the target vehicle ($v_2 < 0$)

v_I is the impact velocity of the radar-equipped car

v_{It} is the total impact velocity ($v_{It} = v_I - v_2$)

μG is the maximum braking deceleration (0.9 G for dry road, anti-skid brakes)

R is the radar detection range

Δt is the reaction delay (0.1 second for the radar processor and algorithm and 0.1 second for the brake system to reach full braking action).

The relation between impact velocity, v_{It}, and the radar detection range, R, can be expressed as

$$R = \frac{1}{2\mu G}\left[(v_1 - v_2)^2 - v_{It}^2\right] + (v_1 - v_2)\,\Delta t \qquad (9\text{-}1)$$

This equation also applies, of course, for an impact with a fixed object (where $v_2 = 0$). Since $v_1 - v_2$ can be replaced by the measured range-rate, $\dot{R}$, we obtain the more general relation

$$v_{It} = \sqrt{\dot{R}^2 - (R - \dot{R}\Delta t)\ 2\mu G} \tag{9-2}$$

The impact velocity as a function of different radar detection ranges, R, and initial closing rates, $\dot{R}$, is shown in Figure 9-9. For a collision with a fixed object, for example, the impact velocity v_{It} is reduced from an initial speed of 55 mph (25 m/sec) to 30 mph (14 m/sec) if a detection distance of 100 feet (30 meters) is maintained. This corresponds to a reduction in impact energy by 70 percent.

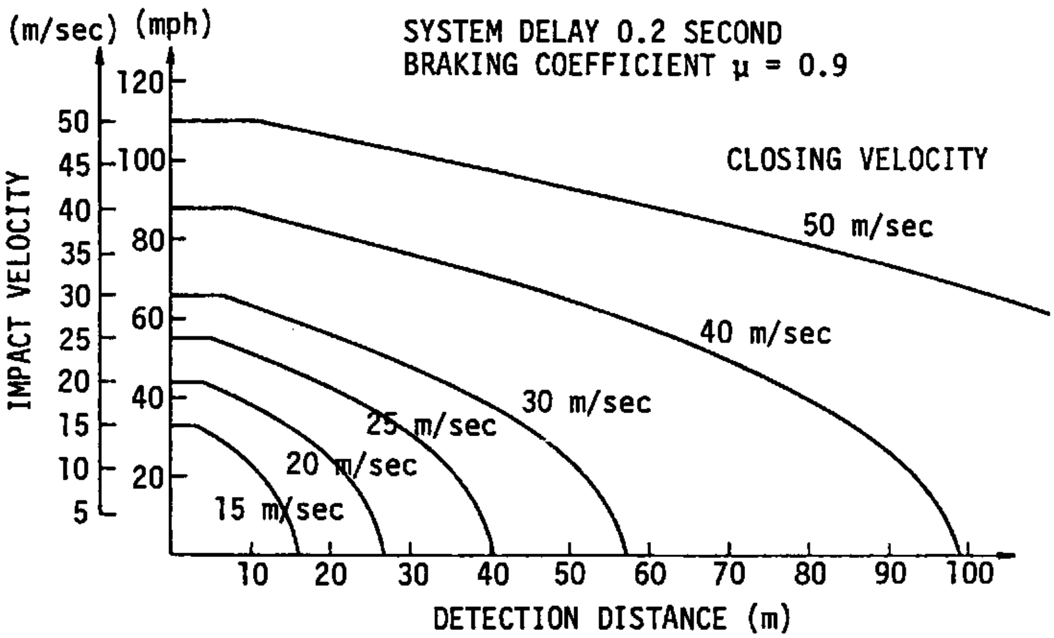

FIGURE 9-9. IMPACT VELOCITY AS FUNCTION OF DISTANCE BETWEEN RADAR CAR AND COLLISION OBJECT

For head-on collisions in which both vehicles are moving at 55 mph (25 m/sec), the impact velocity is reduced by 17 mph (8.8 m/sec), provided both cars have CMS braking with a detection range of 100 feet (30 meters). The impact energy is correspondingly reduced by 30 percent. Here the energy reduction is not so pronounced, but still significant enough to make a substantial difference in the severity of the injury sustained by the driver. Figure 9-10 shows the resulting

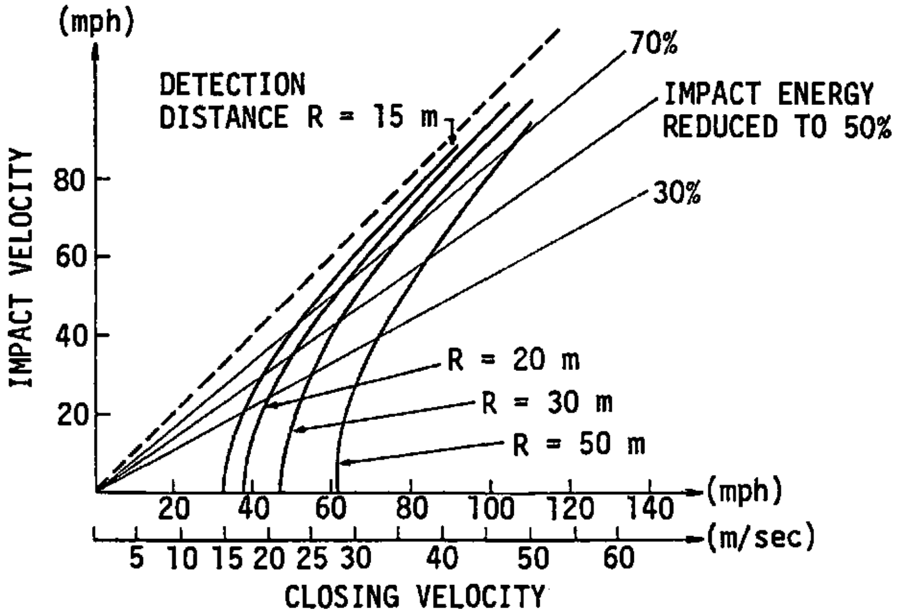

FIGURE 9-10. ENERGY REDUCTION AS FUNCTION OF DETECTION DISTANCE AND CLOSING RATE

impact velocity, v_{It}, as a function of closing rate, R, for different detection ranges. Also indicated are lines of constant energy reduction.

Equation 9-2 indicates the importance of having a large detection range for the radar and a fast reaction time, Δt, for the overall system. These requirements are counteracted by the need for keeping all false alarms at an absolute minimum and, equally important, for ensuring that a driver remains in control of the car as long as there is any possibility of avoiding an accident by skillful driving.

Based on a typical maximum lateral acceleration of 0.3 G (which is rarely exceeded by the average driver), a minimum distance of 105 feet (32 meters) is required (Reference 18) to avoid an obstacle straight in line with a vehicle driven at 55 mph (25 m/sec). Therefore, we conservatively selected a maximum detection distance, R, of 82 feet (25 meters) at a 55 mph closing speed. If a driver at this speed approaches an obstacle without steering wheel or brake pedal activation, the automatic anti-skid braking should take over. At lower speeds, this distance is reduced further.

The inputs to the CMS algorithm are range, range-rate, front wheel angle (ϕ), brake pedal status indicator, and car velocity. The range-rate is derived directly from the beat counts during the up- and downswing of the frequency modulation cycle (and is not generated by differentiating range with time). Range-rate can, therefore, be used to independently check the validity of range data obtained at different time points.

Once range and range-rate data have been computed, the primary purpose of microprocessor software is to sort out real emergency situations from false alarms. To do this, the software performs a number of tests which assess the legitimacy of the range and range-rate data, and then asks the following questions:

- Is $\dot{R} > 36$ mph (16 m/sec)? If not, the target is not considered to be a severe threat.
- Is R<82 feet (25 meters)?
- Is ϕ<1.5 degrees? Is the brake pedal not depressed? An answer of "No" to either of these questions indicates that the driver is already taking evasive action.

If the answer to all of these questions is yes*, the CMS automatically energizes a solenoid valve which dumps high pressure brake fluid into the anti-skid brake system (see Section 5).

The computation and decision making time for the CMS algorithm during Phase II was approximately 160 msec. For the new CMS algorithm, which includes more sophisticated decision making, this time is approximately 80 msec. The reduction can be attributed to two factors. First, the new RCA CDP 1802 microprocessor has a larger instruction set than the 1801 unit used during Phase II. Second, the software is greatly improved and there is more extensive use of look-up tables and faster multiplying chips.

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*These activation criteria are somewhat simplistic regarding the relationship between range, range-rate and the likelihood of an accident occurring. (This effort focused primarily on hardware development.) For a more rigorous treatment, see References 19 and 20.

Headway Control

A collision mitigation system by itself has limited sales appeal because, under normal conditions, a driver would be totally unaware of the system's presence. Emergency braking should take place only when a severe collision is unavoidable, and a good driver would hope to never find it activated. Public acceptance of the radar could be greatly increased if it were also to provide improvements in convenience and traffic flow. Automatic headway control that governs the safe spacing of cars on limited access highways is such an application.

The difference between regular cruise control and radar headway control is illustrated in Figure 9-11. In the normal cruise control (a fairly popular option in American cars), the driver can select a particular cruising speed, v_{set}, and the car will maintain this speed ($v_1 = v_{set}$) until a new speed is set or the brake pedal is tapped. This convenience feature is, unfortunately, not very useful when traffic density increases. Cars ahead, going at only slightly lower speeds, force the temporary disablement of the cruise control or lead the driver to rather dangerous weaving in and out of traffic lanes to avoid having to reset the cruise control.

Under radar headway control, the driver makes inputs to the computer through switches located on the turn signal stalk. When the system is activated by the driver, it operates in either a "cruise" or a "headway" control mode, depending on the presence or absence of a target vehicle. In headway control the radar senses the distance and closing rate to the vehicle ahead and controls the throttle both to match the speed of the that car ($v_2 = v_1$) and to keep a safe headway. If there is no other vehicle ahead, cruise control takes over and the car resumes the preset speed. If the closing rate becomes too high, a warning signal is given on the electronic display and the driver has to take over.

The computer has control of the full travel of the throttle, but cannot (at present) initiate partial brake activation for the cruise control. There is limited deceleration (due to air drag and engine and road friction) when the throttle is fully released. When more rapid deceleration is required, the driver must intervene by directly applying the brakes. Whenever the computer senses the driver's application of the brakes, it responds by fully releasing the throttle

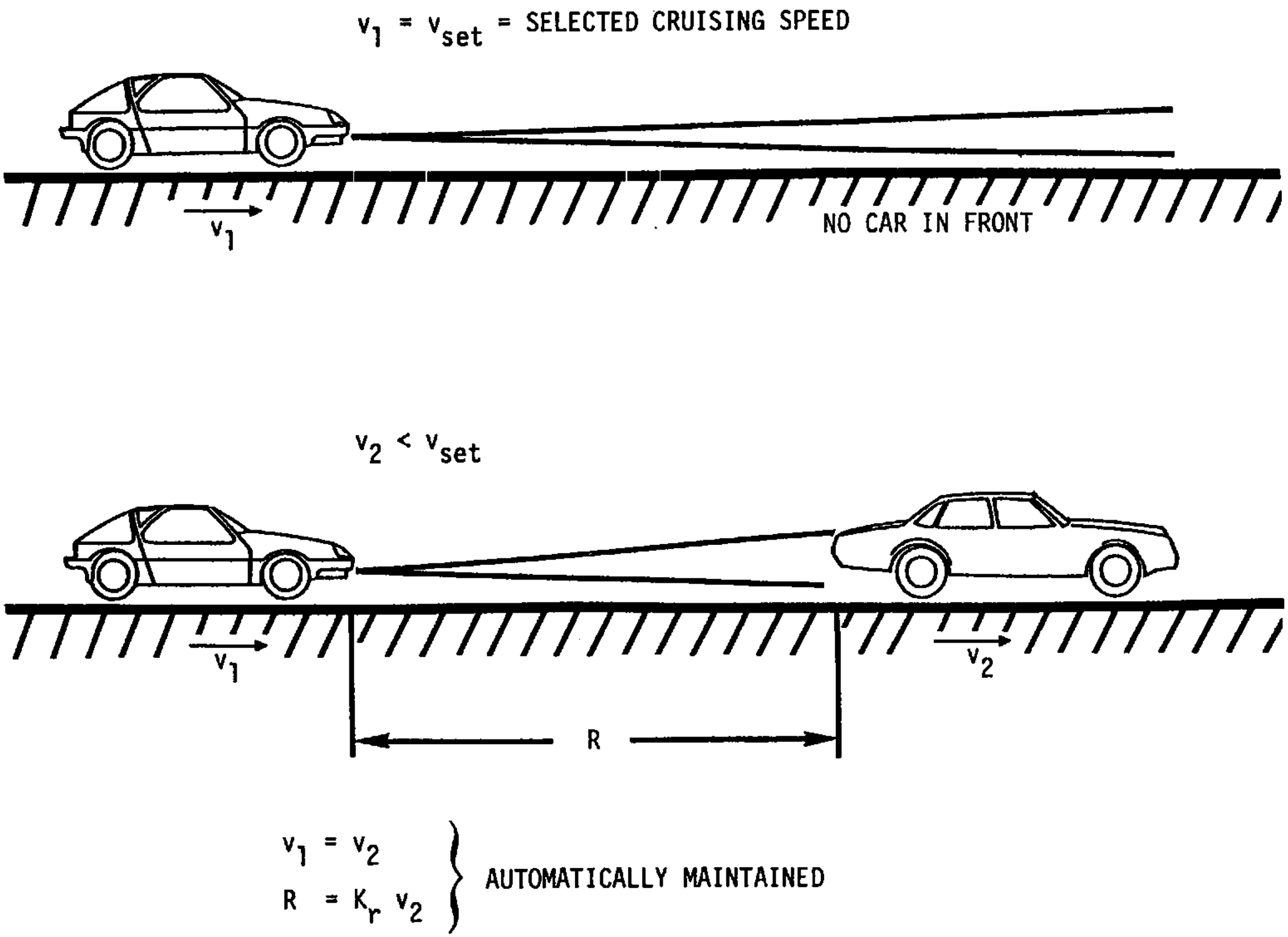

FIGURE 9-11. "SMART" CRUISE CONTROL OPERATION

and relinquishing the control back to the driver - until instructed by the driver to resume control.

There is inherent "noise" in headway control range data because the radar beam looks at different positions on the irregular surface of the target car. Road bounce of both the radar and target aggravate the noise. Quantization noise in the range signal also occurs, because of both the way the radar signal is processed and the finite precision of the microprocessor computations. Range measurements are quantized in steps of 5 cm, and velocity is quantized in steps of 0.1 m/sec. Input noise propagated to the throttle control could cause annoying jerky motions which could be sensed by passengers, so smoothing functions are applied to R, $\dot{R}$ and v. Heavy smoothing provides the quietest outputs, but responsiveness declines as the smoothing is increased. Since $\dot{R}$ is the time derivative of range, it is potentially quite noisy and, therefore, is given heavier smoothing. Care must be taken, however, so that sudden changes in $\dot{R}$ are not unnecessarily smoothed over.

The desired headway distance is computed as

$$R_{des} = K_r V \tag{9-3}$$

where V is vehicle speed and K_r is presently selected as 2.2 ft/mph (1.5 m/m/sec); for example, the desired distance at 55 mph (25 m/sec) is 125 feet (38 meters). Through feedback, we attempt to force the difference of R_{des} and R toward 0 at all times.

In both the cruise and headway control, there are actually two closed loops:

- Throttle servo. A potentiometer feeds back the position of the throttle. Actual throttle position is compared to the desired position, the error is measured by the computer, and the throttle is corrected accordingly.
- Cruise control servo. Ground speed is compared to the desired "set" speed by the computer, and the throttle servo is commanded to increase or decrease the throttle setting.

Thus the cruise control system is a two loop servo system, with the throttle servo inside the main cruise control loop.

The throttle servo is an accurate high performance servo with a frequency response considerably higher than the main cruise control loop. Because the two loops have such a large frequency separation, the performance and stability of the outer loop is virtually unaffected by the inner loop. Therefore, the outer loop can easily be made into a high performance system that smoothly and accurately holds a "set" speed over varying road conditions.

There is one additional element in the outer loop. When the computer senses an error between ground speed and "set" speed, it does not simply command throttle changes based on the error alone. If it did, there would always be an error, even under steady-state conditions. To eliminate this error, the computer actually computes the error plus the integral of the error (this is called "integral control" in servo theory). Under steady-state conditions, the error will now truly be zero, since the integral will automatically be the proper value for the throttle servo.

9.5 CMS AND HEADWAY CONTROL TESTING

Developmental Testing

During Phase III, RCA equipped a special test van to record radar and video data for the optimization of hardware and software. Aside from providing a test platform for the radar, the van was fully instrumented with recording equipment and other test gear for evaluating various system components. It was driven under a wide variety of road and weather conditions, and records were made of the radar beat frequency return, the steering wheel angle, and the brake pedal position to complement a video recording. For headway control development a strip chart recorder provided readouts of vehicle velocity, range, throttle position and throttle control voltage.

These records proved to be valuable developmental tools, because they contained all the necessary inputs to the microcomputer. If a blizzard on a hilly road caused a false alarm, for instance, then the identical conditions could be played back repeatedly until the hardware or software causes were isolated and corrected.

For CMS development, RCA made test runs in which the test vehicle struck disposable targets placed on an airport runway. The airport runs were made for 10 and 100 square foot (1 and 10 square meter) targets at 20, 30, 40, 50 and 60 mph.

Fuel Economy Testing

Late in the Phase III Program a series of controlled test runs were performed to investigate the effect of cruise and headway control on fuel consumption.* Contrary to some earlier, not well documented, tests that showed a superiority of cruise/headway control, no significant difference could be established within the bounds of run-to-run fluctuations (± 2 percent). Some drivers, indeed, had the habit of using a "heavy" foot on the gas pedal and, consequently, ended up with poor fuel economy. However, anybody aware of the causes of poor fuel economy could, without difficulty, duplicate the fuel economy of the cruise control. The tests were performed over a 26 mile stretch of highway (in both directions to average any wind loading); each test consisted of several runs.

Based on these limited tests, we concluded that no claims to significantly better fuel economy could be made. The headway control system, however, did perform equally to a cruise control system (or the average conscientious driver) and was capable of keeping the space between cars to much closer values than average drivers can. The latter effect may be quite beneficial in establishing better column stability and higher throughput for high density "safe" traffic flow. However, these factors require considerably more theoretical and practical study.

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*These tests were run by RCA to evaluate their headway control system. The final RSV headway control system, developed by Dubner Computer Systems, was not tested for fuel economy.

CMS Testing

The final tests of the crash mitigation system in the high technology RSV were conducted on September 26, 1980, by RCA and Minicars on an airport runway at Princeton, New Jersey. The RSV was driven at various speeds toward a corner reflector target suspended on strings. Speed traps measured car velocity prior to automatic CMS operation and at the target reflector. The results are presented in Table 9-4.

TABLE 9-4. COLLISION MITIGATION SYSTEM TEST RESULTS

Test	v_1 (mph)	v_1 (km/h)	v_2 (mph)	v_2 (km/h)	Acquisition Range (feet)	Acquisition Range (meters)	Percent Energy Loss
1	38.8	62.4	0	0	85	25.8	100
2	46.0	74.0	30.9	49.7	68	20.9	55
3	50.4	81.1	35.8	57.6	89	27.1	50

In this table v_1 is the RSV speed, measured, before braking commences, or 82 feet (25 meters) from a target (a 100 square foot – 10 square meter – corner reflector), and v_2 is the speed at the target (impact speed). The acquisition range is the last reading displayed by the radar and represents the distance to the target 50 msec before the system decides to activate the brakes. The percent energy loss is simply the amount of the original kinetic energy dissipated through braking.

SECTION 10
FINAL DESIGN AND PERFORMANCE SPECIFICATIONS

The following pages contain a list of the final design and performance specifications of Minicars' RSV. This list is organized along the lines of the Intermediate Experimental Safety Vehicle Specifications, as follows:

1. General Design Requirements
2. Safety Performance Requirements
3. Vehicle Systems Requirements
4. Producibility Requirements.

Category		Final Specifications
10.1	GENERAL DESIGN REQUIREMENTS	
10.1.1	OBJECTIVE	A vehicle that demonstrates the compatibility of safety with energy, environment, and economy requirements.
10.1.2	VEHICLE DESCRIPTION	
10.1.2.1	General	
	Body style	Sedan (2 gull-wing doors)
	Curb weight	2578 pounds
	Vehicle capacity	750 pounds
	Weight distribution	42/58 front/rear
10.1.2.2	Exterior Dimensions	
	Wheelbase (L101)*	104 inches
	Turning circle	40 feet
	Overall length (L103)*	177 inches
	Overall length/wheelbase	1.70
	Wheel tread (W101, W102)*	62 inches
	Overall width (W103)*	71 inches
	Overall height (loaded)	55 inches
	Ground clearance at curb weight	6.1 inches
	Overhang, front/rear	43/30 inches
	Angle of approach	20 degrees
	Angle of departure	37 degrees
	Angle of ramp breakover	11 degrees
10.1.2.3	Interior Dimensions	
	Characteristics	4-passenger
	Front	5th percentile female through 95th percentile male
	Rear	5th percentile female through 50th percentile male

*Motor Vehicle Manufacturers Association designation numbers.

Category		Final Specifications
10.1.2	VEHICLE DESCRIPTION (cont'd)	
10.1.2.3	Interior Dimensions (cont'd)	
	Effective head room	
	Front (H61)	38.0 inches
	Rear (H63)	38.0 inches
	Effective leg room	
	Front (L34)	44.0 inches
	Rear (L51)	42.0 inches
	Shoulder room	
	Front (W3)	51.0 inches
	Rear (W4)	49.0 inches
	Interior volume	91.1 cubic feet
10.1.2.4	Cargo Space	Combined trunk and hatchback space, 9.5 cubic feet
10.1.2.5	Fuel Capacity	8.3 U.S. gallons

Category		Final Specifications
10.2	SAFETY PERFORMANCE REQUIREMENTS	
10.2.1	HANDLING AND BRAKING	
10.2.1.1	Braking	
	Service brakes	
	Characteristics	Four-wheel disc 8.9" diameter and power assist
	60 mph dry straightaway	
	Stopping distance	155 feet
	Pedal force	Per Figure 10-1, between lines 1 & 2
	Fade characteristics	Per FMVSS 105-75*
	40 mph dry turn	63 feet stopping distance*
	Pedal force	Per Figure 10-1, between lines 1 & 2*
	Wet performance	Per Table 10-1*
	Water recovery	Per FMVSS 105-75*
	System failure	
	Booster failure	155 feet stopping distance, with pedal force per Figure 10-1, between lines 1 & 3
	Front system failure	293 feet stopping distance, with pedal force per Figure 10-1, between lines 1 & 4*
	Collision mitigation braking**	
	System concept	Rapid pressurizing of wheel cylinders
	Actuation	Radar, via microprocessor algorithm; 3-way solenoid valves
	Deceleration capability	0.7 G
	Anti-skid braking	Anti-skid braking on all four wheels**
	Parking brake	
	Type	Hand-actuated friction brake
	Actuation effort	Less than 90 pounds*
	Holding capability	30 percent grade
	Vehicle jacking	No jack (run-flat tires)

*Not tested. Specification based on engineering judgment.

**Available in the High Technology RSV.

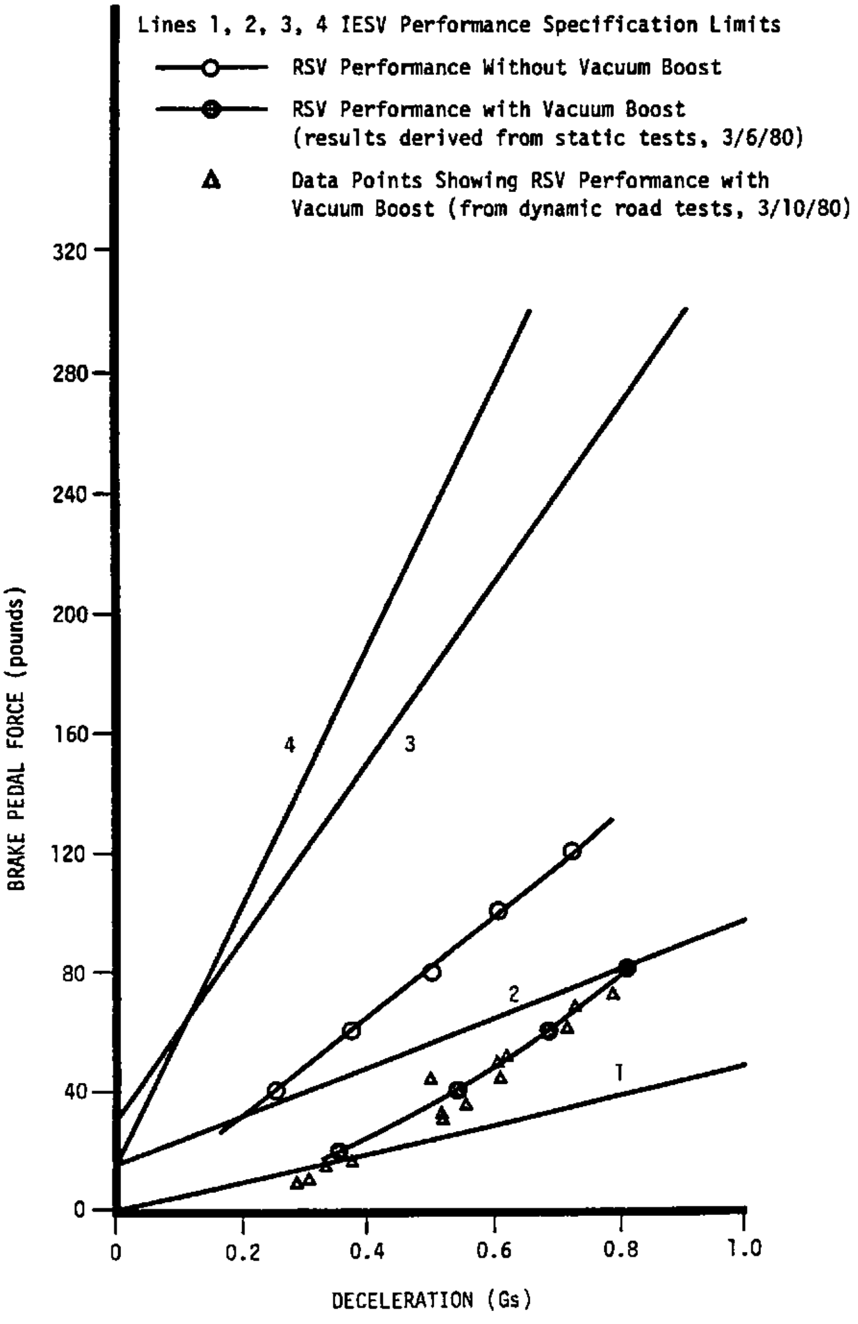

FIGURE 10-1. VEHICLE DECELERATION VERSUS BRAKE PEDAL FORCE

TABLE 10-1. IESV BRAKING PERFORMANCE SPECIFICATIONS

	E*	F*	R*	M*
Normal	80.0	1.25	100.0	--
Front system failure	30.0	1.25	37.5	--
Booster failure	40.0**	1.25	50.0	--
Wet pavement	90.0	1.15	103.5	0.98
Minimum load	90.0	1.25	112.5	--

*As defined in the Highway Safety Research Institute report, "A Procedure for Evaluating Vehicle Braking Performance" (DOT-HS-800 628):

E = brake system efficiency

F = tire factor

R = brake weighting

M = wet to dry performance rating

**150 pound pedal force.

Category		Final Specifications
10.2.1	BRAKING & HANDLING (cont'd)	
10.2.1.2	Steering	
	Characteristics	Fiat X1/9 rack and pinion; overall ratio 20:1; turns lock-to-lock 3.0
	Steady state yaw response	
	0.4 G, 25 mph	Per Figure 10-2
	0.4 G, 37.5 mph	Per Figure 10-2
	0.4 G, 50 mph	Per Figure 10-2
	0.4 G, 70 mph*	Per Figure 10-2
	Transient yaw response	
	0.4 G, 25 mph	Per Figures 10-3a & 10-3b
	0.4 G, 70 mph**	Per Figures 10-3c & 10-3d
	Returnability (feedback)	
	0.4 G, 25 mph	Per Figure 10-4a between curves 1 and 3
	0.4 G, 50 mph	Per Figure 10-4b between curves 2 and 3
	0.4 G, 25 mph	Yaw rate less than 1 degree per second within 2 seconds (Figure 10-5a)
	0.4 G, 50 mph	Yaw rate less than 4 degrees per second within 2 seconds (Figure 10-5b)
10.2.1.3	Handling	
	Characteristics	Front: Modified Fiat X1/9 rear (Chapman) struts and X1/9 rear springs Rear: Fiat X1/9 rear (Chapman) struts and Chevrolet Chevette rear springs
	Lateral acceleration	Stable during lateral acceleration per Table 10-2
	Control at breakaway	
	100 foot radius	Return in 2 seconds
	225 foot radius	Not tested

*Conducted at 60 mph.

**Conducted at 50 mph.

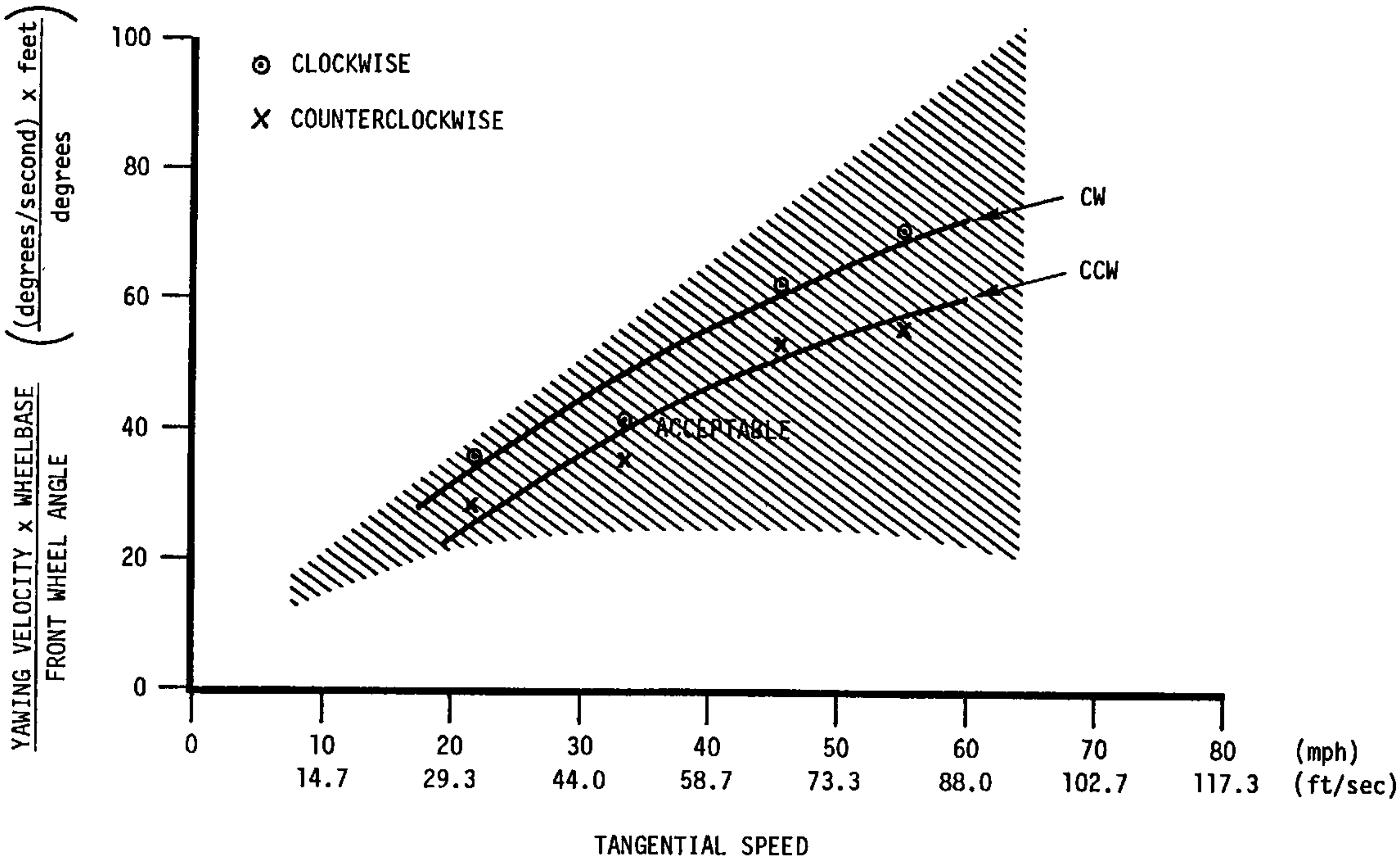

FIGURE 10-2. STEADY STATE YAW RESPONSE VERSUS TANGENTIAL SPEED

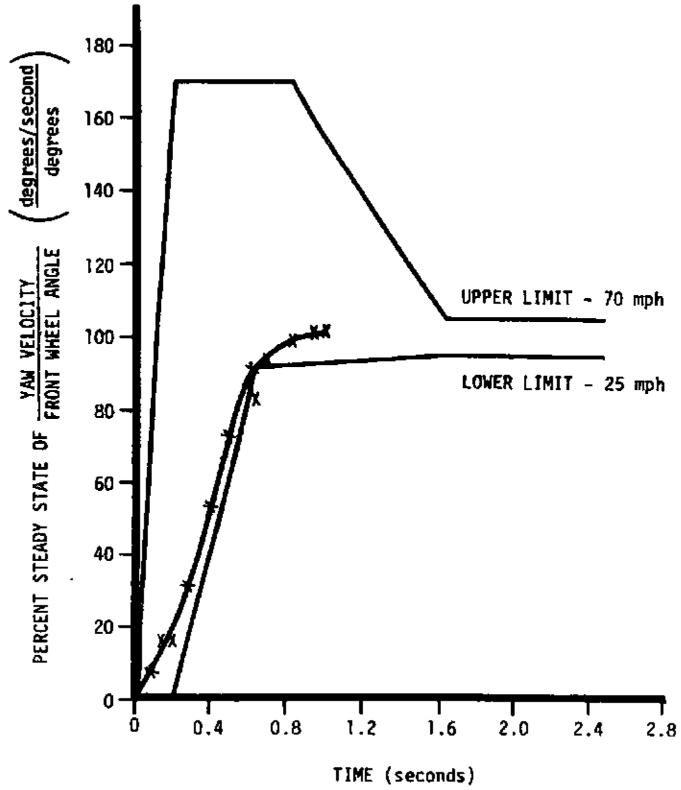

FIGURE 10-3a. TRANSIENT YAW RESPONSE VS. TIME AT 25 MPH CLOCKWISE

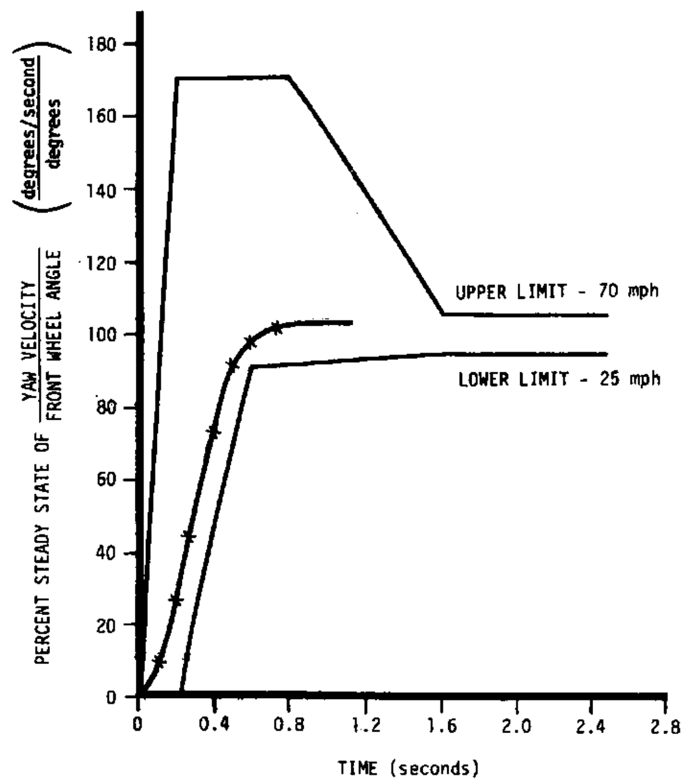

FIGURE 10-3b. TRANSIENT YAW RESPONSE VS. TIME AT 25 MPH COUNTERCLOCKWISE

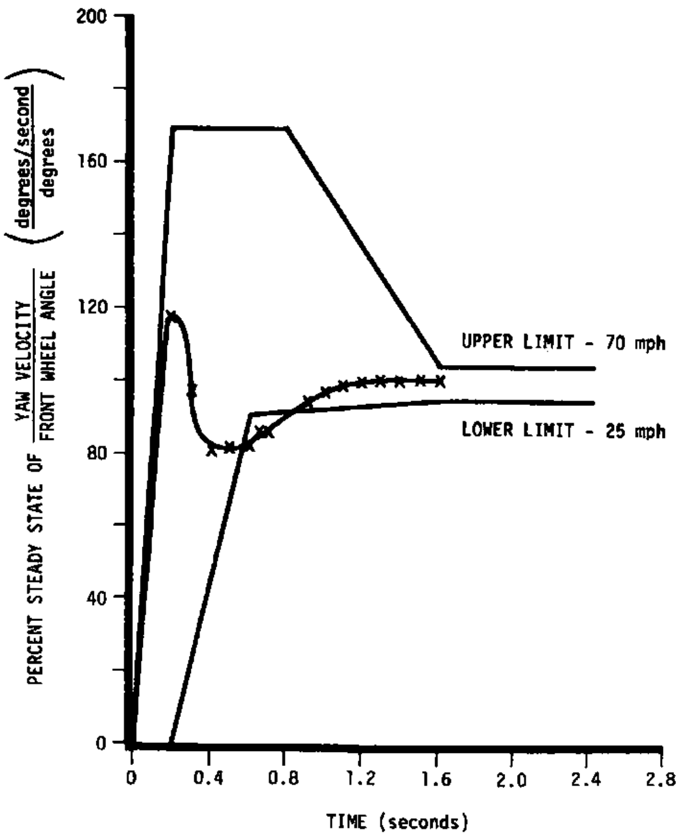

FIGURE 10-3c. TRANSIENT YAW RESPONSE VS. TIME AT 50 MPH CLOCKWISE

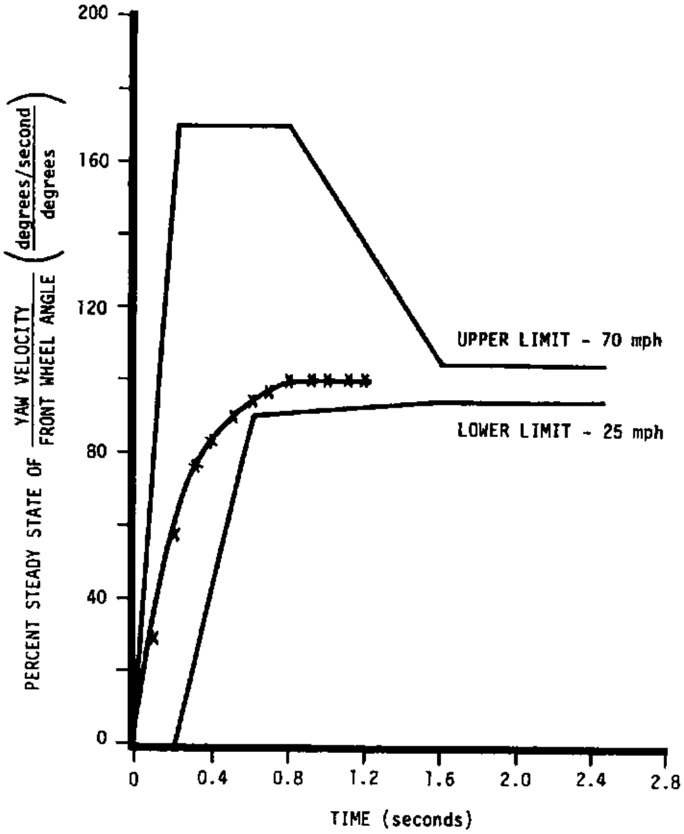

FIGURE 10-3d. TRANSIENT YAW RESPONSE VS. TIME AT 50 MPH COUNTERCLOCKWISE

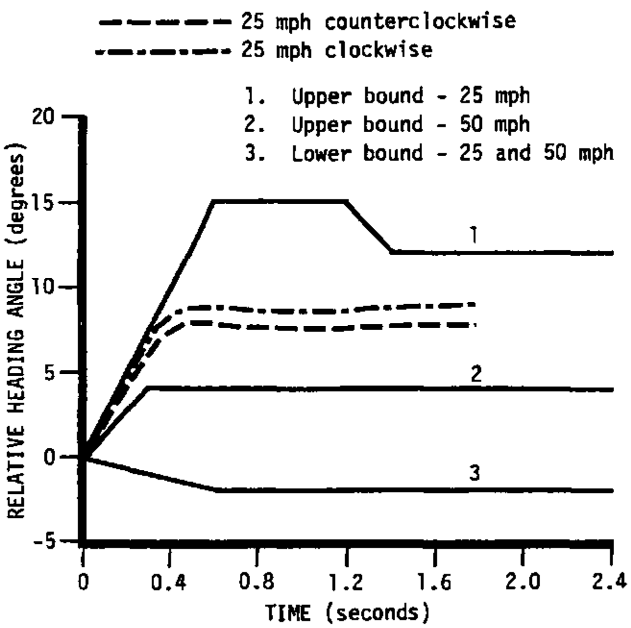

FIGURE 10-4a. RETURNABILITY PERFORMANCE AT 25 MPH

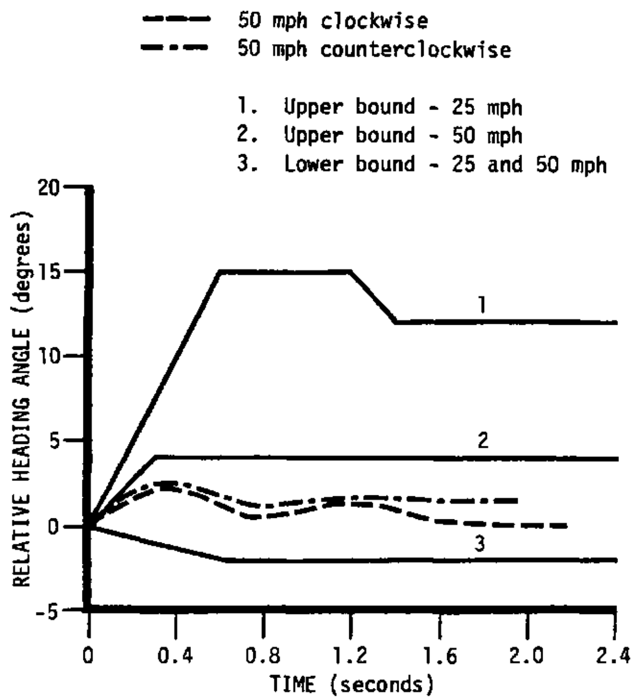

FIGURE 10-4b. RETURNABILITY PERFORMANCE AT 50 MPH

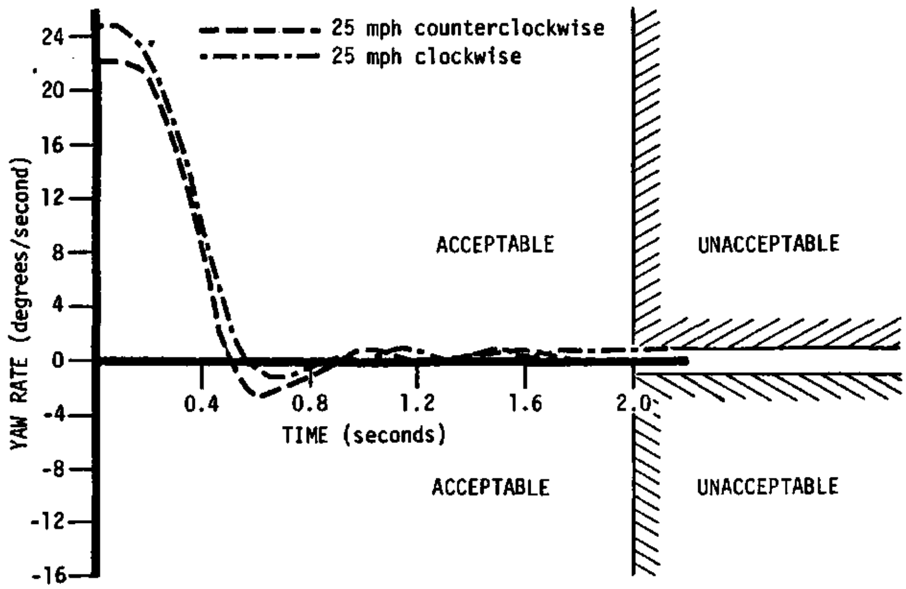

FIGURE 10-5a. YAW RATES AT 25 MPH

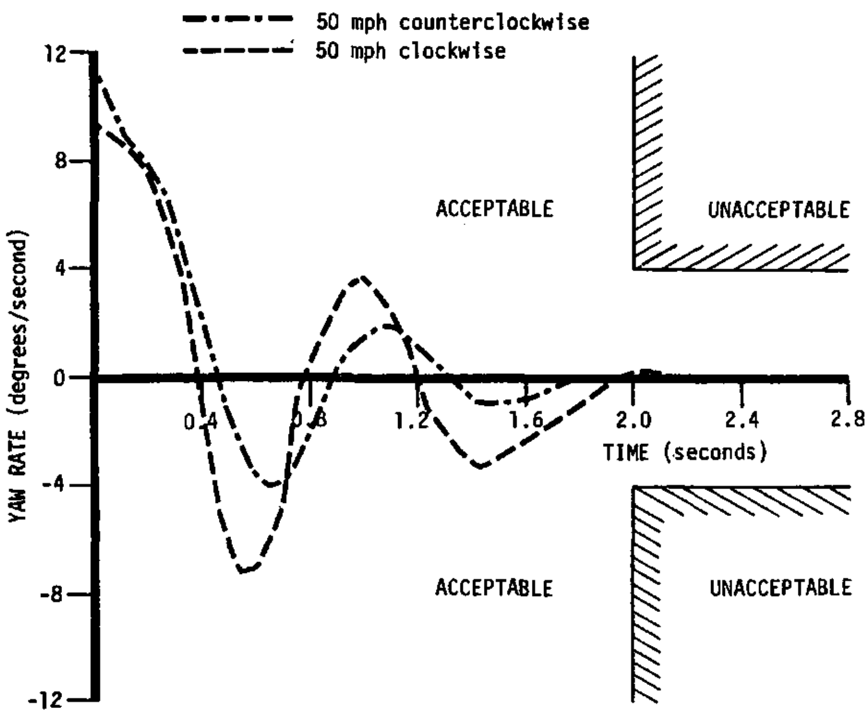

FIGURE 10-5b. YAW RATES AT 50 MPH

TABLE 10-2. IBSV SPECIFICATIONS AND RSV TEST RESULTS FOR LATERAL ACCELERATION

Surface	Tire pressure	Lateral Acceleration (Gs) IBSV Specifications Fixed Control	Lateral Acceleration (Gs) RSV Test Results Fixed Control
Dry concrete or asphalt	Design value	0.60	0.765
	120% design value	0.60	0.765
	80% design value	0.55	0.720
	120% design front 80% design rear	0.63	0.710
	80% design front 120% design rear	0.59	0.745
Wet concrete or asphalt	Design	*	N/A

*Values to be related to actual performance achieved on dry surface in proportion to wet and dry test skid numbers.

Category		Final Specifications
10.2.1	BRAKING & HANDLING (cont'd)	
10.2.1.3	Handling (cont'd)	
	Directional stability (30, 50 and 70 mph)	
	Crosswind	Not tested
	Steering control	Less than 10 inch-pounds*
	Pavement irregularity	Less than 1 foot after 2 seconds
10.2.1.4	Overturning Immunity	
	Slalom course	50 mph
	Drastic steer and brake	Not tested
	J-turns	50 mph, steering wheel input up to ± 180 degrees
10.2.1.5	Engine and Driveline	Fuel capacity 8.3 U.S. gallons; range at 55 mph is 300 miles
	Passing time	30-60 mph less than 15.5 seconds
	Lateral force influence	Constant engine output at 0.765 G on 100 foot radius circle with normal tire pressure and manual control
10.2.1.6	Ride Performance	
	Natural frequencies with shocks disconnected	
	Front	1.38 Hz**
	Rear	1.65 Hz**

*Manual steering

**Analytical results.

Category		Final Specifications
10.2.2	VISIBILITY SYSTEMS	
10.2.2.1	Driver Visibility	
	Field of view	
	Direct	Meets NHTSA's "Recommended Specification for RSV Visibility System Design"
	Indirect	Meets NHTSA's "Recommended Specification for RSV Visibility System Design"
	Exceptions to above:	
	Visibility measurement point	50th percentile male driver
	Shade bands	None
	Transmittance, Zones I-V	Greater than or equal to 80 percent
	Transmittance, Zone VI	Greater than or equal to 70 percent
	Horizontal obstruction width:	
	Zones II and III	4 degrees in Zone II; 6 degrees in Zone III
	Zones IV and V	0 degrees in Zone IV; 5.5 degrees in Zone V
	Obstructions, Pillars	2 pillars
	Front seat head restraints	Clear membrane
	Indirect visibility devices	Adjustable from driver's seat
	Reflective surfaces	
	Bright components	No bright components in Zones I, II and III
	S4 requirements	Matte finish windshield wiper
	Windshield defrost/defog	Designed to meet FMVSS 103
10.2.2.2	Lighting	
	System requirements	Per 37 FR 22801
	Rear light requirements	Per FMVSS 108
	Rear light locations	Per Part 571, S108-9, Table 2

Category		Final Specifications
10.2.3	DRIVER ENVIRONMENT SYSTEMS	
10.2.3.1	Controls and Displays	
	Primary controls	Steering wheel; emergency brake handle; 2-speed windshield wiper switch; headlight switch with high beam control; self-terminating turn indicators; centrally mounted gear selector; horn control; hazard warning control
		Human factors considerations per DOT-HS-800 618, DOT-HS-800 619, DOT-HS-800 742
	Secondary controls	Environmental controls; remote mirror controls; interior door locks
	Control locations	Per DOT-HS-800 742
	Displays	
	Functions displayed	Speed; fuel level; oil pressure; water temperature; engine speed (rpm); trip meter
	Seat and control adjustment	Moveable driver's seat to accommodate individuals ranging from 5th percentile female to 95th percentile male
10.2.3.2	Warning Devices	
	Horn	Per SAE J377
	Speed warning	None
	Restraint malfunction warning	Available
10.2.3.3	Environment	
	Compartment pressure	Designed to be positive under all operating conditions
	CO concentration as tested per SAE J989	Designed not to exceeed 25 ppm when tested per SAE J989
	Air conditioning system	Optional; designed to comply with SAE J639
	Interior noise	Nominal
	Interior storage	Storage space behind rear seat
10.2.3.4	Emergency Equipment	Fire extinguisher; flares and triangle; first aid kit

Category		Final Specifications
10.2.4	CRASHWORTHINESS SYSTEMS	
10.2.4.1	Front Impacts	Protection per FMVSS 208 provided in 50 mph barrier impacts
	Frontal barriers at 0 degrees	Test 6.7, 5/12/1976 Barrier impact speed = 50.8 mph; Delta-V = 54.9 mph

	Driver	Right Front Passenger
HIC	753	722
Chest Gs	50	46
CSI	496	553
L. Femur (lb)	1470	3200
R. Femur (lb)	1300	1800

Test 8.10 (1346), 2/14/1979
Barrier impact speed = 47.6 mph
Delta-V = 54.4 mph

	Driver	Right Front Passenger
HIC	304	554
Chest Gs	46	48
CSI	487	468
L. Femur (lb)	1250	700
R. Femur (lb)	1575	890

(Test indicates FMVSS 208 injury criteria would be met at 50 mph impact speed.)

Right offset frontal barrier

Test 6.9, 7/9/1976
Barrier impact speed = 45.4 mph
Delta-V = 49 mph

	Driver	Right Front Passenger
HIC	474	189
Chest Gs	55	30
CSI	488	216
L. Femur (lb)	1300	980
R. Femur (lb)	1200	690

(Test indicates FMVSS 208 injury criteria met at 46 mph impact speed)

Category		Final Specifications
10.2.4	CRASHWORTHINESS SYSTEMS	
10.2.4.1	Front Impacts (cont'd)	
	Vehicle-to-vehicle frontal offset	Test 8.11 (1529), 8/7/1979 Left frontal offset collision between RSV and Chevrolet Impala at 70.8 mph closing speed. RSV delta-V = 40.8 mph

	Driver	Right Front Passenger
HIC	183	261
Chest Gs	35	25
CSI	213	95
L. Femur (lb)	1300	800
R. Femur (lb)	1600	700

(Test indicates FMVSS 208 injury criteria may be met at delta-V of 45 mph)

	Vehicle-to-vehicle aligned frontal	No valid test data
10.2.4.2	Side Impacts	
	RSV struck by conventional vehicle corner	Test 6.8, 6/22/1976 Stationary RSV struck by Ford Pinto at 300 degree impact angle at door opening reference. Pinto speed = 34.7 mph RSV delta-V = 15.4 mph

	Driver	Right Front Passenger
HIC	270	465
Chest Gs	32	44
CSI	76	132
Pelvic Gs	22	18

Category	Final Specifications
10.2.4 CRASHWORTHINESS SYSTEMS (cont'd)	
10.2.4.2 Side Impacts (cont'd)	
	Test 7.10, 1/12/1977 Moving RSV struck at 300 degree impact angle, forward of A-post, by Chevrolet Impala Chevrolet speed = 39.1 mph RSV speed = 19.6 mph Closing speed = 51.8 mph delta-V = 31.8 mph

	Driver	Left Rear Passenger
HIC	211	81
Chest Gs	36	34
CSI	177	93
Pelvic Gs	34	34

(Test indicates FMVSS 208 injury criteria may be met at delta-V of 35 mph)

Category	Final Specifications
RSV struck by conventional vehicle front	Test 7.7, 11/19/1976 Moving RSV struck at 270 degree impact angle, forward of A-post, by a Volvo. Volvo speed = 39.2 mph = RSV speed Closing speed = 55.4 mph RSV delta-V = 30.1 mph

	Driver	Right Front Passenger
HIC	66	39
Chest Gs	40	40
CSI	193	72
Pelvic Gs	35	26

Category		Final Specifications
10.2.4	CRASHWORTHINESS SYSTEMS (cont'd)	
10.2.4.2	Side Impacts (cont'd)	
	RSV struck by conventional vehicle front (cont'd)	Test 8.18 (1466), 6/8/1979 Moving RSV struck at 90 degree impact angle, forward of A-post, by a Chevrolet Impala. Chevrolet speed = 35 mph = RSV speed Closing speed = 49.5 mph RSV delta-V = 31.3 mph

	Right Front Passenger	Right Rear Passenger
HIC	574	244
Chest Gs	32	65
CSI	80	248
Pelvic Gs	28	50

(Tests indicate that front seat occupants may meet FMVSS 208 criteria at delta-V of 30 mph.)

	Conventional vehicle side struck by RSV (aggressivity)	Test 7.1, 7/16/1976 RSV struck stationary Pinto at 300 degree impact angle at door opening reference. RSV speed = 30.3 mph Pinto delta-V = 13.5 mph

	Driver	Right Front Passenger
HIC	47	49
Chest Gs	38	34
CSI	71	49
Pelvic Gs	40	22

(Test indicates FMVSS 208 injury criteria may be met at RSV speed of 34 mph.)

Category	Final Specifications

10.2.4 CRASHWORTHINESS SYSTEMS (cont'd)

Conventional vehicle side struck by RSV (aggressivity) (cont'd)

Test 7.6, 11/12/1976
Moving Volvo struck at 270 degree impact angle, forward of A-post, by an RSV.
RSV speed = 40.0 mph = Volvo speed
Closing velocity = 56.5 mph
Volvo delta-V = 24.3 mph

	Driver	Right Front Passenger
HIC	298	44
Chest Gs	55	29
CSI	260	N/A
Pelvic Gs	45	32

(Test indicates FMVSS 208 injury criteria met at delta-V of 24 mph)

10.2.4.3 Rear Impacts

Test 7.11B, 7/29/1976
Stationary RSV struck in the rear by a Volvo.
Volvo speed = 39.7 mph
RSV delta-V = 21.6 mph

	Driver	Right Rear Passenger
HIC	185	104
Chest Gs	50	40
CSI	201	131
Pelvic Gs	50	75

(Test indicates FMVSS 208 injury criteria met at delta-V of 19 mph. Subsequent design changes should improve performance, but have not been tested.)

Category		Final Specifications
10.2.4	CRASHWORTHINESS SYSTEMS (cont'd)	
10.2.4.4	Rollover Protection	Test 7.8, 12/17/1976 Rollover test using inclined dolly per FMVSS 208 Dolly speed = 30.8 mph Three complete rolls

	Driver	Left Rear Passenger
HIC	100	100
Chest Gs	7	6
CSI	30	20
Pelvic Gs	10	8

(No occupant ejection; passenger compartment integrity maintained; maximum residual crush = 3.1 inches)

10.2.4.5	Exterior Protection	
	Characteristics	Extensive use of polyurethane reaction injection molded (RIM) exterior panels.
	Frontal barrier impacts	Test 1414, 4/23/1979; 8.2 mph - no damage
	Car-to-car rear impacts	Test 7.11A, 9/13/1976 Stationary RSV struck in the rear by a Volvo. Volvo speed = 10.0 mph RSV delta-V = 5.4 mph No damage to RSV.
	Repairability in moderate collisions	Test 1246, 10/31/1979 Bolt-on replaceable module contained all damage in 8 to 17 mph frontal barrier impact.
10.2.4.6	Fuel System Integrity (All crash modes)	No release of fuel from fuel tank No rupture of connecting lines Fuel releases from carburetor float bowl only. No fuel loss observed in Tests 8.11, 8.13, 8.13A and 8.18

Category		Final Specifications
10.2.4	CRASHWORTHINESS SYSTEMS (cont'd)	
10.2.4.7	Pedestrian/Cyclist Protection	
	Energy absorption	Meets all FMVSS 208 injury criteria at 20 mph; meets all FMVSS 208 injury criteria, except HIC, at 25 mph.
	Trajectory control	No special pedestrian retention devices
	Exterior geometry	Convex front and rear, flush glazing.
	Exterior finish	No frictional or harshly abrasive materials.
	Exterior protrusions	No exterior protrusions.
	Audio visual signaling	Automatic backup alarm.
10.2.5	OCCUPANT COMPARTMENT SYSTEMS	
10.2.5.1	Seats	
	Front seat characteristics	Frame mounted energy-absorbing front seats. Conventional cantilever seat back gains structural integrity through membrane between upper seat back and roof. Membrane provides force limitation (rebound control and rear end collision protection), yet see-through capability.
	Weight per front seat	28 pounds
	Rear seat characteristics	Rear seat has two separate seat cushions and a full seat back (built on a foundation sheet with flexible urethane foam).
	Rear seat weight	12 pounds
	Occupant protection in interior impact	Per FMVSS 201
	Neck injury protection	Per FMVSS 202

Category		Final Specifications
10.2.5	OCCUPANT COMPARTMENT SYSTEMS (cont'd)	
10.2.5.2	<u>Occupant Restraint Systems</u>	
	Driver system	
	Characteristics	Dual airbag design; Thiokol solid pyrotechnic inflator; Minicars' tube and mandrel energy-absorbing steering column; styrofoam knee restraint.
	System weight	31 pounds
	Performance over anthropometric range	Sled Test 1332 Occupant: 5th percentile female Speed = 45.5 mph HIC = 528 Peak chest Gs = 55 L. Femur load = 900 pounds R. Femur load = 800 pounds
		Sled Test 1329 Occupant: 50th percentile male Speed = 50.9 mph HIC = 521 Peak chest Gs = 47 L. Femur load = 1600 pounds R. Femur load = 1300 pounds
		Sled Test 1333 Occupant: 95th percentile male Speed = 44.8 mph HIC = 615 Peak chest Gs = 60 L. Femur load = 1700 pounds R. Femur load = 2000 pounds
	Right front passenger system	
	Characteristics	6 cubic foot dual airbag; Thiokol solid pyrotechnic inflator; polyurethane foam knee restraint.
	System weight	34 pounds
	Performance over anthropometric range	Sled Test 1330 Occupant: 5th percentile female Speed = 42.0 mph HIC = 710 Peak chest Gs = 49 L. Femur load = 100 pounds R. Femur load = 200 pounds

Category		Final Specifications
10.2.5	OCCUPANT COMPARTMENT SYSTEMS (cont'd)	
10.2.5.2	Occupant Restraint Systems (cont'd)	
	Right front passenger system (cont'd)	
	Performance over anthropometric range (cont'd)	Sled Test 1334 Occupant: 50th percentile male Speed = 51.1 mph HIC = 595 Peak chest Gs = 50 L. Femur load = 700 pounds R. Femur load = 400 pounds
		Sled Test 1331 Occupant: 95th percentile male Speed = 41.6 mph HIC = 700 L. Femur load = 400 pounds R. Femur load = 700 pounds
	Rear seat system	
	Characteristics	Three-point force-limited belt
	System weight	15.2 pounds
	Performance over anthropometric range	Sled Test 42 Occupant: 6-year-old child Speed = 34.3 mph HIC = 823 Peak chest Gs = approximately 50
		Sled Test 42 Occupant: 5th percentile female Speed = 34.3 mph HIC = 806 Peak chest Gs = approximately 50
		Sled Test 31 Occupant: 50th percnetile male Speed = 45.0 mph HIC = 892 Peak chest Gs = approximately 50

	Category	Final Specifications
10.2.5	OCCUPANT COMPARTMENT SYSTEMS (cont'd)	
10.2.5.3	Flammability	
	Interior materials	Per FMVSS 302
	Fire extinguisher	Rated for B and C fires; will extinguish small A fires; extinguishing agent not harmful to humans; located in easy reach; inexpensive
10.2.5.4	Interior Design	Per FMVSS 201
10.2.5.5	Emergency Egress	Provisions for escape/rescue in any attitude (including escape through the rear hatch)

Category		Final Specifications
10.3	VEHICLE SYSTEMS REQUIREMENTS	
10.3.1	ENGINE, FUEL COOLING AND EXHAUST SYSTEMS	
	Engine characteristics	
	Engine location	Transverse mid-engine
	Engine type	4-cylinder inline OHC stratified charge
	Engine	1978 Honda CVCC
	Bore x stroke	74.0 x 93.0 mm
	Displacement	1599 cc
	Compression ratio	8.0:1
	Engine power	68 hp @ 5000 rpm
	Engine torque	85 foot-pounds @ 3500 rpm
	Transmission characteristics	
	Transmission type	Five-speed manual
	Gear ratios: 5th	0.72
	4th	0.85
	3rd	1.18
	2nd	1.82
	1st	3.18
	reverse	2.92
	Final drive ratio	4.27
	Passing time, 30-60 mph	Less than 15.5 seconds
	Acceleration	
	0-30 mph	6 seconds
	0-60 mph	21 seconds
	Range at 55 mph	300 miles
	Fuel economy (city/highway/combined)	27.8/42.3/32.9 mile/gallon
	Emissions, HC/CO/NO_x	1.18/10.7/1.1 gm/mile
	Radiator, location	Fiat X1/9, behind front bumper
	Engine coolant	Per SAE J814

Category		Final Specifications
10.3	VEHICLE SYSTEMS REQUIREMENTS (cont'd)	
10.3.2	TIRES AND WHEELS	
	Tire specification	200/65HR370 Dunlop Denovo 2 run-flat
	Wheel specification	Denloc 370 x 125 x 33
10.3.3	ELECTRICAL SYSTEM	
	Characteristics	Accommodates normal operating loads with a DELCO Freedom (87-60) 12V battery and a 12V-50AH alternator; provides economical, low maintenance operation
10.3.4	INTERIOR COMFORT	
	Characteristics	Seats representative of standard practice; conventional heater; optional air conditioner; courtesy lighting; thermal and noise insulation; fresh air ventilation; radio; clock
10.3.5	MAINTENANCE	
	Durability	Consistent with production vehicles
	Maintainability	Consistent with production vehicles
	Service includes:	
	Oil change	6000 miles
	Filter change	6000 miles
	Chassis lube	25,000 miles

Category		Final Specifications
10.4	PRODUCIBILITY REQUIREMENTS	
10.4.1	MATERIALS AND APPLICATIONS	
10.4.1.1	Materials	Body-in-white structure: low carbon steel, some HSLA, urethane foam-filling; aluminum gull-wing doors; RIM polyurethane body glove; high density polyurethane bumpers
10.4.1.2	Fabrication Technology	300,000 units per year in 1985
10.4.2	COMPONENTS AND SUBSYSTEMS	
10.4.2.1	Producibility Design	Advanced, yet production-oriented design; a design for the 1980's that was producible in the 1970's
	Price (1980 dollars)	
	300,000 units/year	
	Manufacturing cost	$3,098
	Dealer selling price	$6,196

SECTION 11

LARGE RESEARCH SAFETY VEHICLE

11.1 INTRODUCTION

The Large Research Safety Vehicle (LRSV) Program was devised to show that RSV technology could be applied to other vehicle sizes - in this case, full-size automobiles. The central goal of the program was to develop a six passenger sedan having a curb weight less than 3000 pounds (1360 kg), yet still demonstrating superior crashworthiness, excellent fuel economy and low emissions.

Because the LRSV Program was limited in scope (compared to the RSV Program), we based our design on a modified production vehicle (rather than developing a vehicle from the ground up). Three candidates were considered for the base vehicle: Ford LTD, Plymouth Fury and Chevrolet Impala. We chose the Impala because it (and other GM B-bodies) had recently been subjected to a comprehensive weight reduction treatment and because its construction (weld fences and panel formations) would be the simplest to integrate with RSV-style structural components. Since the Impala's interior and exterior configurations were left essentially intact, the LRSV has almost identical dimensions to the Impala. It is 213 inches (541 cm) long, 76 inches (193 cm) wide and 59 inches (150 cm) high, and has an EPA Interior Volume Index of 111 cubic feet (3.14 cubic meters). By incorporating the smaller RSV fuel cell (8.3 gallon capacity), we increased the cargo volume to 20.5 cubic feet (0.58 cubic meters). The curb weight is 3004 pounds (1363 kg), which, because of our weight reduction efforts, is 865 pounds (392 kg) less than that of the stock Impala. Figure 11-1 shows the operational mockup of the LRSV.

The LRSV structure, like that of the RSV, evolved through lumped mass model computer simulations, component crush tests and full-scale vehicle crash tests. Its design also is based on a comparatively stiff passenger compartment, foam-filled sheetmetal boxes, and flexible urethane front and rear bumpers. We reduced vehicle weight by using closed sheetmetal box structures and by substituting plastic for steel in some of the non-stuctural Impala parts

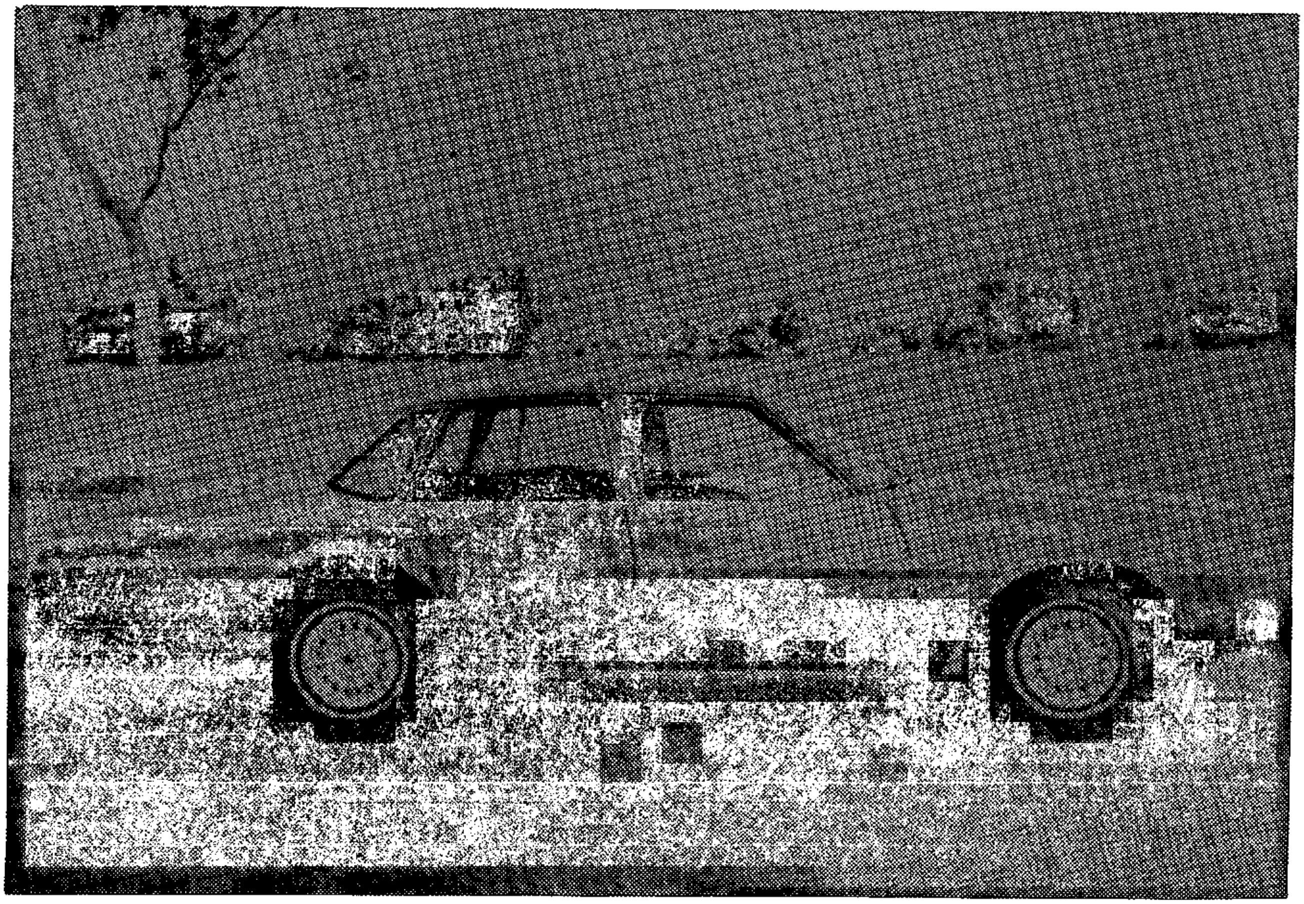

FIGURE 11-1. LARGE RESEARCH SAFETY VEHICLE (LRSV)

(including the hood, front fenders and deck lid). The structural development of the LRSV is discussed in Subsection 11.2.

The LRSV also utilizes much of the RSV's occupant packaging technology. The driver's foam and sheetmetal knee restraint is of similar design, the energy-absorbing steering column is virtually identical, and both steering wheel airbags are cylindrical (although the LRSV has only a single chamber). On the other hand, the LRSV passenger restraint is significantly different, because two front seat passengers must be protected. Three airbags are mounted in the dash: two individually-vented torso bags and a single, downward-deploying knee bag. Subsection 11.3 lists the specific crashworthiness objectives set at the start of the program, describes the development of the occupant packaging systems, and discusses the LRSV's performance in crash tests.

To maximize emissions and fuel economy performance, the LRSV's powertrain is front engine/front wheel drive, and to maximize frontal crush space, the engine is transversely mounted. The modified Volvo B-21 fuel injected, four cylinder in-line engine (with a three-way catalyst and Lambda-Sond* feedback emissions control) is mated to a GM X-body four-speed manual transmission. The propulsion system development is discussed in Subsection 11.4.

The LRSV steering and suspension systems consist mostly of stock and modified components from the Fiat Lancia Beta sedan, which has front wheel drive and a front/rear weight distribution similar to that of the LRSV. The main exceptions are the Chevrolet Citation rear axle and Volvo 244 rear springs. This choice of components gives the LRSV four-wheel disk brakes with rack and pinion steering.

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*Registered trademark of A.B. Volvo.

11.2 LRSV STRUCTURAL DEVELOPMENT

11.2.1 Front Structure

Operational Mockup

The operational mockup of the LRSV was constructed on a ladder frame of 2 x 4 x 0.083 inch (51 x 102 x 2.1 mm) rectangular steel tubing, extending the full length of the vehicle. The front rails provided the main support for the front suspension lower control arms and the powertrain. The front suspension selected was a McPherson strut assembly from the Lancia Beta sedan. The upper ends of the struts were attached to foam-filled sheetmetal fender boxes, cantilevered over the front wheels (Figure 11-2). These fender boxes were designed to be one of the major load paths in frontal collisions.

The forward ends of the fender boxes were connected by vertical supports to a foam-filled sheetmetal crossmember. Loads were also to be fed into the main frame by extensions of this vertical support structure. The crossmember was used, in turn, to support the bumper system.

Bogey Crash Test Articles Preliminary Design

The LRSV front structure design was initially based on a lumped mass mathematical model of a transverse engined, front-wheel drive vehicle. This simple model consisted of three masses and six springs, a schematic of which is shown in Figure 11-3. The materials and sizing of the structural members were based on a series of static crush tests; samples of the basic size and shape of each structural element were crushed. The metal gauge of the samples was varied until a wide variety of force-deflection characteristics was obtained. These force-deflection characteristics were then used to define the nonlinear springs in the lumped mass model; and the spring characteristics were varied until an acceptable crash pulse was obtained.

The preliminary design of the first crash test bogey represented a second iteration of the front structure. Figure 11-4 shows a partial section of the

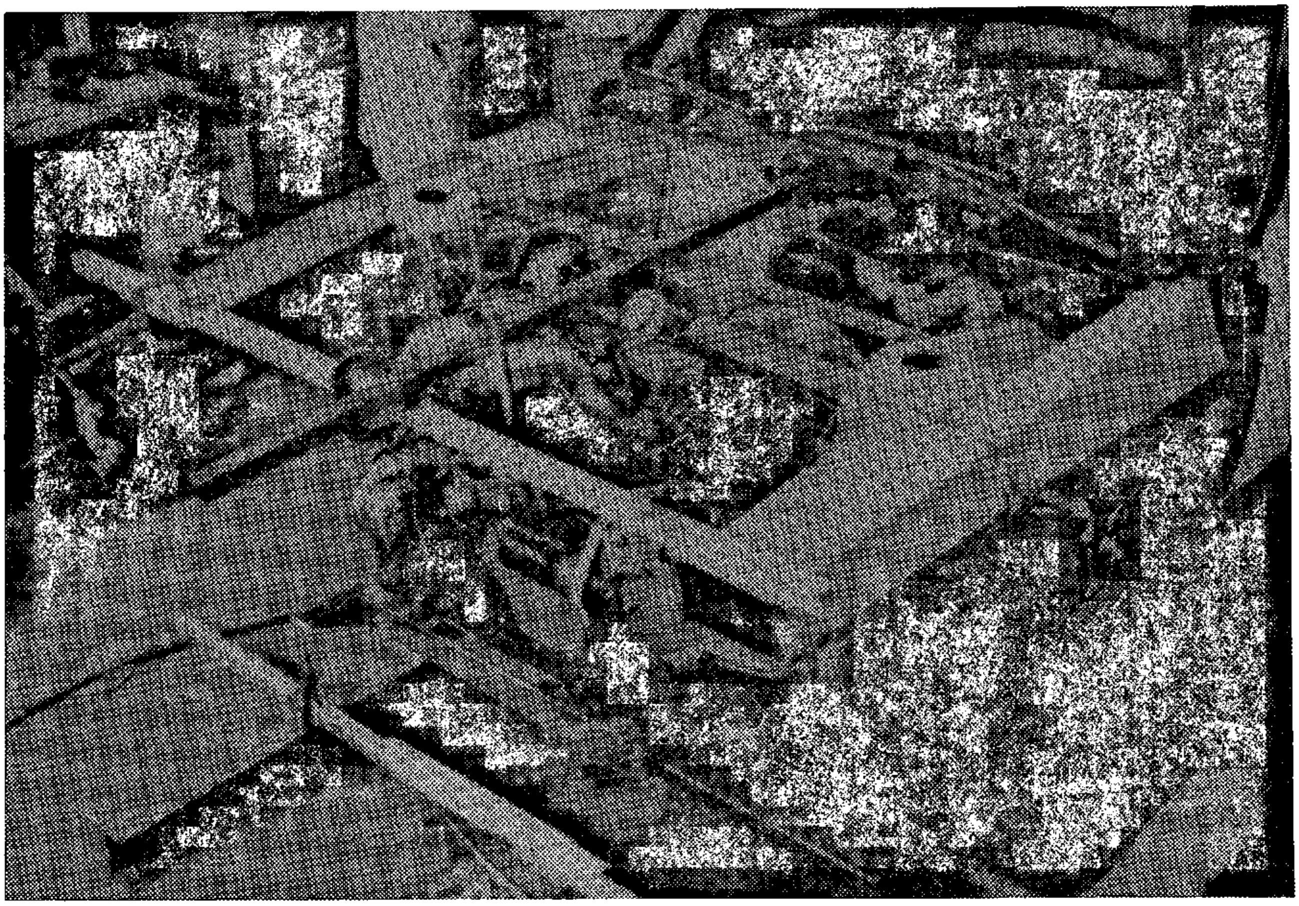
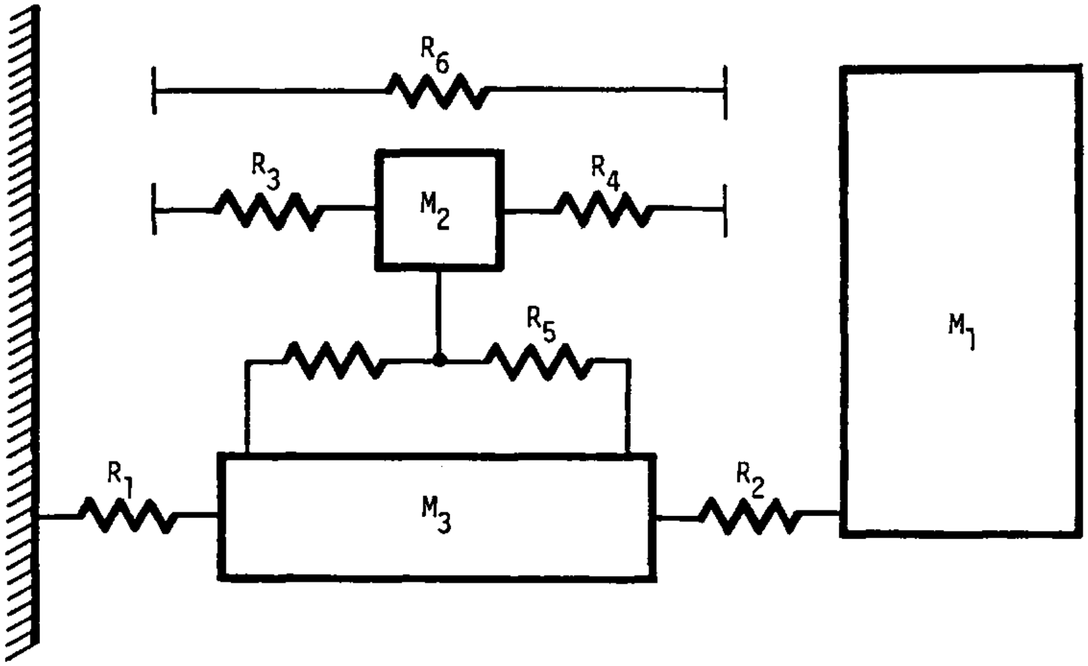


FIGURE 11-2. MOCKUP OF LRSV FRONT STRUCTURE



Mass	Definition
M_1	Body
M_2	Engine, radiator and front sheetmetal
M_3	Front suspension, bumper and front frame

Force	Definition
R_1	Front frame
R_2	Rear frame
R_3	Engine-to-radiator, etc.
R_4	Engine-to-firewall
R_5	Engine mount system
R_6	Upper load path structure

FIGURE 11-3. LUMPED MASS MODEL OF THE LRSV FRONT STRUCTURE

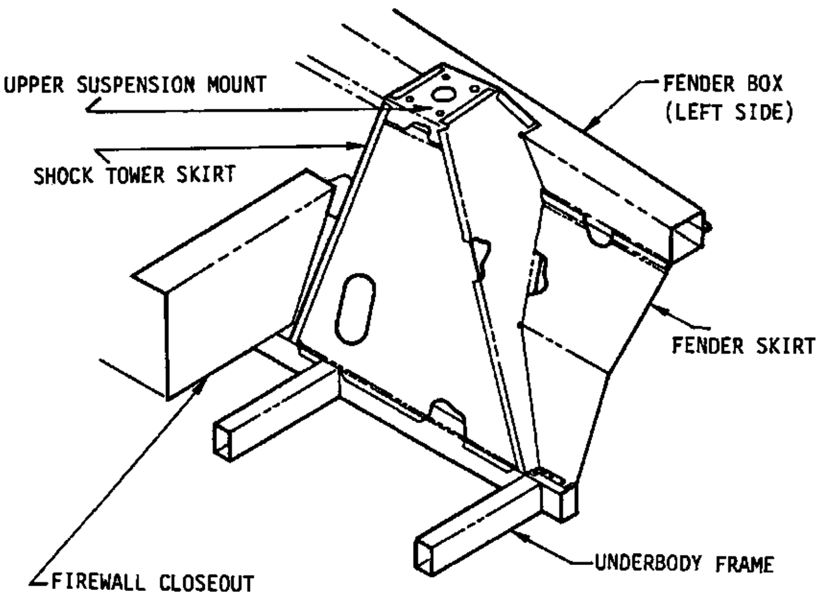


FIGURE 11-4. SUSPENSION MOUNT - FIRST DESIGN ITERATION

front structure in the first iteration; this design combined the upper mount for the suspension and the skirt around the shock absorbers into a structural element integrated with the fender skirt. The second iteration (Figure 11-5) simplified the design. We incorporated a fore/aft beam halfway down the fender skirt to better control frontal crash loads. The upper suspension mount became a smaller, simpler can which was integrated into the upper part of the fender skirt.

The configuration of the underbody frame is shown in Figure 11-6. The basic frame was made up of crossmembers, side rails and corner gussets (Items 1, 2, 3, 4 and 11 in Figure 11-6). Side rail extensions (Items 6 and 7) supported the front bumper channel (Item 5), which incorporated mounting brackets (Item 8) for the energy-absorbing bumper. The side rails also supported the brackets for mounting the front and rear control arms and sway bar (Items 9 and 10).

The configuration of the nose section is shown in Figure 11-7. The fender boxes and the fender closeout cans supported the nose. The nose, fender boxes and closeouts were foam-filled to improve their energy absorption.

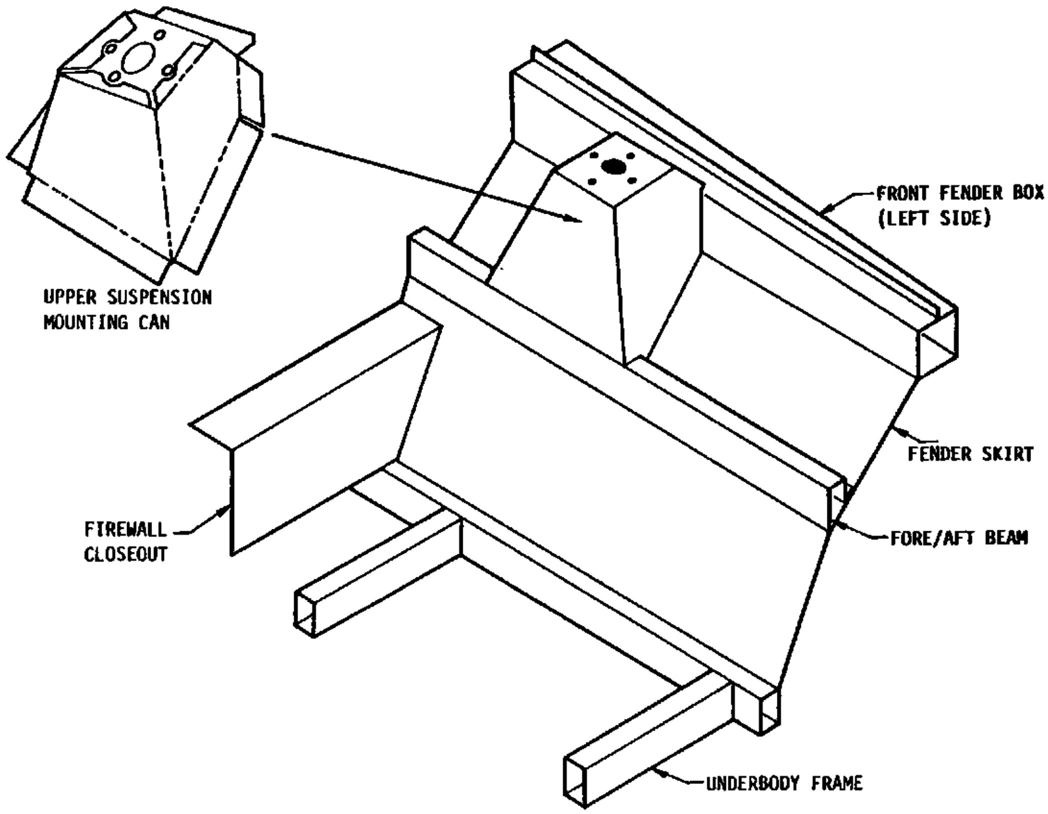


FIGURE 11-5. SUSPENSION MOUNT - SECOND DESIGN ITERATION

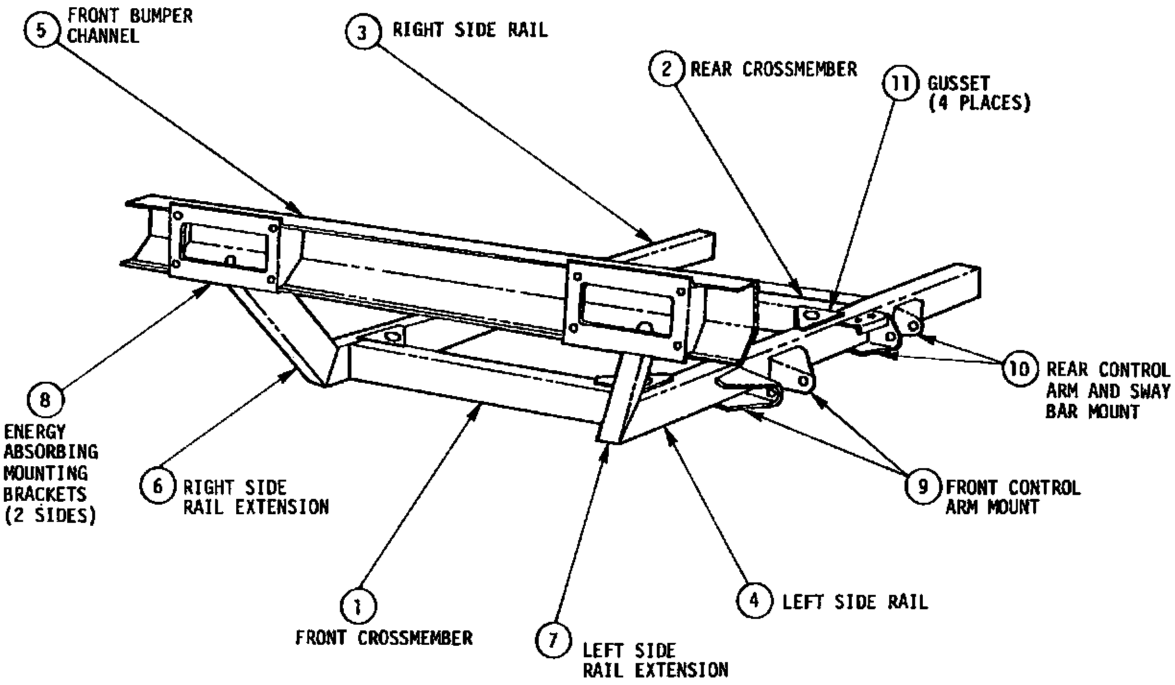


FIGURE 11-6. FRONT UNDERBODY FRAME STRUCTURE

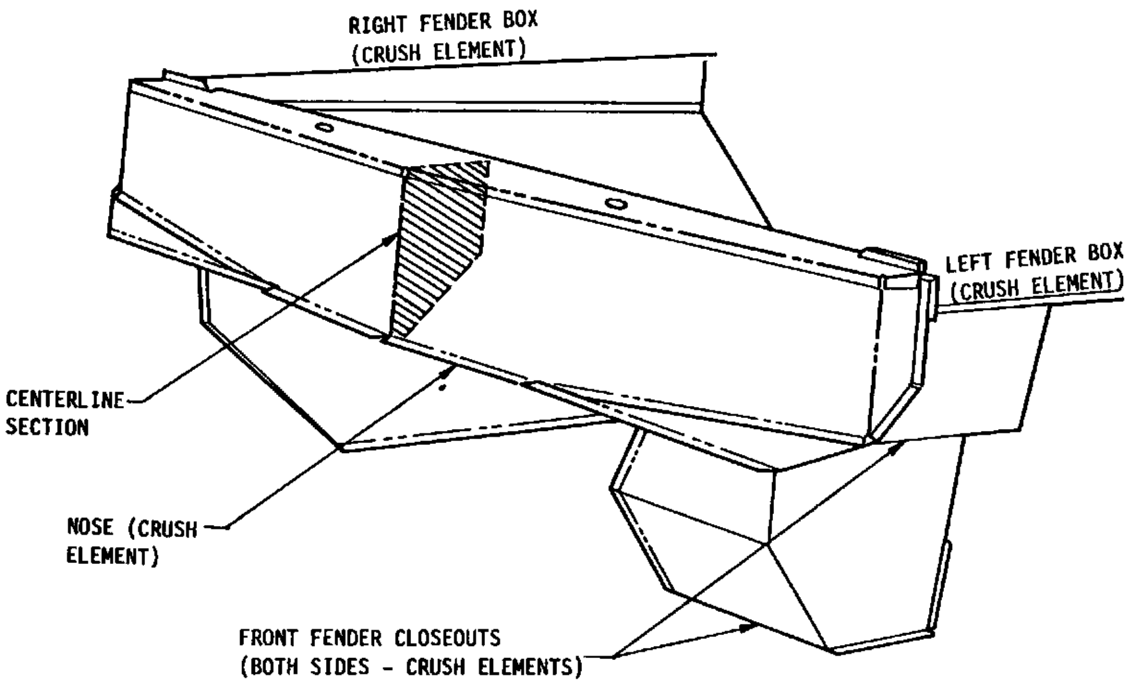


FIGURE 11-7. NOSE SECTION

Bogey Vehicle Development

For the first bogey vehicle, the left and right fender boxes were fabricated from 16 gauge (0.060 inch; 1.5 mm) brake-formed sheet steel. The side rails, side rail extensions and front and rear frame crossmembers were constructed from 2 x 3 x 0.083 inch (51 x 76 x 2.1 mm) mild steel rectangular tubing. Suspension mounting cans were brake-formed from 18 gauge (0.048 inch; 1.2 mm) steel. The front bumper channel and energy-absorber mounting brackets were fabricated from 16 gauge steel. All other components (e.g., the nose crush element, front and rear fender closeouts and inner fender skirts) were formed from 22 gauge (0.030 inch; 0.76 mm) steel.

We conducted a 40 mph (actual speed was 37.2 mph) barrier crash test of this front structure. Unfortunately, an unprecedented instrumentation malfunction caused the loss of all longitudinal acceleration data. An analysis of the test films indicated that the dynamic crush was between 25.3 and 26.2 inches (64.3 and 66.5 cm). The time required for the vehicle to decelerate was approximately 77 msec.

We calculated that the front structure would have crushed between 28.0 and 29.1 inches (71.1 and 73.9 cm) in a 40 mph impact. Since a dynamic crush of 34 inches (86 cm) was optimal, the stiffness should have been only 82 to 85 percent of the actual stiffness of the test structure. Consequently, we undertook a minor redesign of the front structure to soften the crash pulse (and to reduce the vehicle's tendency to pitch nose up). This redesign consisted of a gauge reduction of the structure in the upper load path and a change in the lower load path to increase the frame crush at the rear of the structure.

In the lower load path we replaced the compartment portion of the lower frame with a "torque box" which fed the frame rail loads outward into the sill sections. Figure 11-8 shows a bottom view of the torque box configuration. In the upper load path, the gauge of the fender box crush elements was reduced to 18 gauge (0.048 inch; 1.2 mm). These structural changes were then implemented in a second bogey vehicle, which was crash tested at 39.4 mph (63.4 km/h).

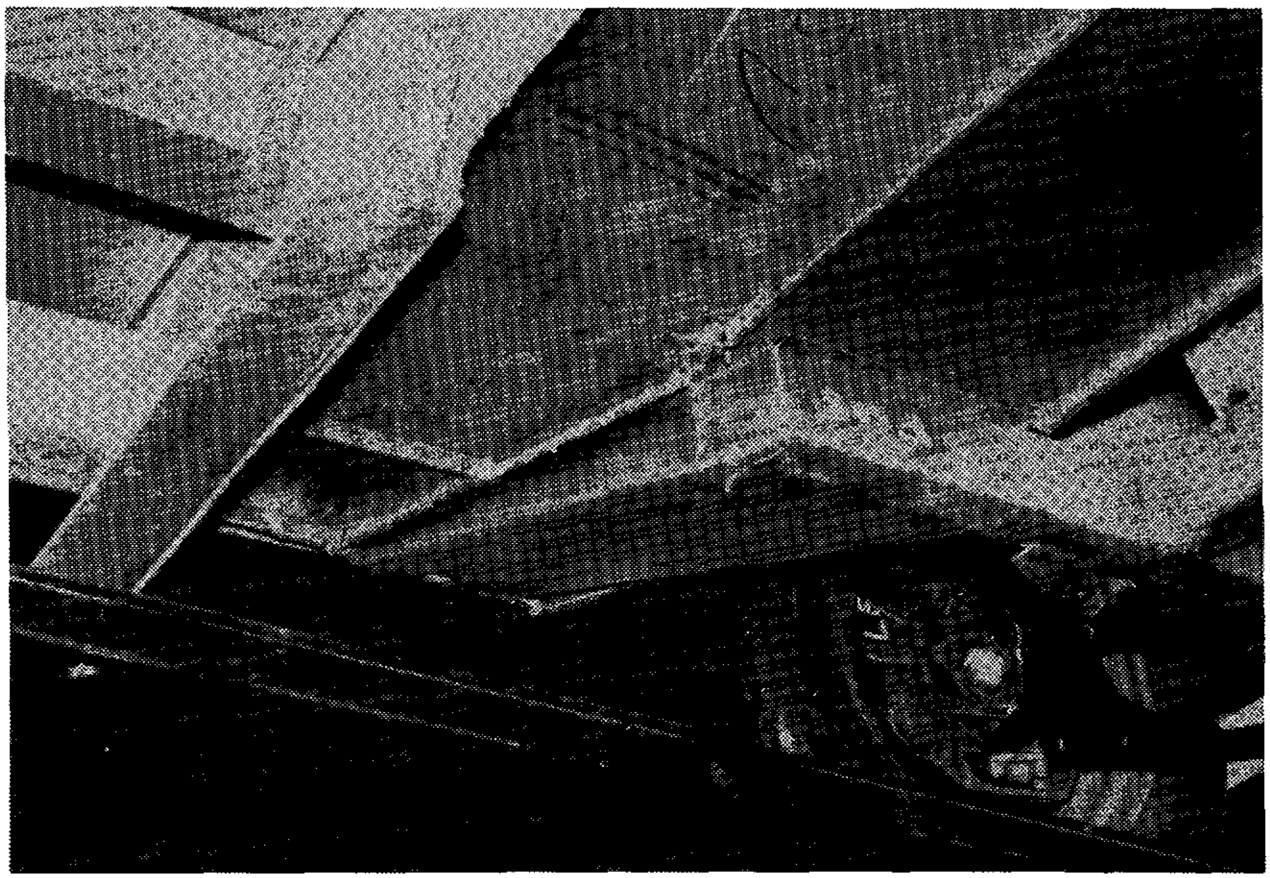


FIGURE 11-8. TORQUE BOX (BOTTOM VIEW)

An excellent crash pulse was obtained; however, the redesigned lower load path reduced the rear frame stiffness excessively, causing excessive lower dash deformation and accentuating the nose-up pitch seen in the previous 40 mph barrier impact. These results indicated a need for several revisions, including a reduction of the gauge of both the lower frame structure and the structure in the upper load path, and a change in the design of the interface between the lower frame and the body structure. The lower frame structure was reduced from 0.083 to 0.060 inch (2.1 to 1.5 mm) wall, 2 x 3 inch (51 x 76 mm) rectangular tubing. The upper load path was further downgauged from 18 to 20 gauge (0.036 inch; 0.91 mm) steel. The torque box structure was reinforced with a longitudinal tapered hat section beam which would feed loads rearward into the front seat crossmember (Figure 11-9). These design revisions were implemented and third barrier test was conducted.

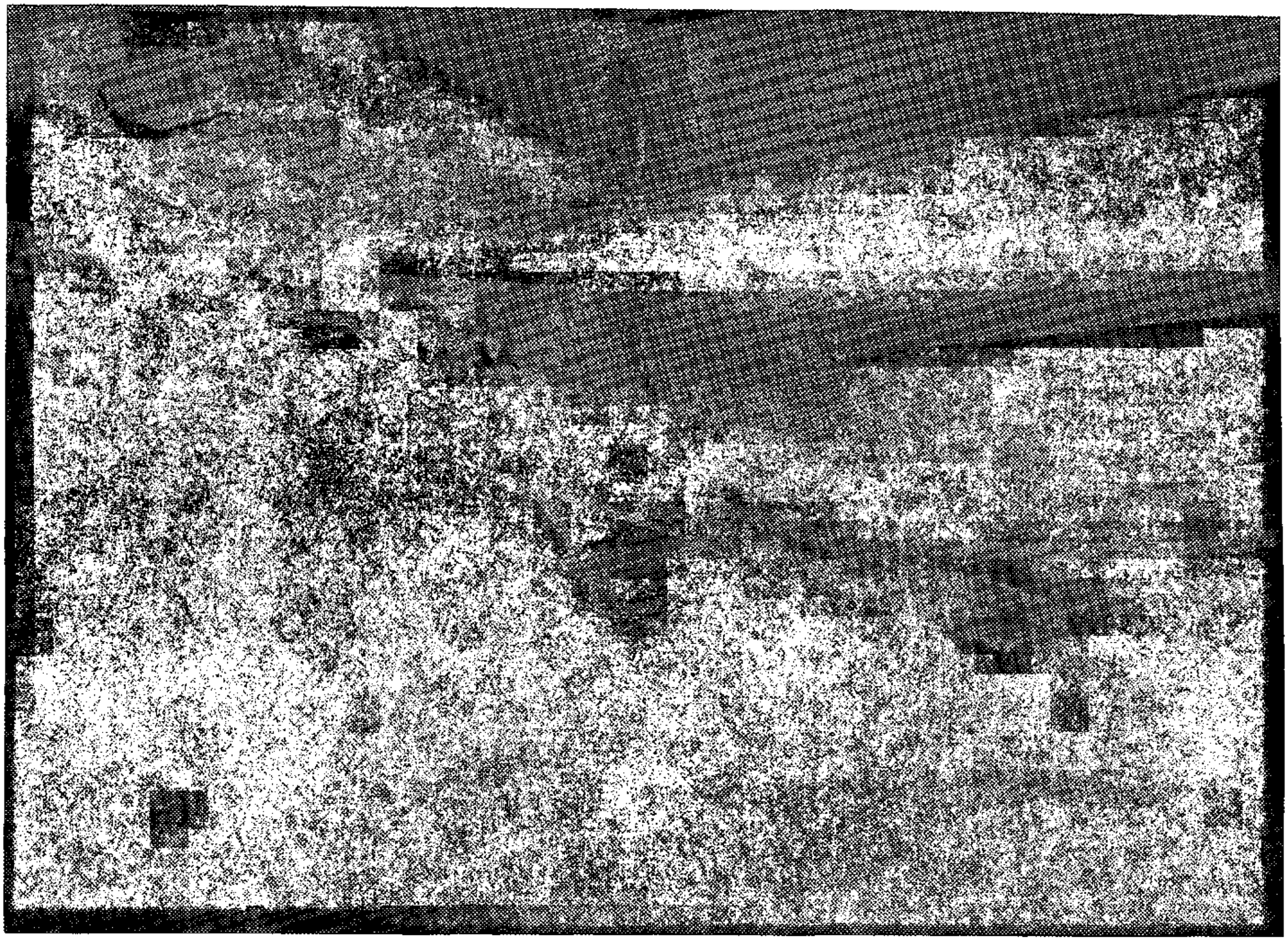


FIGURE 11-9. TORQUE BOX REINFORCEMENT

As expected, the crash pulse measured in the third test had a slightly higher acceleration level than did the previous pulse; however, the nose-up pitch and the rear frame deformation were significantly reduced. Table 11-1 compares the results of Bogey Tests 2 and 3.

TABLE 11-1. COMPARISON OF RESULTS FROM TEST NUMBERS 1341 AND 1386

	Test 1341 Bogey Test 2	Test 1386 Bogey Test 3
Test speed (mph)	39.4	41.5
Dynamic crush (inches)	41.0	39.0
Vehicle deceleration time (msec)	119	102
Toe pan intrusion (inches)	10	3 to 5

The front structure developed in the three bogey tests was then integrated into two crash test vehicles to be barrier-tested at 40 mph (64 km/h). The first test would involve an aligned barrier and the second either an aligned or a 30 degree angle barrier, depending on the results of the first test.

We conducted a nominal 40 mph frontal barrier crash test (Test 1436, shown in Figure 11-10) of the first LRSV crash vehicle. Post-test inspection indicated that the structure deformed similarly to the LRSV bogey test vehicle in the preceding 41.5 mph (66.8 km/h) frontal barrier crash. The toe pan intrusion and door deformation were within acceptable limits, and all four doors were readily opened by hand after the test. The basic test data were:

Test Speed	39.0 mph
Dynamic Crush	45.0 inches
Vehicle deformation time	124 msec
Toe pan intrusion	4 inches

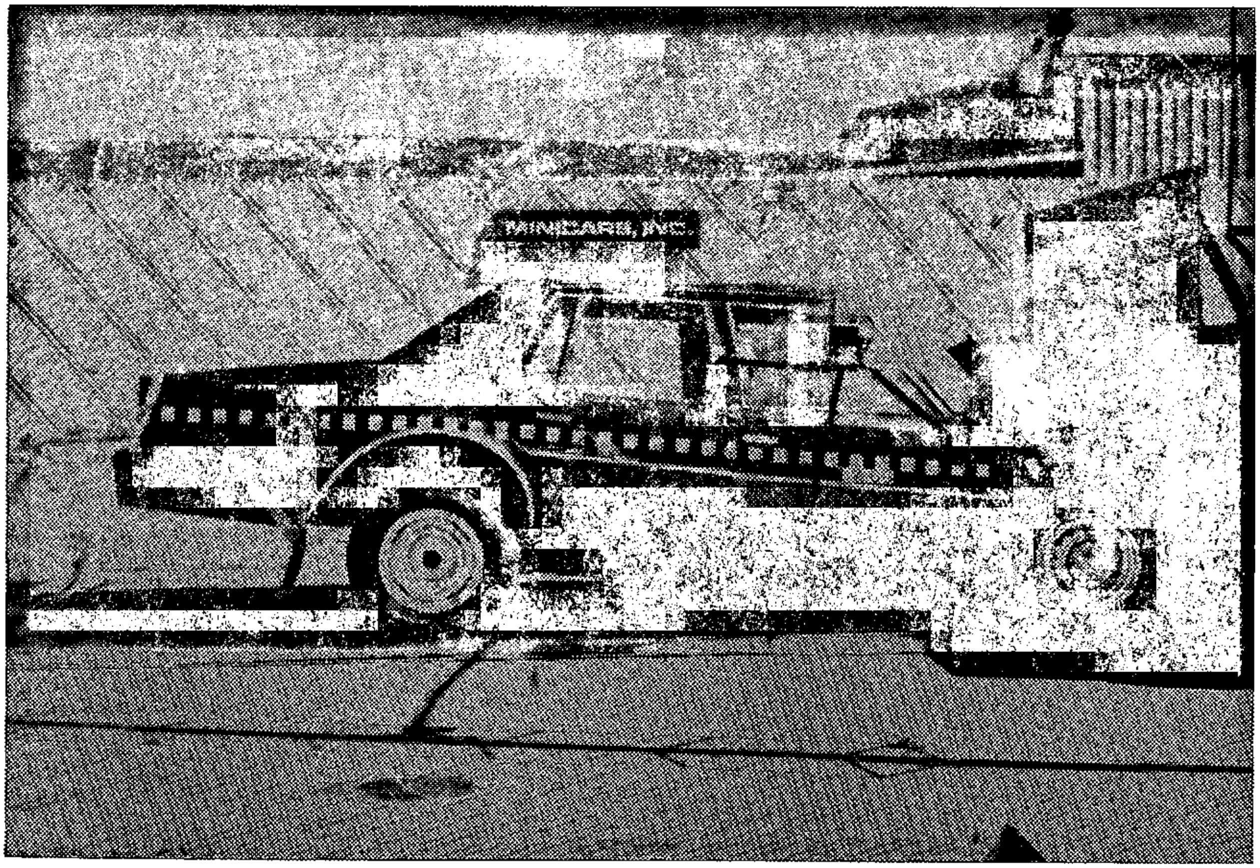


FIGURE 11-10. LRSV 39 MPH ALIGNED BARRIER IMPACT

The low average acceleration level of the crash pulse, the minimal compartment deformation, and the efficient restraint system combined to produce remarkably low injury numbers for the three dummy occupants. These good results led to the decision to proceed to the 30 degree barrier test.

The second crash had a very long duration, low acceleration level crash pulse. The vehicle did not exhibit significant steering column rearward displacement, and the toe pan rearward displacement of 4 inches was also relatively low (for an impact in which the decelerating forces were concentrated on one side of the vehicle).

Show Vehicle Structure

We continued to make minor modifications to the LRSV front structure after the frontal crash testing was completed. Two goals were established (beyond maintaining the successful crashworthiness): to downsize and relocate some of the structural components (as indicated by the crash test data), and to revise the assembly procedures for easier handling and spot welding. This redesign also provided an opportunity to "clean up the design" and to establish a common structural design theme for the rest of the structure.

The front impact beam weldment (Figure 11-11) was modified to accommodate the headlamp mounting panels and the hood latch mounting plate. The front bumper weldment (Figure 11-12) remained unchanged, but the front inner fender assemblies (Figure 11-13 shows the left side unit) underwent the most extensive changes. The upper fender box was revised to incorporate the final interface attachment at the hinge post. The inner fender was changed to accommodate a strut tower reinforcement spanning the distance between the front and rear fender closeouts. Previously, the reinforcement ran the full length of the fender; this caused assembly problems and, under crush, produced severe floor and firewall deformation. The front and rear fender closeouts were changed to conform with the new inner fender configuration.

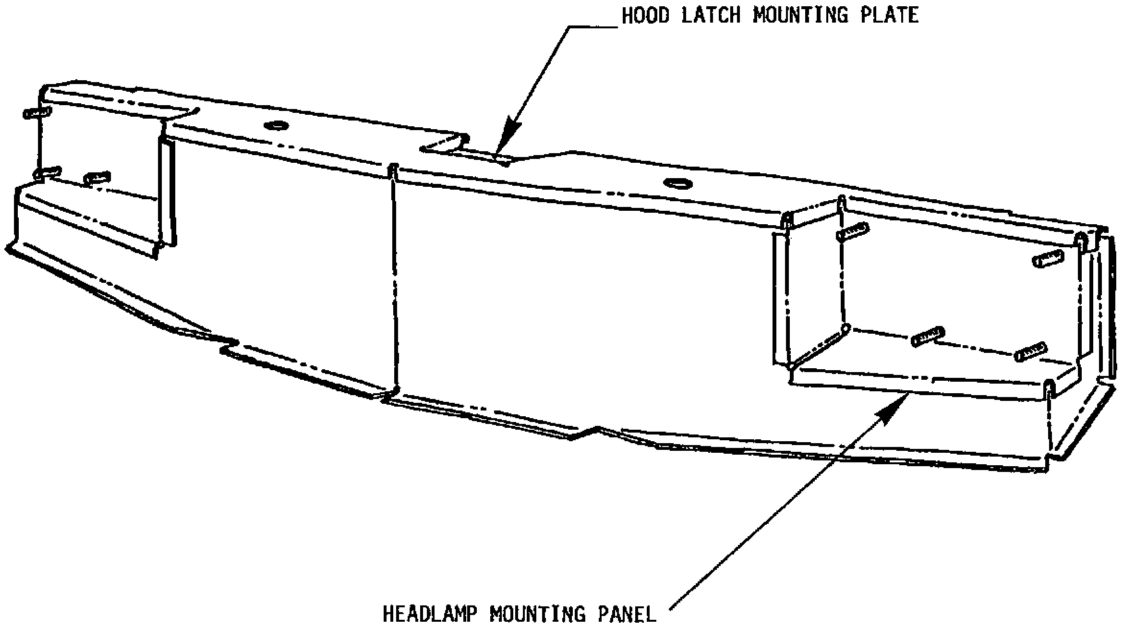


FIGURE 11-11. FRONT IMPACT BEAM WELDMENT

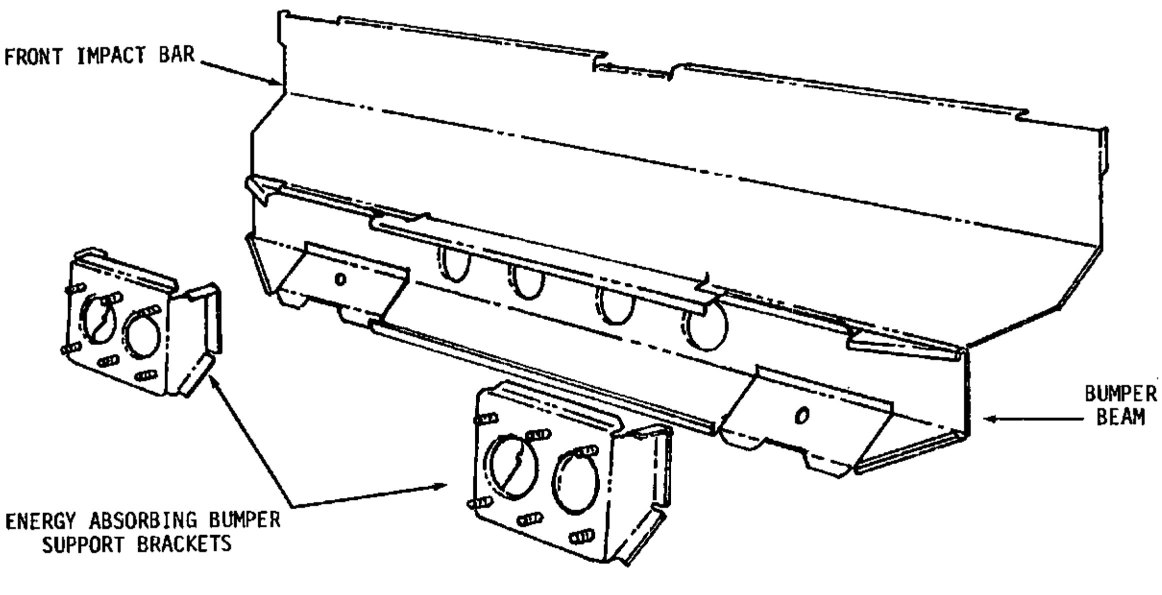


FIGURE 11-12. FRONT BUMPER WELDMENT

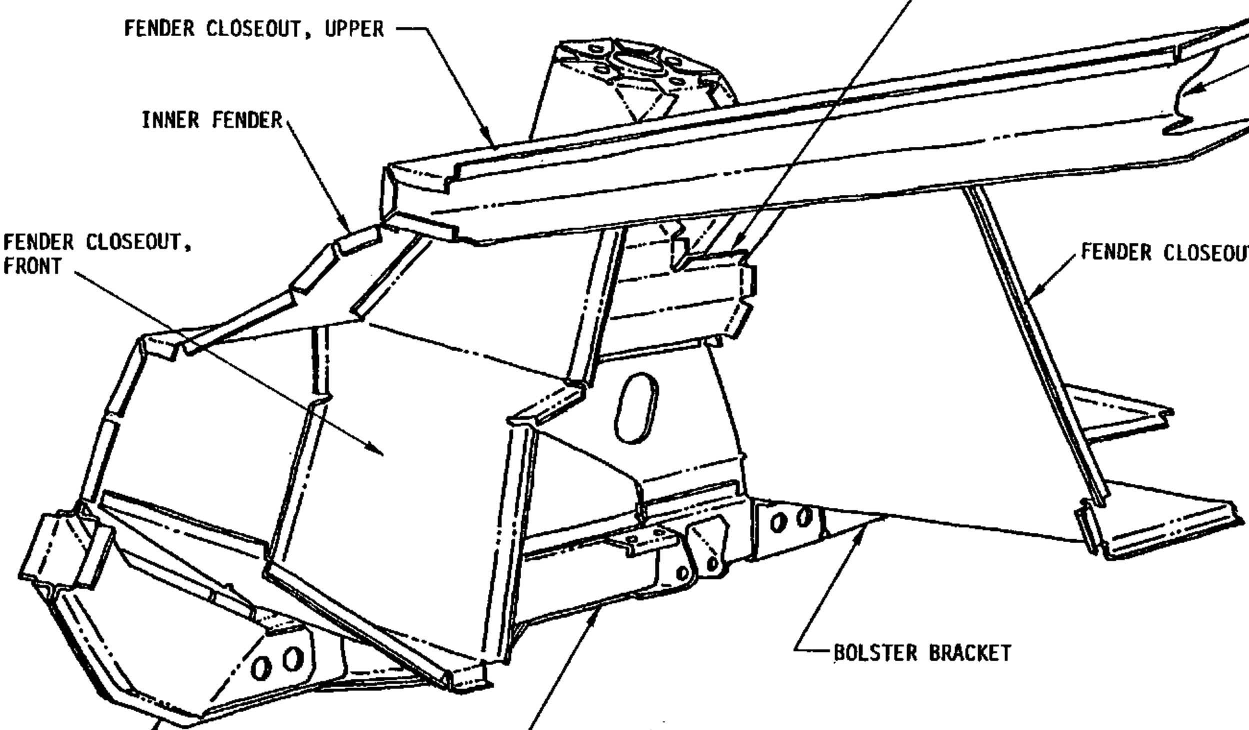


FIGURE 11-13. LEFT FRONT INNER FENDER WELDMENT

11.2.2 Compartment Structure

Operational Mockup

Inside the passenger compartment of the operational mockup the conventional floor was replaced by a thin foam-filled sheetmetal sandwich. Additional longitudinal support was provided by increasing the depth of, and foam-filling, the rocker panels (sills). Lateral crossmembers were fixed underneath the front and rear seats (Figure 11-14).

The four doors (Figure 11-15) of the mockup were modified to meet the augmented side impact performance requirements described in Section 11.3. The standard door beam was replaced with a foam-filled Aramid section between the exterior door skin and the window mechanism; and an additional tubular steel door beam was added above the standard latch assembly. The steel exterior skins of the doors were retained.

Preliminary Design for Frontal Crash Protection

The structure of the mockup vehicle was found to have some minor deficiencies which compromised occupant kinematics in crashes and occupant entry into the vehicle. The occupant kinematics was hampered by an inadequate knee trajectory; the entrance problem was primarily a matter of a high sill.

To produce a more desirable knee trajectory, we lowered the forward portion of the floor (between the front seat box and the firewall). We also lowered the seat box to provide more room for forward H-point translation. These changes reduced the under-floor room available for the vehicle frame structure, thereby eliminating the continuous front-to-rear frame rails of the mockup. Fortunately, we were able to decrease the depths of the mockup's sills, since structural analysis showed they were stiffer than necessary to provide adequate beaming and torsional capability in the compartment. Reducing the sill depth also eliminated the entry/egress problems with step-over height.

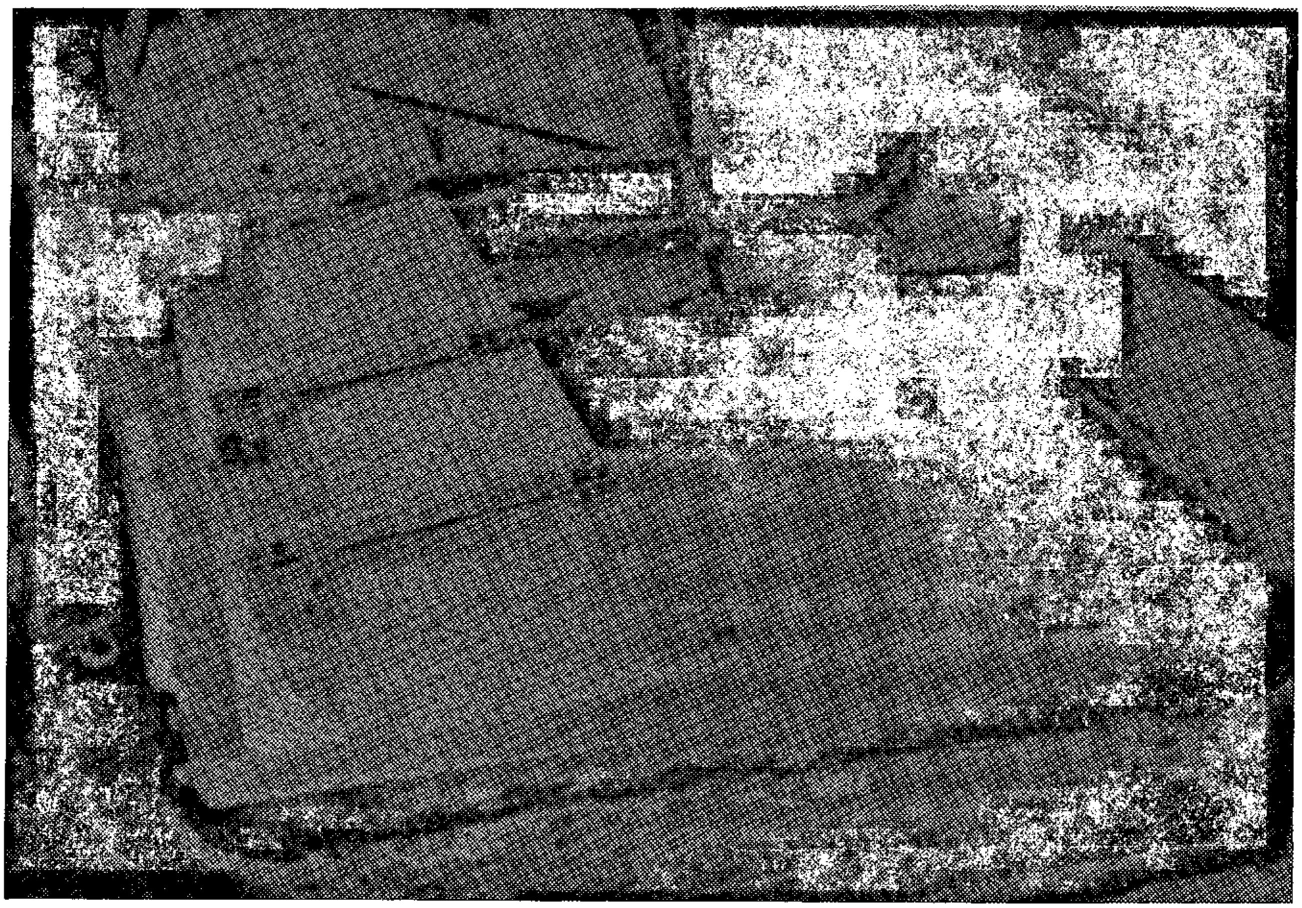


FIGURE 11-14. LRSV MOCKUP COMPARTMENT FLOOR

FIGURE 11-15. LRSV MOCKUP REAR DOOR DURING CONSTRUCTION

During the bogey tests load cells were used to monitor the upper load path forces transmitted to the front hinge pillar by the upper fender boxes. The magnitude of these loads caused concern that the compressive stiffness of the base vehicle's upper door, even with the hat section reinforcements used in the mockup, would be inadequate to handle forces of this magnitude. We, therefore, conducted a static compression test of the base vehicle's upper door and found it to buckle at 10,000 pounds (44,000 N) less than the required force level. A brake-formed upper door reinforcement was designed to replace the upper 3 inches (7.5 cm) of the base vehicle's inner door panel (Figure 11-16).

We also replaced the Aramid reinforced foam-filled doors of the mockup with a lightweight HSLA steel side guard beam. The design used in the mockup was revised because of significant problems in sealing and bonding the Aramid reinforcements to the door skins.

11.2.3 Rear Compartment Structure

In the operational mockup the rear spring towers were attached to the top of the rear inner fenders near the package tray. The towers were connected to the frame by large vertical members along the inner fenders and were separated laterally by a small member behind the rear seat. The luggage compartment floor rested on three longitudinal members running from the rear suspension support to the rear bumper. The no-damage bumper system was mounted on the rear bumper support, a foam-filled sheetmetal section extended across the rear face of the vehicle. Additional longitudinal strength was provided by closing out and foam-filling the rear fender sections (Figure 11-17).

The rear compartment structure of the prototype LRSV was considerably simplified in comparison to the mockup. This simplification was obtained by substituting a Chevrolet Citation beam rear axle for the mockup's Lancia independent rear suspension. Adaptors were used to mount the Lancia rear disc brakes and hubs to the Citation axle, providing the correct track width and a compatible brake system with the Lancia front brakes. The kickup section from a Chevrolet Citation was integrated with the LRSV foam-filled sill structure; this section provided mounting points for the Citation suspension control arms.

FIGURE 11-16. NEW SIDE GUARD BEAM

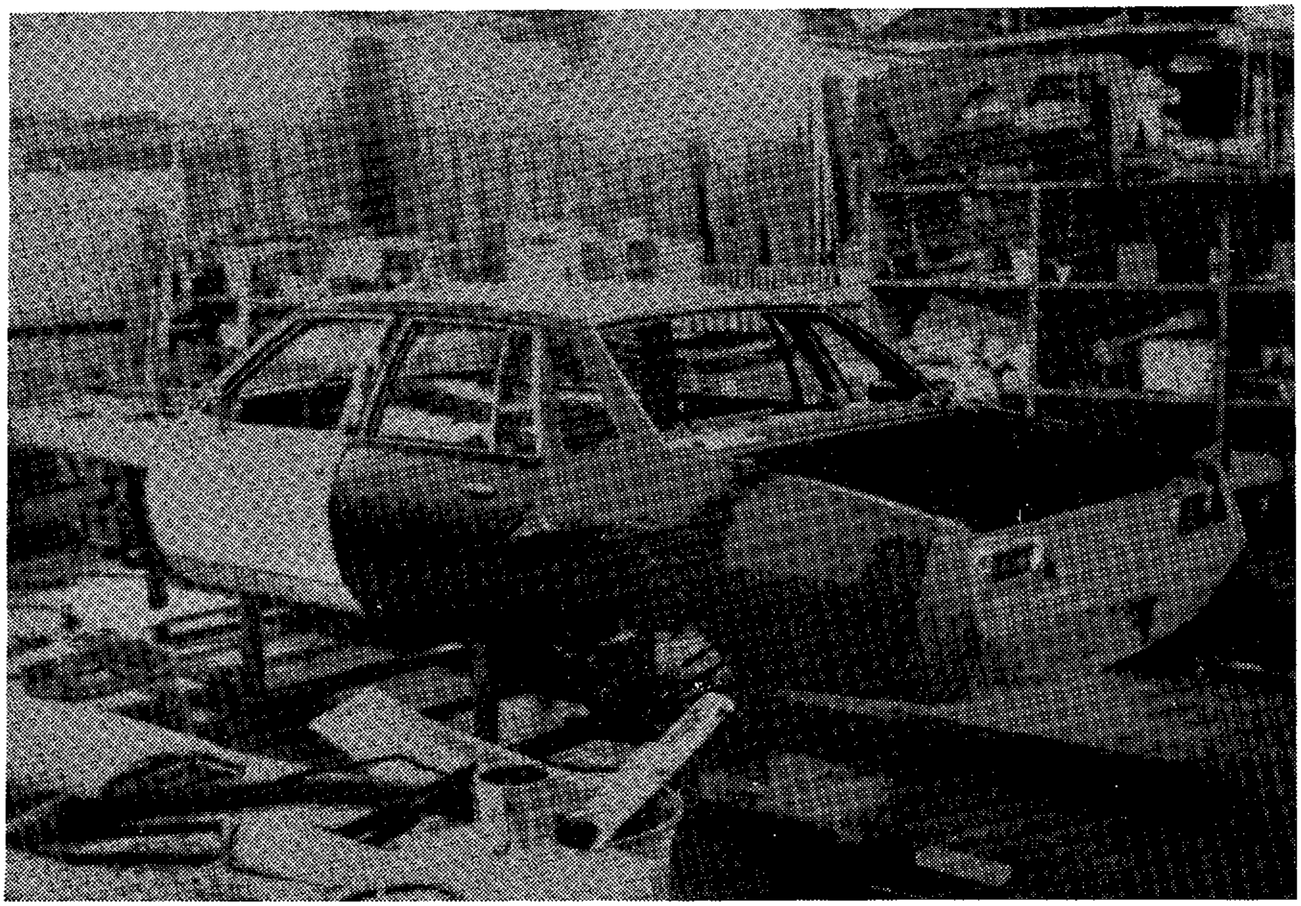


FIGURE 11-17. LRSV COMPARTMENT

As there were no contractual goals for improved rear crashworthiness, our consideration of high speed rear impacts was limited to the placement of the prototype's fuel tank in a protected location over the rear axle. For low speed impacts the prototype retained the mockup's no-damage bumper (with rubrics) and flexible fascia. Two rectangular steel tubes were mounted longitudinally beneath the trunk floor to reinforce the trunk for the low speed impacts.

11.3 LRSV OCCUPANT PACKAGING SYSTEM

The objective of the LRSV occupant packaging system is to function together with the vehicle's structural crashworthiness features to provide the occupant protection levels above those specified in current safety standards in front and side impacts. The packaging system is designed to at least meet the occupant protection requirements of FMVSS 208 at 40 mph (64 km/h) - rather than 30 mph (48 km/h) - and to meet the side impact requirements of FMVSS 208 at a bogey velocity of 25 mph (40 km/h) - rather than 20 mph (32 km/h).

The following section describes the features and performance of the LRSV air cushion and door padding systems.

11.3.1 LRSV Air Cushion System

The layout of the complete LRSV air cushion system is illustrated in Figure 11-18. Essentially, the system is comprised of the sensor and diagnostic circuitry, the driver restraint system, and the passenger restraint system. The system is designed to provide 40 mph barrier impact protection to the driver and two front seat passengers.

11.3.2 LRSV Driver Restraint System

The LRSV driver restraint system is a derivative of the earlier RSV system; in fact, it uses a number of the same components (e.g., the steering shaft assembly and steering wheel). But the LRSV had much less severe performance criteria

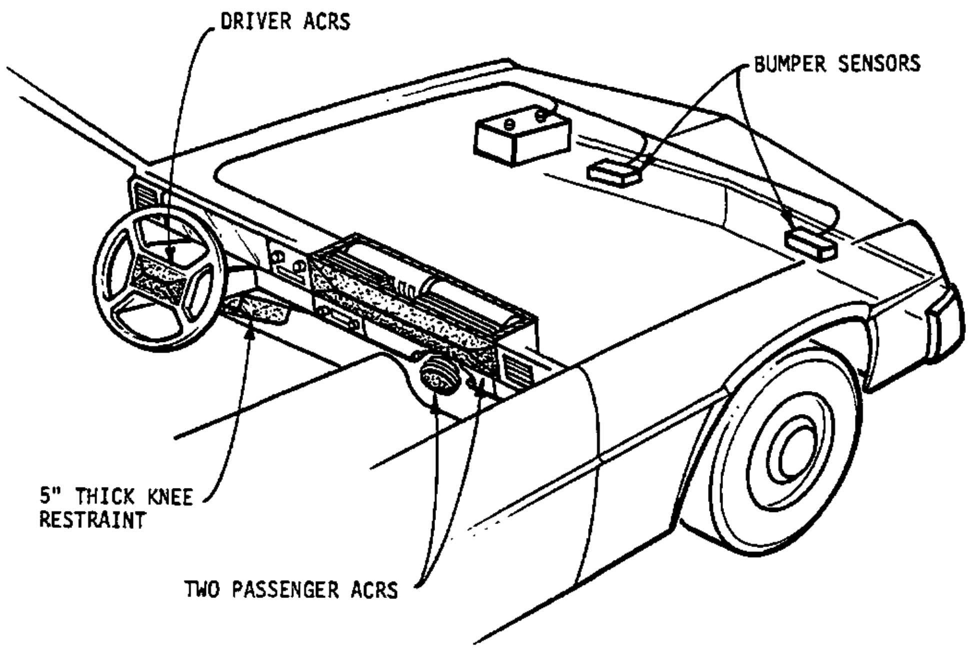
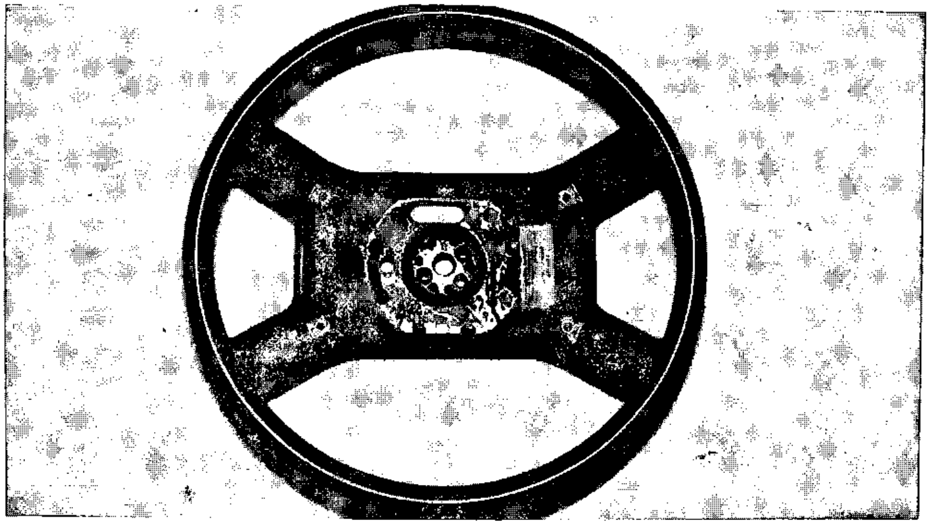


FIGURE 11-18. MAJOR COMPONENTS OF THE RESTRAINT SYSTEMS

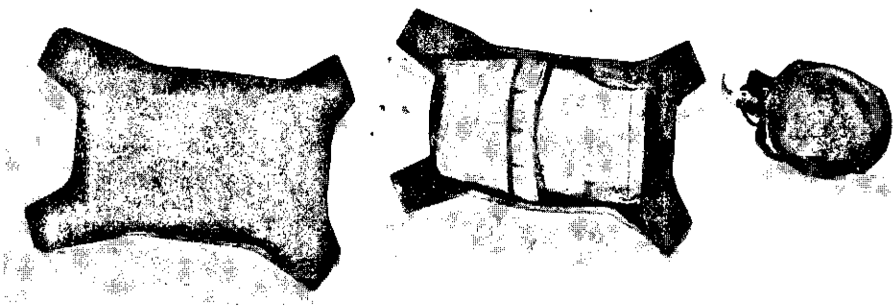
(requiring only about two thirds of the energy absorption capability of the RSV system). It, therefore, was possible to configure the LRSV system in a more conventional manner.

Wheel Module Subsystem

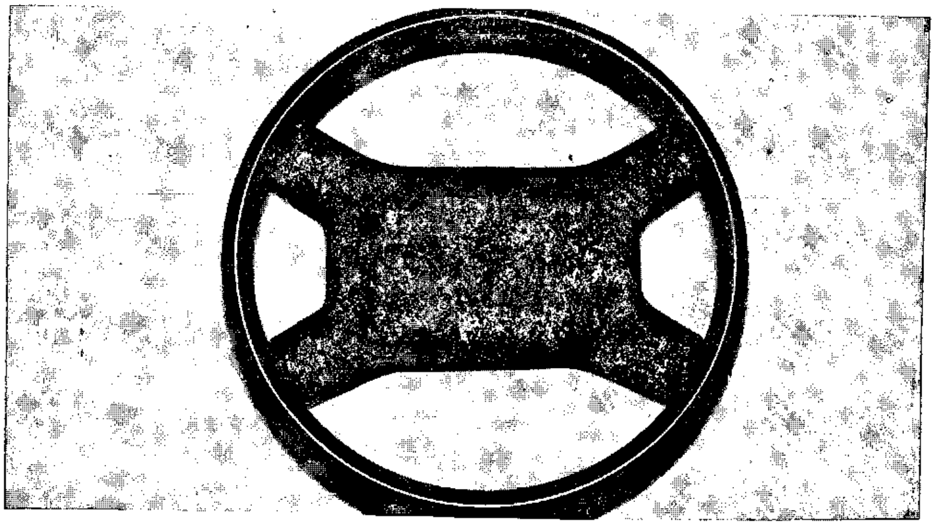
The LRSV driver system uses the GM ACRS wheel module assembly, with substitutions for the inflator and airbag. The GM module is shown in Figure 11-19 and consists of a (specially-designed) ACRS steering wheel, module pack, driver inflator, air cushion and bag cover. The module pack is basically a hard plastic box with a metallic rear surface; the rear surface forms the reaction plate and the front surface (which is formed with an H-shaped tear pattern) opens like flower petals during bag deployment. The inflator is bolted to the reaction plate and is linked with the airbag (also secured to the reaction plate) through an orifice in the plate. A textured outer cover is also secured to the reaction plate and is provided with an H-shaped tear pattern (seam) which matches the pattern in the



(a) ACRS Steering Wheel



(b) ACRS Internal Components



(c) Completed Wheel Assembly

FIGURE 11-19. LRSV DRIVER ACRS ASSEMBLY

module pack face. The inflator, module pack, air cushion and bag cover thus form a unit which bolts to the ACRS wheel.

In the LRSV module the GM ACRS inflator is removed and an uploaded inflator, identical to the RSV driver inflator, is substituted for it. The GM ACRS air bag is replaced by a vented (4.5 square inches) air cushion which has about 75 percent of the volume of the unvented GM ACRS bag (estimated at about 2.75 cubic feet). This modification speeds the coupling of the driver's upper body to the vehicle. This coupling is also facilitated by configuring the air cushion in a cylindrical pattern; it has two 18 inch (46 cm) diameter circular ends which are linked by a 9 inch (23 cm) long center. This construction encourages the inflated bag to take on more depth and less breadth, thus involving the driver with the airbag sooner.

Steering Column Assembly

The LRSV steering column assembly is similar to the RSV assembly. The principal areas of difference are:

- The LRSV column is oriented at an angle of 17 degrees from horizontal, while the RSV column is at an angle of 9 degrees.
- The EA unit of the RSV column has a second phase stroking force of 3300 pounds (1500 kg); the LRSV column strokes at 2000 pounds (900 kg).
- The sheetmetal bridge and retainer ring assembly linking the column mast to the steering wheel (see Subsection 4.2) was found to be unnecessary and was eliminated.

Knee Restraint Subsystem

The driver knee restraint system of the LRSV is configured similarly to that of the RSV. The essential difference is that the LRSV subsystem is designed to have a lesser EA capacity and to rely more on the yielding of the 20 gauge (0.037 inch; 0.93 mm) sheet steel knee restraint reaction plate. Thus the foam itself is only 3 inches (8 cm) thick and is faced with 1-3/8 inches (35 mm) of resilient EA foam (Ensolite, Type AH). The cover design is similar to that of the RSV.

The performance of the driver restraint system was defined in sled and crash tests. Table 11-2 summarizes the results from these evaluation tests (three sled tests and two barrier crash tests).

Test 1436 provided the best data for defining the performance of the system under the primary design condition. As is evident from the table, the system exceeds the requirements by quite a large margin. A comparison of the results of this crash test with those from the previously conducted sled simulation (Test 1411) indicates that the simulations quite closely match the barrier environment and suggest that the system possesses more than satisfactory repeatability. Sled Tests 1412 and 1416 indicate that the extremes of the driver somatotypes are protected at 40 mph, even though the 95th percentile male has little margin on the chest injury criterion. Further development could lower the chest injury measures for the 95th percentile male at 40 mph, at the expense of a tolerable increase in the corresponding injury measures for the 50th percentile male and 5th percentile female. This was not done because of time and money considerations.

Test 1509 is representative of the performance of the LRSV driver restraint system during oblique flat barrier crashes. Although there was 65 inches of crush on the driver side of the vehicle, the early sensing time, mild crash pulse, and low intrusion combined with the restraint system to produce very low injury measures.

11.3.3 LRSV Passenger Restraint System

The LRSV must accommodate three 50th percentile male adult occupants in its front seats. Consequently, the RSV passenger restraint system could not be easily adapted to the LRSV. We also found (by comparing high and low mount air cushion systems) that a system employing a knee cushion (low mount) would have advantages, including greater leg room and the potential to handle a wider range

TABLE 11-2. LRSV DRIVER TEST SUMMARY

Test No.	Test Description	Velocity (mph)	Squib Firing Time (msec)	Dummy Size	Dummy Injury Measurements			
					HIC	Chest Gs	Right Femur (pounds)	Left Femur (pounds)
1411	Sled simulation of perpendicular flat barrier impact	39.3	14	50M	130	36	1550	1450
1412	Sled simulation of perpendicular flat barrier impact	39.8	14	5F	259	40	875	725
1416	Sled simulation of perpendicular flat barrier impact	39.8	14	95M	435	57	1920	1500
1436	Perpendicular flat barrier impact	39.0	14	50M	174	37	1100	1150
1509	30° Left oblique flat barrier impact	40.1	25	50M	248	32	1300	1000

of occupant sizes and seated positions. The RSV passenger restraint is a high mount (non-knee cushion) system.

The selected configuration is essentially a two-passenger adaptation of a so-called hybrid system developed for the Chevrolet Vega under another NHTSA contract (DOT-HS-6-01412). The term "hybrid" is used because the inflator is located relatively high on the dash, but (as in a low-mount system) a knee bag is used for lower body energy management.

The overall layout of the LRSV passenger restraint is shown in Figure 11-20. The system is comprised of an air cushion module, passenger seat and sensor system. The sensor system is described above; the other two subsystems will be described here.

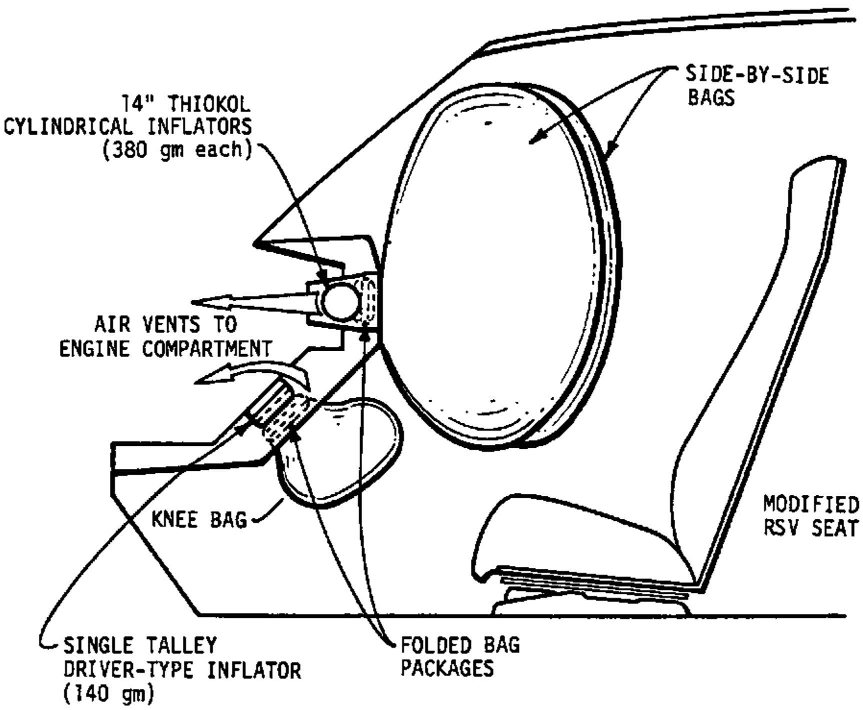


FIGURE 11-20. LRSV PASSENGER RESTRAINT SYSTEM

Air Cushion Module

The LRSV passenger air cushion module is comprised of a bag assembly, module pan, brackets, inflator and cover.

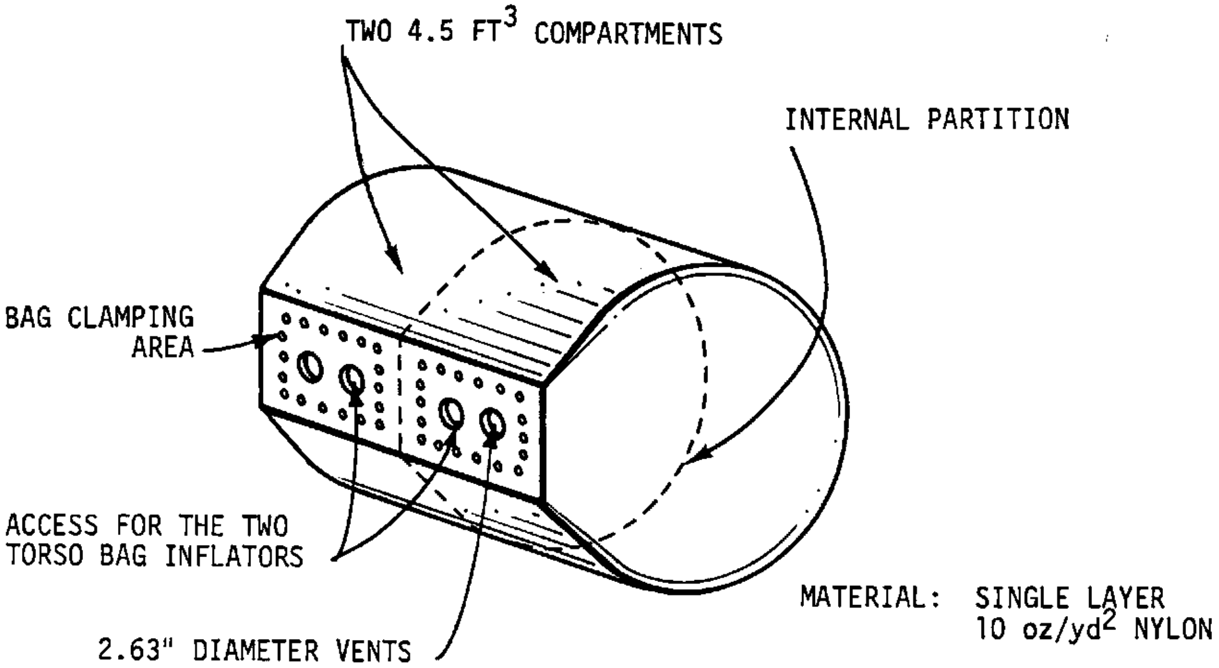
The LRSV airbag configuration is shown in Figure 11-21. Both the torso and knee bags are attached to the module pan via a bag clamping and backing plate system (as opposed to a "sock" attachment). The clamping assembly was used both to provide better bag stability and to allow the bag to vent directly through the module pan (as shown in Figure 11-20) into the engine compartment. This venting scheme insured that the high speed photographic coverage of the passenger response and restraint behavior during the development and evaluation testing was not obscured by vented gases. It also obviates issues about the effects of vented gas on crash victims.

A fabric partition divides the torso bag laterally into two chambers. This partition was installed primarily to give the rather wide bag a flatter aft (occupant side) surface. It would also allow for different venting to each chamber. This could be a desirable design feature, in that occupancy characteristics suggest that the middle seat, when occupied, is more likely to contain relatively small occupants (children, females). Thus there is reason for making the inboard chamber softer than the outboard cell by providing it with additional venting. In its present configuration, however, the two chambers have the same venting.

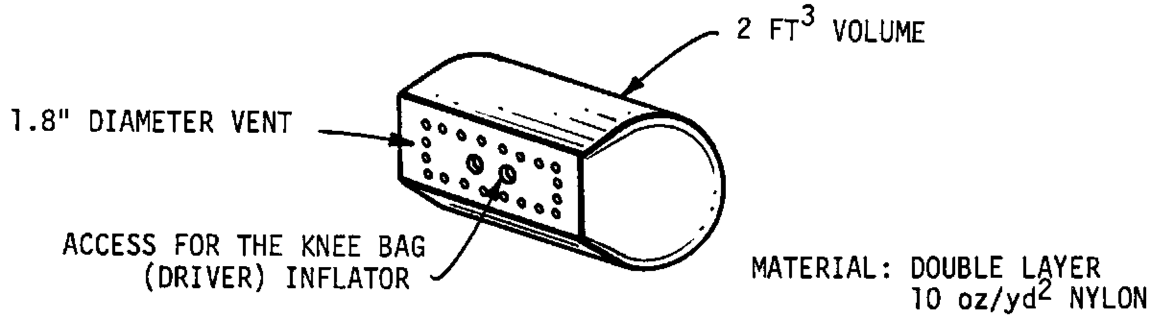
The module pan and bracketry are shown in the photographs of Figure 11-22. The module pan consists of a box-like upper structure (which houses the two torso bag inflators and torso bag) and a lower extension plate, to which is attached the knee bag and its inflator. This lower plate, because it serves as the knee bag reaction plate, must possess high structural integrity and must be well anchored to the compartment.

The rear surface of the module box and the lower plate are provided with orifices. These orifices primarily serve to vent gas, but they also allow some undetermined amount of engine compartment air to be drafted into the deploying air cushions. The torso bag vents are 5.43 square inches (35.0 cm^2); the knee bag vents are 2.54 square inches (16.4 cm^2).

The torso bag is inflated by the simultaneous initiation of two Thiokol small car passenger inflators. Each cylindrical unit is about 14 inches (36 cm) long and contains 430 grams of a sodium azide based propellant (in pellet form). The knee

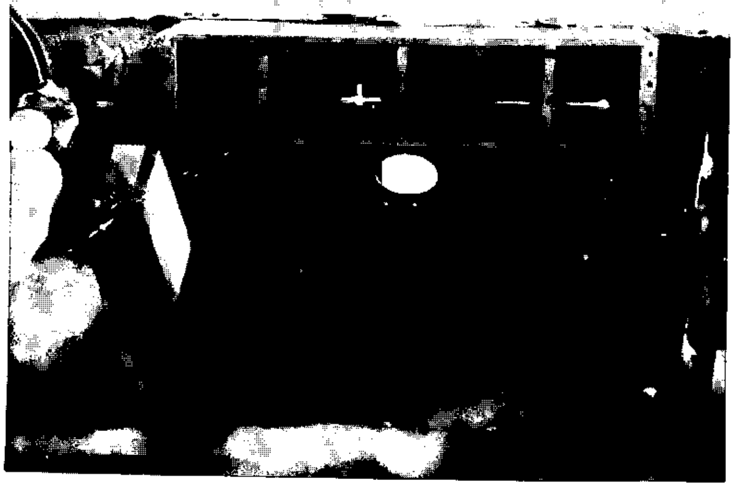


(a) Torso Bag

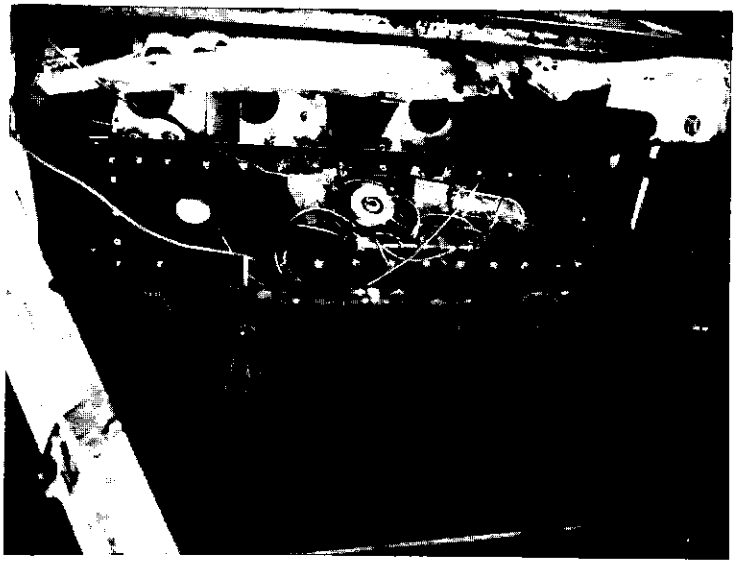


(b) Knee Bag

FIGURE 11-21. LRSV PASSENGER AIRBAG



(a) Passenger Restraint Bracketry



(b) Passenger Restraint Venting
(From the Engine Compartment)

FIGURE 11-22. LRSV PASSENGER RESTRAINT SYSTEM bag is inflated by a driver-type Talley Industries inflator containing 140 grams of sodium azide propellant.

The LRSV passenger system has two separate covers over the torso and knee bags. Both are configured in the same manner as the RSV passenger air cushion cover.

LRSV Passenger Seat

The LRSV has a split bench seat; the driver seat is separate from the two-passenger right front seat. The seats are constructed similarly, the passenger seat being a two-occupant adaptation of the driver seat. Both seats are modeled on the RSV front seats - with one important difference: there is no attachment of the LRSV seats to the roof. For this reason the seat backs had to be strengthened, since the ability of the Dodge van seat back structure to withstand occupant-induced rearward forces was judged to be exceedingly poor. This problem was resolved by reinforcing the connection of the seat back frame to the cushion frame.

The seat is constructed as a double seat with separate support springs (shown schematically in Figure 11-23). The separate cushion supports were found necessary in order to achieve a satisfactory degree of control over occupant H-points, as the weights of the two passengers would vary. The cushion frame was lowered 13 degrees to ensure that the center spring support does not interefere with occupant trajectory. A foam wedge was added to compensate for this lowering.

A 10 inch (25 cm) wide head restraint is provided for the outboard passenger by extending the seat back height locally. No head restraint is provided for inboard passengers, since (1) the seat is rarely occupied, (2) when it is occupied, it is frequently used by shorter occupants who do not need a head rest, and (3), most importantly, a center head rest would seriously compromise rearward vision.

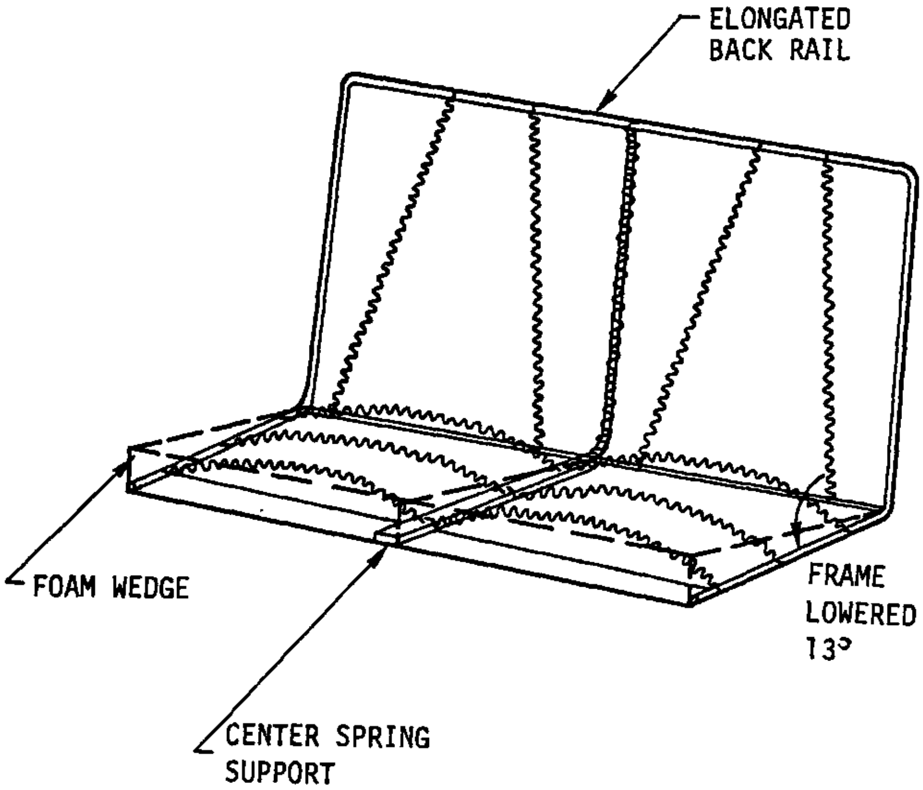


FIGURE 11-23. LRSV FRONT PASSENGER SEAT CONFIGURATION

Performance

Table 11-3 summarizes the sled and crash test results which define the performance of the LRSV passenger restraint system.

Sled Tests 1422 and 1437 were both conducted under the basic design condition and hence illustrate the excellent repeatability of the system. Test 1432, the objective of which was to evaluate the system under a reasonable light-load condition, produced excellent results.

Two vehicle crash tests were performed under FMVSS 208 conditions, but at a nominal speed of 40 mph. Test 1436, a perpendicular crash produced excellent results - lower in fact than those of the prior sled tests. In Test 1509, an oblique impact, the reinforced passenger seat back unexpectedly yielded while the LRSV was traveling to the barrier. This placed the dummies in a

TABLE 11-3. LRSV PASSENGER TEST SUMMARY

Test No.	Test Description	Velocity (mph)	Squib Firing Time (msec)	Dummy Size*	Dummy Injury Measurements			
					HIC	Chest Gs	Right Femur (pounds)	Left Femur (pounds)
1422	Sled simulation of perpendicular flat barrier impact	40	14	50M(C)	472	43	1000	725
				50M(R)	492	45	750	725
1432	Sled simulation of perpendicular flat barrier impact	40	14	None(C)	-	-	-	-
				5F(R)	571	37	275	400
1437	Sled simulation of perpendicular flat barrier impact	40	14	50M(C)	**	**	**	**
1436	Perpendicular flat barrier impact	39.0	14	50M(C)	169	30	1100	800
				50M(R)	178	30	1000	800
1509	30° left oblique flat barrier impact	40.1	25	50M(C)	74	25	1200	600
				50M(R)	130	35	600	1250

*Center (C), Right (R)

**Uninstrumented dummy

significantly reclined position. Despite this detrimental condition, the injury measures were all well below the FMVSS 208 criteria. The excellent results in this test are a joint consequence of the restraint design, the early sensing time and the very low LRSV compartment decelerations in this crash mode.

11.3.4 LRSV Side Impact Padding

The LRSV side impact protection is provided by a structural system, designed to limit the velocity of the struck door, and a padding system, designed to limit near-side occupant accelerations. The specific goal was to limit the injury measures experienced by the Part 572 dummy in the FMVSS 208 test [conducted at a 25 mph (40 km/h) bogey velocity rather than the required 20 mph (32 km/h)] to the limits prescribed in FMVSS 208 – and also to hold the pelvic lateral accelerations below 80 Gs.

The padding system is composed of separate shoulder and hip pads attached to the door interior panel. Each pad consists of a sheetmetal case filled with energy-absorbing foam. Cross-sectional views of the pads are shown in Figure 11-24; the finished door interior is shown in Figure 11-25.

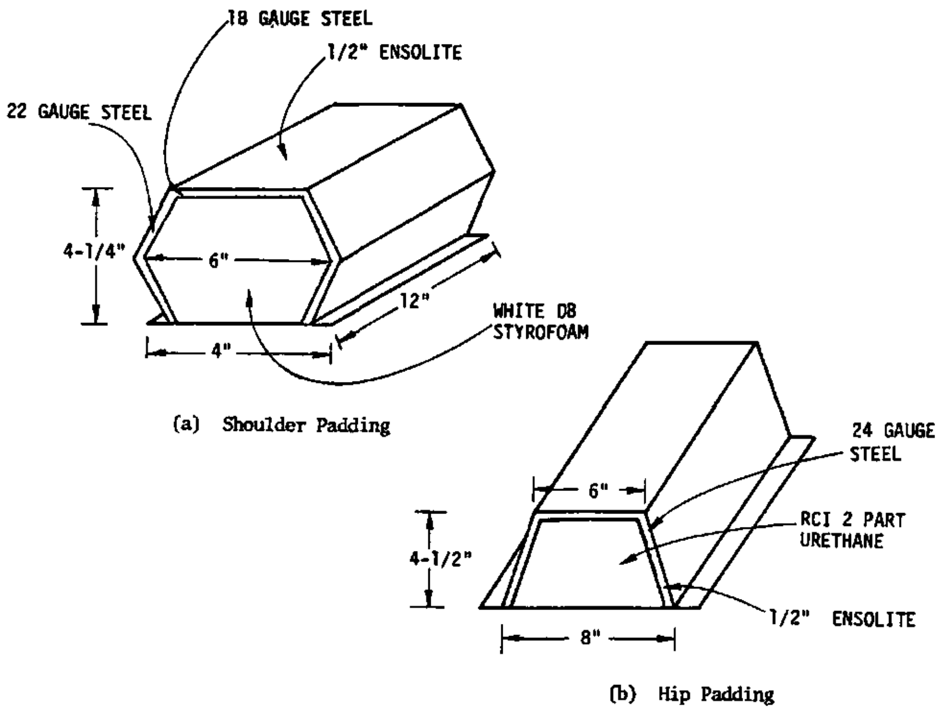


FIGURE 11-24. PADDING DESIGNS

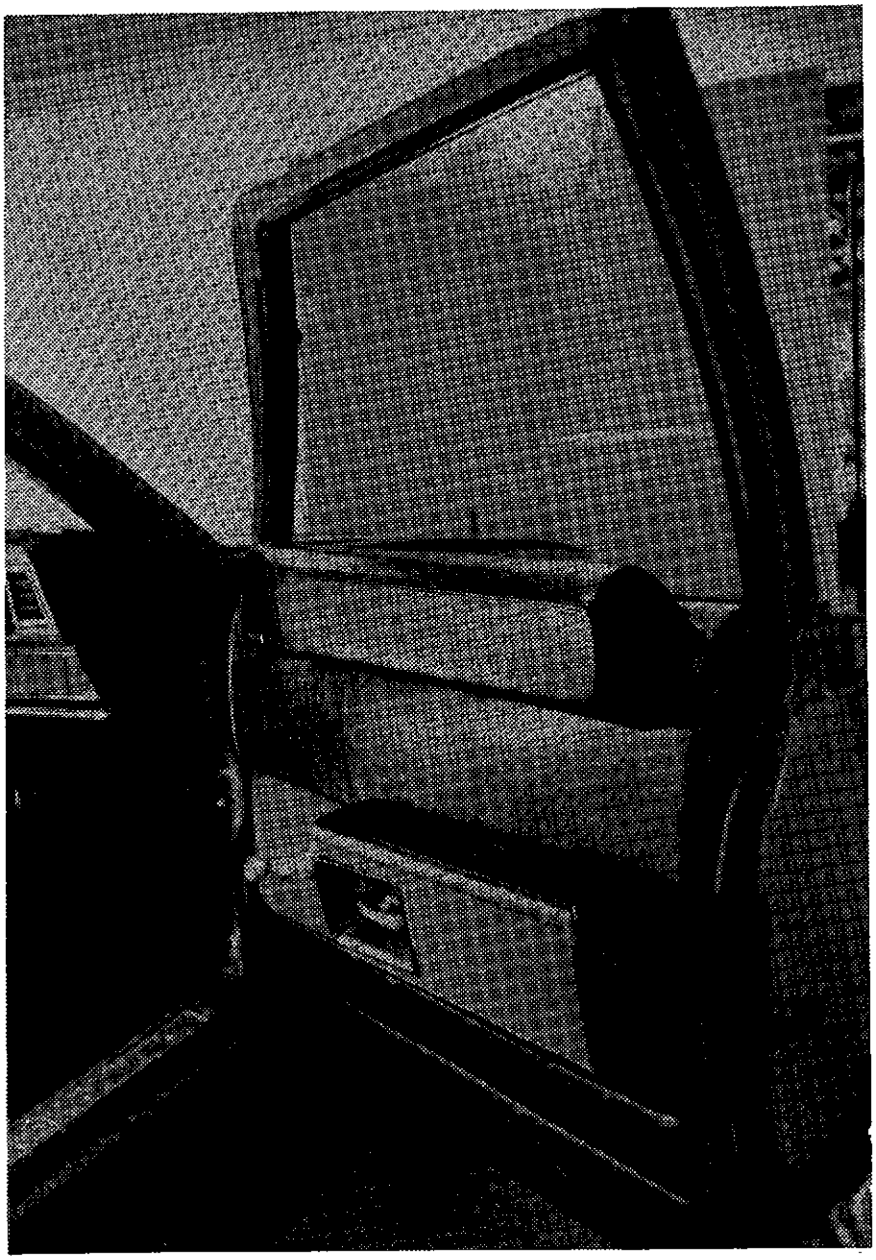


FIGURE 11-25. LRSV DOOR INTERIOR

The door padding was developed by conducting sled test simulations of crash Test 1580. In that crash test a stationary LRSV (with stock Impala door padding) was impacted laterally by an FMVSS 208 flat-faced bogey moving at 30 mph (48 km/h). Initial sled tests simulated the door velocity found in the Test 1580 crash. The results indicated that satisfying the injury criteria at that crash velocity was feasible, but that it would require an unacceptable degree of padding (about 5 inches at each pad). Subsequently, we conducted a satisfactory sled test simulating a 25 mph bogey impact; in this test the pad thicknesses were reduced by about 1-1/4 inch (32 mm).

An evaluation crash test (Test 1711) was conducted to confirm the design. The results of this test were

Impact Velocity	25.6 mph (41.2 km/h)
Maximum Interior Intrusion (at B-pillar)	4-3/4 inches (12.1 cm)
HIC	132
Peak chest Gs	55
Pelvic Gs	55

11.3.5 LRSV Sensors and Diagnostic Circuitry

The LRSV sensor sytem consists of two Technar (Rolamite) sensors (Curve B) mounted on the bumper reaction surface. As in the RSV, each sensor is mounted at the rubric location, the rubric covering the sensor.

The diagnostic package is essentially the same as that used in the RSV (described in Section 4).

11.4 LRSV PROPULSION

An additional goal of the LRSV Program was to develop an engine that is feasible, affordable and producible in the mid-eighties and yet which can provide clean, fuel efficient propulsion for vehicles in the LRSV's inertia weight class. The goals were: exhaust emissions of 0.41 gm/mi HC, 3.4 gm/mi CO and 0.4 gm/mi NO_x

(maximum acceptable of 0.41 HC, 3.4 CO and 1.0 NO_x); combined EPA city/highway fuel economy of 27.5 mpg; and acceleration of 0 to 60 mph in 13.5 seconds (maximum acceptable of 20.0 seconds).

Minicars subcontracted the major portion of the engine development to the Volvo of America Corporation* (VAC) in Rockleigh, New Jersey. Volvo, in turn, issued a subcontract to DM Engineering, Inc. of Brookfield, Connecticut for hardware development and engine construction. Developmental fuel economy and emissions testing was conducted at the Brooklyn Air Resources Laboratory, at Automotive Environmental Systems, Inc. (AESi) in Westminster, California and at Custom Engineering in Garden Grove, California.

The Volvo B-21F 2.1 liter, in-line four cylinder engine was selected as the base powerplant. It runs on 91 RON unleaded gasoline and has a cast iron block, belt-driven overhead camshaft, and light alloy cylinder head of cross flow design. For emissions control, the engine incorporates Volvo's Lambda-Sond three-way catylist system, which monitors oxygen concentration in the exhaust and provides closed loop feedback inputs to a Bosch K Jetronic fuel injection system.

Volvo and Minicars evaluated several methods of improving the overall performance of the B-21 engine. In most cases the engine modifications were tested by steady state engine operation at various speeds (between 1600 and 2800 rpm) with a constant manifold vacuum of 13 inches (33 cm) Hg, which was chosen to simulate the EPA city cycle. By measuring the brake specific fuel consumption (BSFC), the effects of each modification could be assessed on a first order basis without running through the entire federal test procedure. The modifications and their effects are summarized below. It must be cautioned that these effects are not additive and may not be accumulative.

Displacement

As an initial step, the engine displacement was reduced from 2.1 to 2.0 liters. As expected, the fuel economy substantially improved; decreases in BSFC varied

*Appendix B contains a separate report describing Volvo's efforts.

from 3 percent at 1700 rpm to 8 percent at 4000 rpm. (In this case the BSFC was measured under wide-open throttle.)

Lubricant Pumping Losses

Two methods were employed to reduce the lubricant pumping losses: lowering the oil pump output pressure from 65 psi (719 kPa) to 35 psi (241 kPa) and switching to a low viscosity synthetic lubricant. The marginal fuel economy improvements which resulted from the lower pump output pressure did not warrant the possibility of reduced bearing life; consequently, that approach was discarded. The synthetic lubricant, however, accrued a maximum decrease in BSFC of 4 percent (at 2200 rpm), caused in part by reduced friction in the main bearing, rod bearings and cylinder walls.

Accessory Drive Speed

The alternator and water pump are the two accessories that are mechanically driven by the engine. By reducing their speeds 30 percent, we obtained a maximum decrease of 7 percent in BSFC (at 2200 rpm). The improved fuel economy in this case justified the reductions in excess engine cooling and electrical power generating capacity.

Multispark Ignition

A commercially available multispark ignition system was installed and set to spark repetitively over 30 degrees of crankshaft rotation. There was a substantial decrease in fuel consumption at speeds below 2500 rpm — at the cost of somewhat increased consumption at higher speeds.

Coolant Temperature

The cooling system was modified by replacing the engine driven fan with an electric fan controlled by the coolant temperature. The possibility of increasing the coolant temperature from 195°F (91°C) either to 210°F (99°C) or to 220°F (104°C) was investigated, but the small increases in cycle efficiency did not warrant the risk of increased thermal degradation of the engine. Therefore, the final system retained the electric fan, but with thermostatic setpoints of 210°F on and 200°F (93°C) off.

Turbocharging

At the start of the program, Volvo and Minicars felt that turbocharging the base powerplant might be necessary to meet the acceleration objectives. Consequently, a turbocharger was adapted to the B-21 engine to provide a positive pressure boost above 2500 rpm. Knocking was suppressed by incorporating a modulated water injection system, an independent manifold fuel injector and a vacuum ignition retard system. Turbocharging increased the maximum engine power (at 5000 rpm under wide-open throttle) from 100 hp (75 kW) to 122 hp (91 kW).

One serious developmental problem was the relatively long transport time (i.e., the time required for air to travel from the airflow sensor to the cylinder) that was evident when the air was routed through the compressor. Increasing the transport time lengthens the feedback loop controlling the air/fuel ratios and thus degrades fuel emissions performance under transient conditions. Although this was not an insurmountable problem (the turbocharged engine eventually met the maximum allowable emissions levels), Volvo and Minicars decided that the acceleration objective could be obtained without turbocharging, and development subsequently progressed with a naturally aspirated engine.

Other Modifications

We also investigated the possibility of reducing the engine inertia (by substituting a lighter flywheel, clutch and pressure plate), using matched fuel injectors to insure more consistent cylinder-to-cylinder air/fuel ratios, and incorporating negative crankcase pressure (by siphoning air to the intake manifold) to reduce piston pumping losses. The reduced inertia substitutions and the matched fuel injectors were retained in the final version of the engine.

The final engine was coupled to a Volvo chassis and drivetrain tested according to standard EPA test procedures. The results are listed in Table 11-4.

TABLE 11-4. LRSV ENGINE TEST RESULTS

	Objective	Maximum Acceptable	Test Results
Exhaust Emissions			
HC (gm/mi)	0.41	0.41	0.19
CO (gm/mi)	3.4	3.4	2.38
NO_x (gm/mi)	0.4	1.0	0.57
Fuel Economy			
EPA City (mpg)			22.8
EPA Highway (mpg)			36.5
EPA Combined (mpg)	27.5		27.4
Acceleration			
0-60 mph (sec)	13.5	20.0	14.5

Dynamometer setting = 10.8 hp at 50 mph
Inertia Weight = 3250 pounds

Transmission

Fuel economy, emissions and acceleration all depend on the selection of an appropriate transmission. For maximum efficiency, we limited the choice to manual transmissions. We originally specified the Lancia Beta five-speed transaxle, because of its easy integration with other LRSV front suspension components (which also are Lancia Beta parts). It soon became apparent, however, that the Lancia Beta's N/V (engine rpm/vehicle mph) ratio (54.1 in fifth gear with size 205-14 tires) was too high to achieve optimal fuel economy. Therefore, we replaced it with the Chrysler Omni/Horizon four-speed transmission (manufactured by Volkswagen) which has an N/V ratio of 44.9. Later in the program the GM X-body four-speed transaxle, which has an N/V ratio of only 36.1, became available and was integrated into the LRSV. In our judgment, this unit provides an optimal combination of fuel economy, acceleration and more than adequate durability.

SECTION 12
ACCIDENT ENVIRONMENT ANALYSIS

12.1 INTRODUCTION

The RSV design is based on the results of Phase I computer simulations which calculated the safety payoffs and benefit/cost ratios of alternative vehicle configurations. In all, 5040 different combinations of safety subsystems (structures, restraints, radar activated brakes, etc.) were assembled, and the most promising were evaluated in the projected 1985 automotive accident environment.

The analytical techniques used in this study were improved as the RSV Program progressed. While most of this later work did not directly affect the design of the RSV, the resulting techniques are important on two other counts: they are valuable for fully understanding the implications of proposed Federal mandates, and they introduce significant improvements in the benefit methodology available to assess benefits of new system and future conditions (which have recently been assembled). Thus the improvements in the analytical tools of the RSV Program are directly in line with one of the program's fundamental goals: to assist in understanding the effects of new systems in the potential future accident environment.

Early in Phase III, Kinetic Research* conducted a brief study of rear impacts. This was followed by a comprehensive study of some proposed passive restraint implementation scenarios. The model constructed for this study is suitable for a wide range of applications, so Kinetic Research subsequently refined it into a simpler, more flexible form: the Kinetic Research Accident Environment Simulation and Projection (KRAESP) model. Additional algorithms for property damage costs and advanced braking systems were devised to directly interface with the basic KRAESP model.

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*Kinetic Research is a division of Minicars, Inc. It was a separate company, located in Madison, Wisconsin, when Phase III began.

Subsections 12.2 through 12.4 discuss the KRAESP model and its complementary algorithms, Subsection 12.5 discusses the rear impact study, and Subsection 12.6 discusses the passive restraint implementation study.

12.2 THE KRAESP MODEL

The KRAESP Model was developed to describe the future automobile accident environment and to evaluate the safety impact of changes in automobiles and automobile systems in that environment.

The outputs of the KRAESP Model are the expected numbers of fatalities and injuries at various levels of the Abbreviated Injury Scale (AIS).* These numbers can be presented for the

- Year of impact
- Vehicle size class
- Vehicle manufacturer
- Vehicle model year
- Impact mode (vehicle-to-vehicle or fixed object)
- Vehicle damage area (clock position)
- Occupant seat position.
- Impact crash severity

The model is capable of presenting output considering such variables as occupant age and body area of injury, but this degree of refinement has not yet been employed (in the absence of adequate input data to justify such detail).

Input

The user of the model must specify one or more implementation schemes. An implementation scheme consists of a specific mix of vehicle crash management systems for each occupant seat position and vehicle size class, manufacturer and

*Developed by the American Medical Association.

model year. A vehicle crash management system is a combination of the restraint system (belt, airbag, etc.) and the vehicle structural characteristics that affect the occupant during the crash (accelerations, force loads, etc.). Its performance is usually specified in the form of dummy injury measures, taken as functions of impact mode (IM), damage area (DA), crash severity and seat position (SP).

Crash severity is almost always measured by a vehicle's velocity change (delta-V) during an accident. In this section we will use the terms "delta-V" and "crash severity" interchangeably; but it must be remembered that other measures (such as vehicle crush) may, as well, be used to specify crash severity. The model also uses the following data:

- Vehicle population statistics and weights from 1952 to the present
- Vehicle population statistics and weights for new vehicles in future model years
- An injury severity (AIS) probability distribution in terms of vehicle class, impact mode, damage area, seat position and delta-V for unrestrained occupants
- A probability distribution that subdivides the total number of accidents into cells defined by relative velocity (V_{rel}), impact mode and damage area (referred to simply as a "V_{rel} distribution")
- Other pertinent data (occupancy rates, restraint usage rates, etc.).

The KRAESP program contains default values for many of these inputs. For example, future market shares are estimated by extrapolating data from the 1976 and 1980 model years, and AIS distributions are compiled from NCSS data. The selection of the data and default values are governed by the circumstances of each application.

Methodology

Table 12-1 presents a basic list of the KRAESP variables. (Reference 21 gives a complete description of the model.) The first column lists the primary variables used in the KRAESP program and in the complementary BRAKE and Property Damage

TABLE 12-1. KRAESP VARIABLES

Variable (Symbol)	Function Of:	Possible Values	Remarks
The following variables define the case vehicle and its safety systems:			
Case vehicle class* (VC)		Mini, Subcompact, Compact, Intermediate, Standard	Because safety performance may vary markedly between vehicle classes, KRAESP performs computations on a class-by-class basis. Automobiles are subdivided into classes according to interior dimensions.
Manufacturer* (M)		GM, Ford, Chrysler, AMC, Import	
Model year* (Y)		1952-1990	
Case vehicle weight** (m)	VC,Y,PD		Vehicle weight depends only on vehicle class, model year, and property damage system (PD). This means, for example, that all 1975 compacts have the same weight. Where weight data are available, KRAESP uses the average weight of all vehicles in a class. The model contains projections for future vehicle weights by class and model year.
Restraint system* (R)	VC,M,Y,SP		The user must specify the restraint system used at each seat position in the case vehicle. The manner in which restraint systems are phased in by class, manufacturer and model year is referred to as an "implementation scheme."

*These variables must be selected by the user. Specifying them narrows the scope of the investigation.

**KRAESP incorporates default values for these variables. The user may specify other values as desired.

(continued)

TABLE 12-1. (Cont'd)

Variable (Symbol)	Function Of:	Possible Values	Remarks
Brake system* (BS)	VC,M,Y		
Property damage system* (PD)	VC,M,Y		
The following variables specify the performance of the above systems:			
Usage** (U)	VC,R,SP	0.0-1.0	Usage is the probability that a given restraint system will be in use if an accident occurs. For instance, it might refer to the fraction of front seat passengers in intermediate cars who wear seat belts.
Dummy injury** (g)	R,SP,IM,DA,ΔV		Dummy injury is a measurement of restraint system performance derived from testing or theoretical considerations. Typically, test results take the form of peak acceleration versus delta-V curves for a given seat position and damage area.
Range* (r)	BS		Range is the distance at which a radar-activated braking system will sense an impending collision and apply the brakes.
Brake performance* (acc)	VC,M,BS		Brake performance refers to the deceleration capability of an advanced braking system.

*These variables must be selected by the user. Specifying them narrows the scope of the investigation.

**KRAESP incorporates default values for these variables. The user may specify other values as desired.

(continued)

TABLE 12-1. (Cont'd)

Variable (Symbol)	Function Of:	Possible Values	Remarks
Average repair cost ($\$_{ave}$)	VC,M,Y,PD, IM,DA,ΔV		$\$_{ave}$ is the average cost to repair a given case vehicle (VC,M,Y) equipped with a given bumper system (PD) which has sustained an accident of given type (IM,DA) and severity (ΔV). Typically, new bumper systems are evaluated on the basis of $\$_{ave}$ versus delta-V curves obtained from testing.

The following variables specify the environment of a given accident:

Impact year* (I)		1952-1990	I is the year in which the accident occurs.
Seat position* (SP)		Left front, right front, left rear, right rear	Computations are done on a seat-by-seat basis, since injury level probabilities may be strongly dependent on seat position.
Abbreviated Injury Scale* (AIS)		0,1,2,3,4,5,6	Injuries are quantified by severity on a scale from 0 (uninjured) to 6 (fatality).
Impact mode* (IM)		Vehicle-to-vehicle, vehicle-to-fixed object, rollover	
Damage area* (DA)		1,2,3,4,5,6,7,8, 9,10,11,12	Damage area specifies the area of the case vehicle that sustains the most damage. The numbers refer to clock positions: 12 is the front of the car, 3 is the right side, etc.
Other vehicle weight (m_o)	VC_o		See remarks on case vehicle weight.

*These variables must be selected by the user. Specifying them narrows the scope of the investigation.

(continued)

TABLE 12-1. (Cont'd)

Variable (Symbol)	Function Of:	Possible Values	Remarks
Relative velocity (V_{rel})	r,acc		V_{rel} is the relative velocity between the case vehicle and struck object (or other vehicle) at the time of impact. A more complete definition is given in Reference 22.
Crash severity (ΔV)	V_{rel},m,m_o		Crash severity is the magnitude of the velocity change experienced by the case vehicle during impact.
Repair cost ($\$_R$)			$\$_R$ is the cost of repairing the case vehicle.
Other vehicle class (VC_o)		Mini, Subcompact, Compact, Intermediate, Standard, Small Truck, Medium Truck, Large Truck	"Other" vehicles are subdivided in the same manner as case vehicles, except that trucks are also included.
The following variables describe the overall or generalized accident environment:			
Total sales** (S_t)	Y		S_t is the combined sales of all models during a given model year.
Market share** (f)	VC,M,Y	0.0-1.0	

*These variables must be selected by the user. Specifying them narrows the scope of the investigation.

**KRAESP incorporates default values for these variables. The user may specify other values as desired.

(continued)

TABLE 12-1. (Cont'd)

Variable (Symbol)	Function Of:	Possible Values	Remarks
Case vehicle sales (S)	S_t,f		
Other vehicle sales (S_o)	VC_o,Y		
Survival rate** (s)	I-Y	0.0-1.0	Survival rate is dependent only on vehicle age.
Annual vehicle mileage** (VM)	I-Y		VM is the average yearly mileage driven by a vehicle, and depends only on vehicle age.
Number of accidents** (N_a)	I		N_a is the total number of accidents during the impact year I.
The following variables specify KRAESP probability functions:			
Case vehicle exposure (E)	S_t,S,s,VM	0.0-1.0	E is the ratio of case vehicle miles traveled to total vehicle miles traveled during a particular impact year.
Other vehicle exposure (E)	S_t,S_o,s_o,VM	0.0-1.0	See remarks for case vehicle exposure.
Occupancy probability* (P_{SP})	VC,I,SP	0.0-1.0	Given that an occupant is in a particular class of vehicle in a given year, P_{SP} is the probability of being in a particular seat position.

*These variables must be selected by the user. Specifying them narrows the scope of the investigation.

**KRAESP incorporates default values for these variables. The user may specify other values as desired.

(continued)

TABLE 12-1. (Cont'd)

Variable (Symbol)	Function Of:	Possible Values	Remarks
Mode/damage area probability** (P_{id})	IM,DA	0.0-1.0	P_{id} is the probability that an accident is in a given mode and has a given damage area.
Relative velocity probability** ($P_{V_{rel}}$)	IM,DA,V_{rel}	0.0-1.0	Given that an accident occurs in a particular mode and damage area, $P_{V_{rel}}$ is the probability that it occurs at a given V_{rel}.
Crash severity probability ($P_{\Delta V}$)	m,ΔV,m_o, $P_{V_{rel}}$	0.0-1.0	Given that an accident involving the case vehicle and a vehicle weighing m_o occurs in a particular mode and damage area, $P_{\Delta V}$ is the probability that it occurs at a given delta-V.
Injury severity probability (P_{xa})	R,g,SP,DA, AIS,ΔV,$P_{\Delta V}$	0.0-1.0	In an accident occurring at given delta-V, P_{xa} is the probability that an occupant will receive an injury of a particular AIS level, assuming his restraint system is operational.
Injury severity probability (P_a)	U,P_{xa}	0.0-1.0	P_a is identical to P_{xa}, except that it accounts for nonusage of restraint systems.
Repair cost probability ($P_\$$)	VC,M,Y,I,$\$_p$	0.0-1.0	Given that a case vehicle (VC,M,Y) has an accident, $P_\$$ is the probability that the repair costs will equal $\$_p$.

*These variables must be selected by the user. Specifying them narrows the scope of the investigation.

**KRAESP incorporates default values for these variables. The user may specify other values as desired.

(continued)

TABLE 12-1. (Cont'd)

Variable (Symbol)	Function Of:	Possible Values	Remarks
The following variables specify KRAESP outputs:			
Number of injuries/cell (n_i)	N_a,E,P_{SP}, P_{id},$P_{\Delta V}$,P_a		n_i is the total number of injuries at a given AIS level in a particular cell during the impact year. A "cell" is a specific subset of the accident environment. It refers to a specific case vehicle (VC,M,Y), seat position, impact mode, damage area and crash severity.
Number of injuries (N_i)	n_i		N_i is the sum of all n_i's in all cells. It represents the total number of injuries at given AIS during year I.

*These variables must be selected by the user. Specifying them narrows the scope of the investigation.

**KRAESP incorporates default values for these variables. The user may specify other values as desired.

Algorithms. For input variables, the table specifies whether or not default values exist. The second column lists the dependent variables for each variable. (Note that some dependent variables also have dependent variables of their own.) The "Possible Values" column shows where limitations exist, but these limitations are, for the most part, nothing more than limitations in the present software. For instance, there is nothing inherent in the methodology that requires the use of five case vehicle classes – this number can easily be increased or decreased.

There is one facet of the methodology that merits special attention – the injury severity probability distribution (P_a). Past analyses of the accident environment simply assigned an average societal cost to a given set of accident parameters, thus limiting the chances of discriminating between injuries and fatalities. The KRAESP model provides outputs at each AIS, and therefore offers excellent flexibility for the interpretation of results. The technique for constructing AIS distributions is summarized below.

A P_a distribution is first assigned to each ΔV (for given IM, DA and SP) for unrestrained occupants. These distributions are based on accident data and might look something like those shown in Figure 12-1. The task is to construct similar distributions for restrained occupants without the aid of large data files, since none are available. To accomplish this, we assume that a specific P_a distribution exists for each dummy injury (g) level* independently of whether the occupant is restrained or unrestrained (though the delta-V at which it occurs will generally be different).

This technique is illustrated in Figure 12-1, which shows g versus delta-V performance data (typically from crash or sled tests) for a hypothetical System X and for unrestrained occupants. Our assumption simply states, for example, that an occupant protected by System X in a 25 mph delta-V accident has the same probability of being injured at any given AIS level as would an unrestrained occupant in a 15 mph delta-V impact. Figure 12-2 shows another set of P_a distributions, in three-dimensional form.

*We use the letter "g" here to represent dummy injury measures because accelerations are typically used for this purpose. The symbol "g" could also represent something other than accelerations, such as HIC.

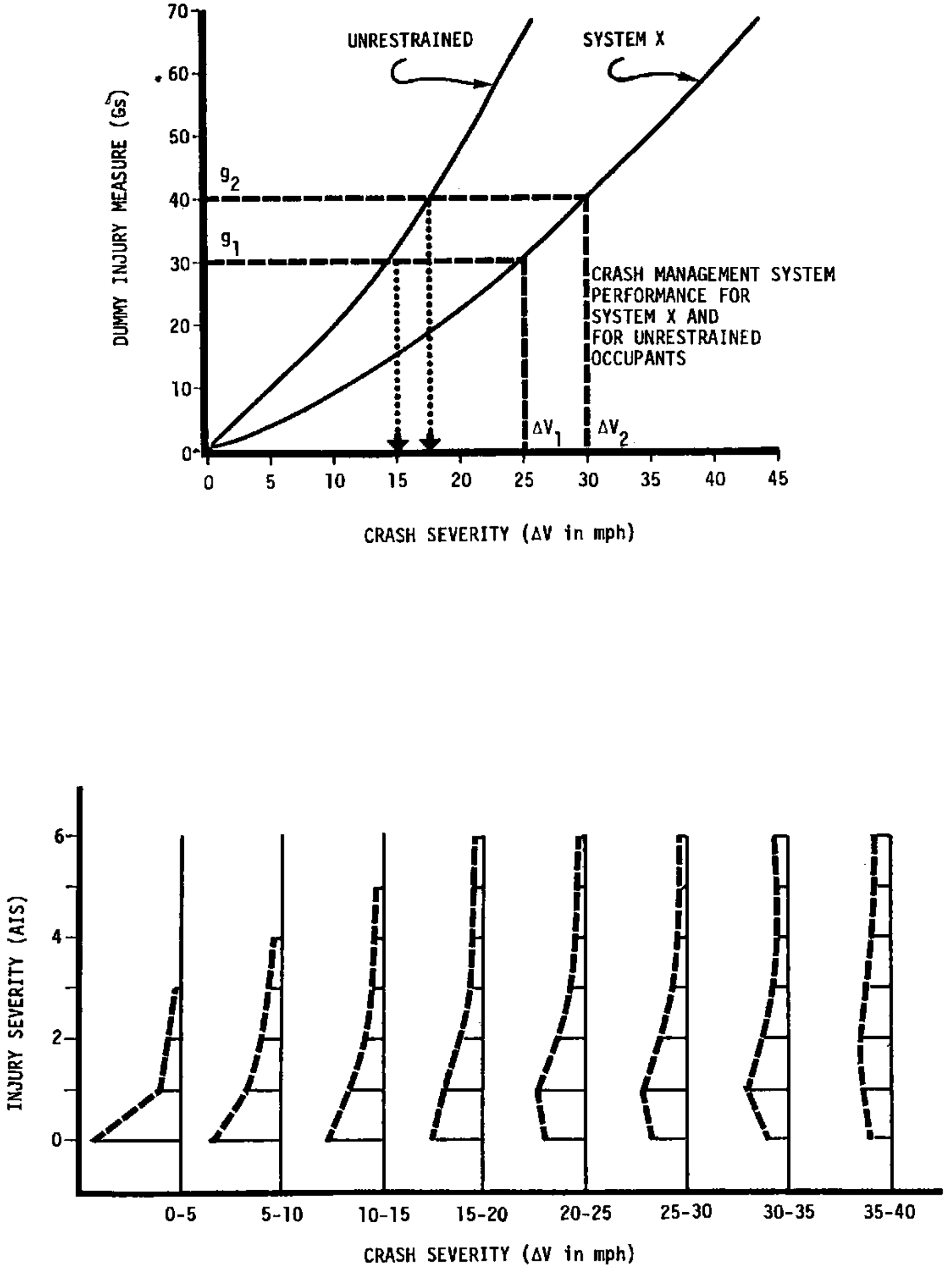


FIGURE 12-1. ILLUSTRATION OF THE COMPUTATION OF INJURY SEVERITY DISTRIBUTION FOR RESTRAINED OCCUPANTS

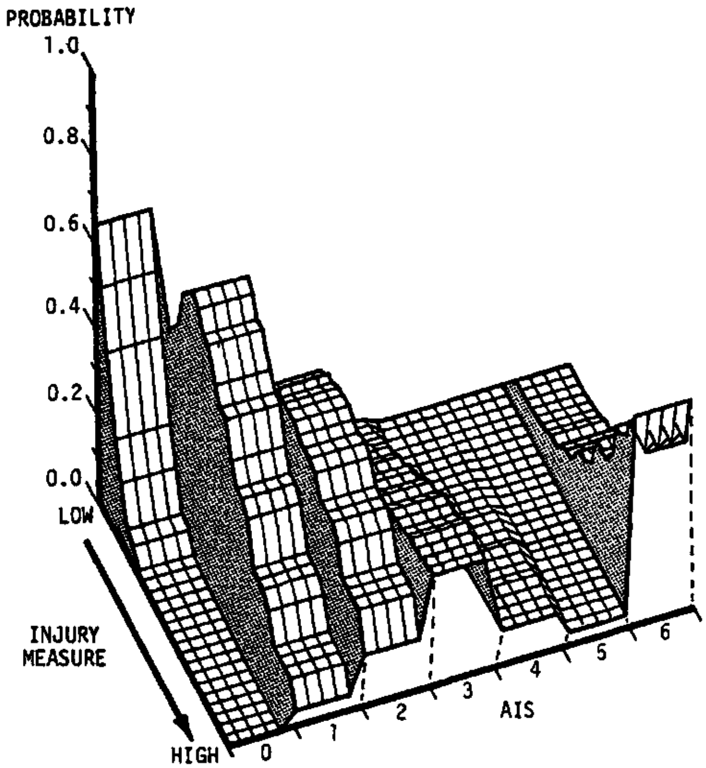


FIGURE 12-2. TRANSFORMATION BETWEEN DUMMY INJURY MEASURE AND INJURY LEVEL

12.3 BRAKE ALGORITHM

The Kinetic Research BRAKE Algorithm was designed to investigate the pre-crash environment of automobile accidents. BRAKE works in conjunction with the KRAESP model to determine to what extent advanced collision avoidance systems reduce impact speeds (or avoid accidents altogether) and to compute the estimated reductions of injuries and fatalities after such systems are introduced into the automobile population. The BRAKE Algorithm was especially designed to evaluate advanced, radar-activated braking systems similar to the one developed for the high technology RSV. Its input includes measures of the radar activation range and of the brake system performance (maximum deceleration). The algorithm makes a number of assumptions about how, when, and under what conditions the system operates, and is constructed so that these assumptions can be easily changed as circumstances dictate.

The algorithm processes a data file on a case-by-case basis. For every accident, BRAKE first determines if the advanced braking system would have had any effect, and, if it would, then calculates a new impact speed (which may equal 0). After evaluating each case, the algorithm compiles two V_{rel} distributions for the accident file - one with and one without the braking system. The user can use these distributions as they come out, or can input them into the KRAESP model (preferably after smoothing the data).

Some of the more important assumptions made by the BRAKE Algorithm are

- Only case vehicles (given VC,M,Y) are equipped with the system.
- The radar will activate the brakes only on straight, flat roads.
- The radar will activate the brakes only in collinear collisions. For a collision to be collinear, the case vehicle must have sustained its primary damage in the 12 o'clock position, and, in vehicle-to-vehicle impacts, the other vehicle must have sustained its primary damage in either the 6 or 12 o'clock positions.
- Other conditions being satisfied, the radar will activate the brakes at the range (r) specified for the system, assuming that they had not yet been activated at that time.
- The time measured from the instant braking begins to the moment of impact does not change when advanced braking is considered, except in cases where the brakes are radar activated.
- Damage areas and impact force directions are not affected in any case. (Of course, the severity of damage may be.)
- Each braking system has performance levels for wet and dry pavement.

These assumptions, and the BRAKE Algorithm itself, were constructed to process the MDAI file. Consequently, the algorithm includes adjustments to remove biases in those data. A number of changes would be required before using other data files.

12.4 PROPERTY DAMAGE ALGORITHM

Kinetic Research also developed an algorithm to estimate the effects of introducing specific property damage systems into the automotive accident environment. The property damage algorithm gives the KRAESP model the capability of calculating the combined repair costs of a fleet of vehicles (VC,M,Y) that are equipped with a specific property damage (e.g., bumper) system (PD) and operated over a given impact year (I). By comparing these costs with the repair costs of the same fleet equipped with a conventional system, we can make a benefit/cost analysis of the new system.

As mentioned in Subsection 12.2, the KRAESP model will compute injury level probabilities for a given accident. In conjunction with the property damage algorithm, it will also compute the average repair cost ($\$_{ave}$) for the case vehicle in that accident. The term "given accident" here refers to an accident of given mode (IM), damage area (DA), severity (ΔV) and year (I) involving a specific case vehicle (VC,M,Y) equipped with a given property damage system (PD).

Average repair cost is a strong function of delta-V, and we expect the relationship between the two to look something like Figure 12-3. Repair cost functions similar to Figure 12-3 may be constructed from either crash testing or theoretical considerations, and the user must supply them as inputs to the model. KRAESP will then use the repair cost functions, the delta-V distributions and the number of accidents (N_a) to compute the repair costs for the specific vehicle fleet.

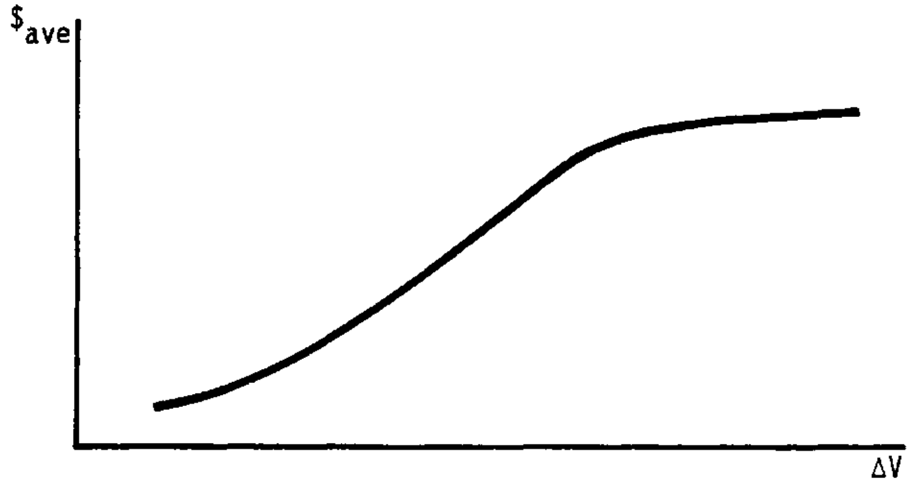


FIGURE 12-3. AVERAGE REPAIR COST VERSUS CRASH SEVERITY

There is an important consideration, however, which prohibits the use of conventional KRAESP delta-V distributions for repair cost calculations. In the analysis of injuries and fatalities, researchers generally use a V_{rel} distribution derived from towaway accident data. But a substantial amount of the property damage is incurred in non-towaway accidents. It follows that a towaway accident V_{rel} distribution would be too biased toward severe accidents to satisfactorily analyze property damage costs.

Kinetic Research therefore developed a technique to obtain a V_{rel} distribution from insurance claim data. (Insurance claim data are much more representative of real world property damage costs than towaway accident data – although they still are somewhat biased, because unreported accidents are not included.) The technique is as follows: a probability distribution ($P_\$$) of dollar loss for the case vehicle (such as shown in Figure 12-4) is compiled from insurance data and entered into the algorithm. The assumption is then made that the cost of repairing a case vehicle after an accident of given severity is always equal to the average repair cost for that severity. In the real world, of course, some losses will be greater and others less than the average. Nevertheless, this assumption is necessary for the analysis of the insurance claim data.

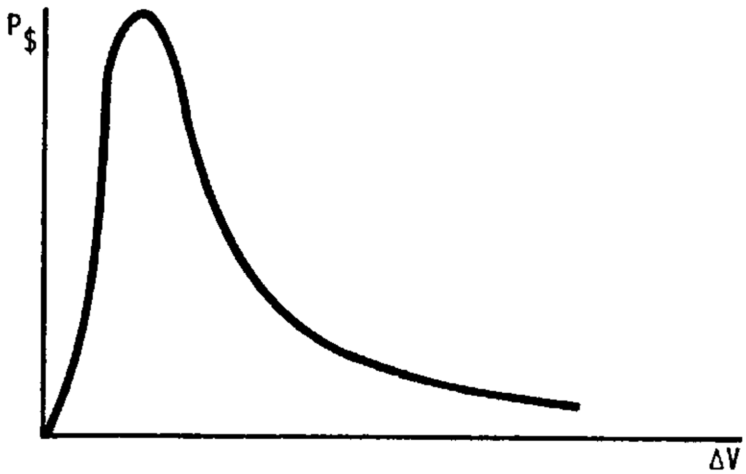


FIGURE 12-4. PROBABILITY OF REPAIR COST

If every ΔV is readily translatable into some $\$_r$, then the reverse also holds true. Given a $\$_r$, we can compute a ΔV (from Figure 12-3). Consequently, we can substitute ΔV for each $\$_r$ in Figure 12-4 and obtain the ΔV distribution shown in Figure 12-5.

FIGURE 12-5. CRASH SEVERITY PROBABILITY DISTRIBUTION

The final step is to convert the ΔV distribution into a V_{rel} distribution. This only requires that we know the weights of the case and "other" vehicles. Unfortunately, insurance claim data do not include the weights of the other vehicles, so they must be estimated. For the sake of simplicity, it is assumed that the other vehicle's weight is always equal to the mean weight of all vehicles. (Note: when KRAESP calculates ΔV distributions from the V_{rel} distribution obtained here, it will not make this assumption.) Therefore, V_{rel} can be calculated via the formula:

$$V_{rel} = \frac{m + m_{ave}}{m_{ave}} \Delta V \quad ,$$

where m_{ave} is the average weight of vehicles in the period of the insurance claim data. Finally, the application of this equation to the function in Figure 12-5 yields the V_{rel} distribution in Figure 12-6.

Kinetic Research has compiled probability functions for repair costs from 1973 accident data that encompass four vehicle classes and three impact modes. These functions, and the results of a number of vehicle-to-vehicle crash tests, were input into the property damage algorithm. The algorithm output, tabulated in Reference 23, consists of a V_{rel} distribution for each combination of vehicle

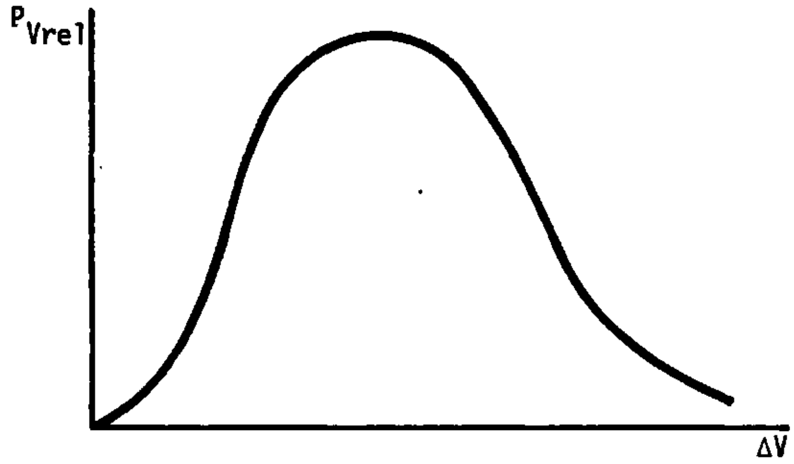


FIGURE 12-6. RELATIVE VELOCITY PROBABILITY DISTRIBUTION

class and impact mode. Each V_{rel} distribution can now serve as a basis for computing the repair costs of vehicle fleets whose property damage system characteristics are known.

12.5 REAR IMPACT STUDY

Early in the RSV Program, Kinetic Research constructed (on a quick response basis) a methodology to estimate the future societal costs of rear impacts. The relationship of losses to relative velocity and crash severity and the effects of increased rear seat occupancy were examined for compact (1400 to 2400 pound) cars in the 1985 accident environment.

The study's methodology, outlined in Figure 12-7, is similar to that of the KRAESP model. (This task was completed before KRAESP became operational.) A V_{rel} distribution, assumed to be independent of vehicle class and impact year, was obtained from adjusted MDAI data. The DeLorean estimates (Reference 24) of the 1977 and 1985 vehicle population distributions (by weight) were adjusted to include an earlier Minicars projection (Reference 22) of future truck populations. The study only considered cases whose primary horizontal damage, was in the rear of the car, was the result of a vehicle-to-vehicle impact, and was caused by an impact force with a direction from 5 to 7 o'clock.

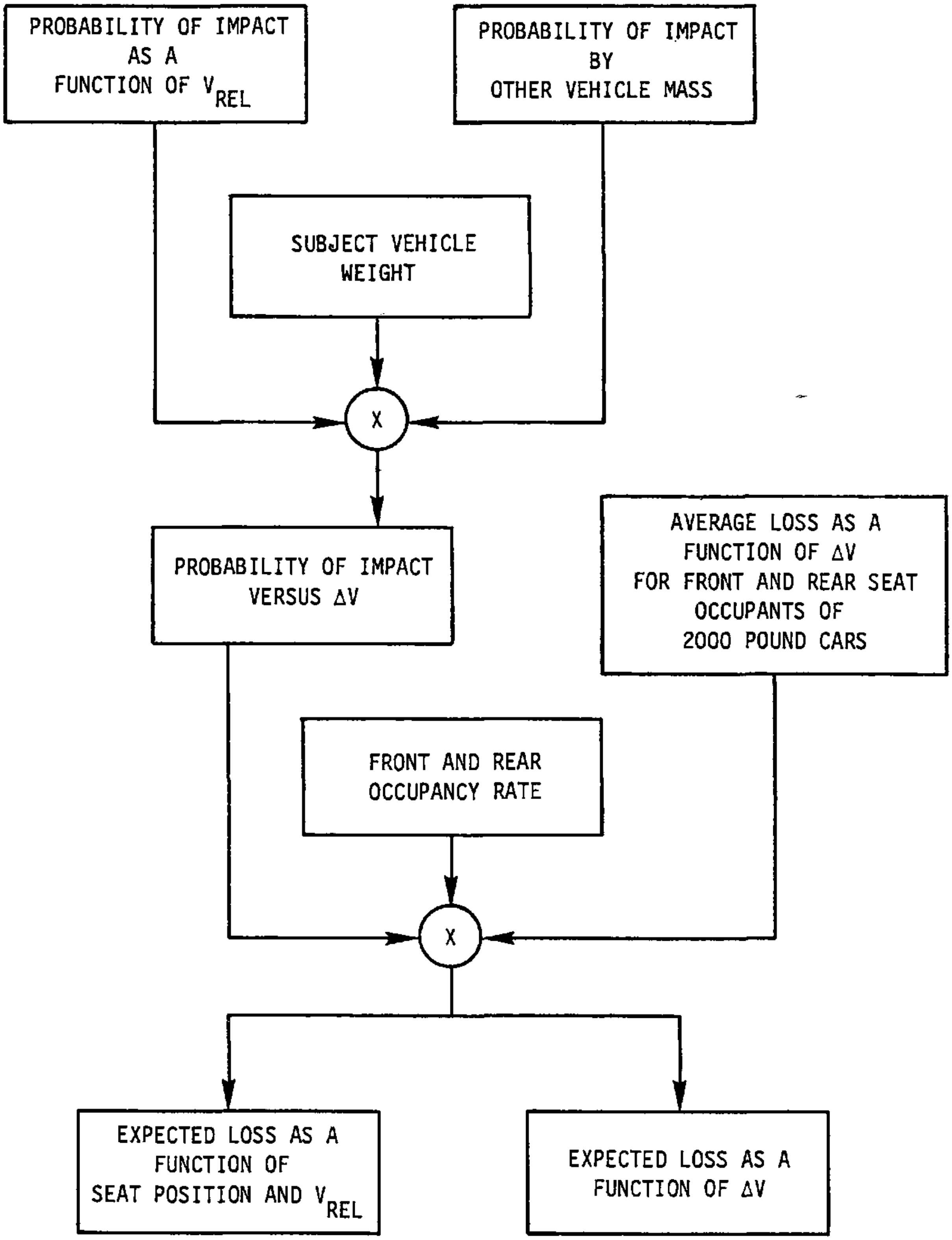


FIGURE 12-7. OUTLINE OF REAR IMPACT STUDY METHODOLOGY

By applying the above to these data, we computed the vehicle-to-vehicle rear impact delta-V distributions for compact cars in 1977 and 1985. An average loss (societal cost), obtained from earlier work in the RSV Program (Reference 22), was then assigned to each level of delta-V. These calculations were made for each seat position, so that the effects of changes in front and rear seat occupancies could be evaluated.

It was recognized that the study's validity was lessened by the scarcity of rear impact data in the MDAI file. Losses in rear impacts only accounted for 4.3 percent of the total societal loss in 1977, a fact that accounts for the RSV Program's emphasis on occupant protection in front and side impacts. We therefore caution against any excessive reliance on the results presented here and suggest that any further study of the rear impact environment be based on more comprehensive data, such as the NCSS or National Accident Sampling System (NASS).

Still, the rear impact study provided some interesting insights into the relationships between seat position, impact mode, and crash severity – for instance:

- For delta-V less than 25 mph, a front seat occupant will receive injuries of equal severity in front and rear impacts.
- For delta-V greater than 25 mph, a front seat occupant is likely to receive injuries of greater severity in rear impacts than in front impacts. At high delta-Vs, the average loss in a rear impact is 50 percent higher.
- For delta-V less than 20 mph, a front seat occupant is likely to be more severely injured than a rear seat occupant. This may be due to the presence of hard objects (windshield, steering wheel, etc.) in the front seat area; occupants often strike these objects in secondary impacts.
- The injury levels of rear seat occupants increase dramatically above 20 mph delta-V. At higher delta-Vs, in fact, a rear seat occupant can expect to receive the same high injury levels as would a nearside occupant in a side impact. This could be explained either by the

failure of front seat backs or the presence of intrusion into the rear passenger compartment.

The front and rear seat occupancy rates in 1977 were 1.43 and 0.22. Due to increasing automobile operating costs (and other forces encouraging car-pooling), it has been suggested that rear seat occupancy may increase in the future. Consequently, the rear impact study analyzed the 1985 accident environment for alternative rear occupancy rates of 0.22, 0.5, 1.0 and 1.5. In each case the front occupancy rate was held at 1.5.

For a rear occupancy rate of 0.22 we found that the total rear impact losses for compact cars should decrease approximately 20 percent by 1985. (The number of accidents was assumed to remain constant.) The total losses would decrease because the vehicles which strike compact cars will steadily become lighter, making the accidents less severe (from the case vehicle's point of view). But if the rear occupancy rate doubles to 0.5, the losses will climb about 20 percent. The larger increases in occupancy will increase the losses accordingly.

When front and rear occupancy rates are 1.50 and 0.22, only 13 percent of all occupants are in the rear seats. But even in this case the rear passengers sustain fully 40 percent of all losses in rear impacts. When both front and rear seat occupancy equals 1.5 (50 percent of the occupants in the rear), the rear occupants will sustain 81 percent of all losses. If rear seat passengers are indeed becoming more common, it would be worthwhile to place more emphasis on their protection in rear impacts.

A final objective of the study was to help specify appropriate rear impact test conditions for the RSV. Crash testing is sometimes conducted at the 75th percentile level - that is, at the speed below which 75 percent of all societal loss is expected to occur. Assuming 1.5 and 0.5 front and rear occupancy rates in the 1985 environment, a compact car accrues 75 percent of all rear impact losses at V_{rel} less than 40 mph and delta-V less than 25 mph. These levels can be achieved by striking a stationary 2000 pound test vehicle with a 3300 pound vehicle traveling at 40 mph. The conclusions about the test conditions are not affected significantly by changes in rear seat occupancy.

12.6 PASSIVE RESTRAINT IMPLEMENTATION STUDY*

While the KRAESP program was being developed, Minicars and Kinetic Research used it to study the effects of introducing passive restraints into the future automobile fleet. Only front impacts (11, 12 and 1 o'clock positions) were considered. This work, which was conducted early in 1977, aided the NHTSA in formulating the passive restraint mandate that was subsequently written into Federal Motor Vehicle Safety Standard (FMVSS) 208. The study is noteworthy because it was the first effort to analyze the simultaneous time phasing of a variety of restraint systems (having different performance and usage characteristics) throughout a range of vehicle classes and seating positions, and the first to quantify injury and fatality reductions based on the relationship of injury probability distributions to restraint structure performance quantified by dummy injury measures.

The study is not, however, the last word on the subject. While the methodology is quite thorough and complete, there are serious shortcomings in some of the data used. Most importantly, the work was based on the MDAI file, which contains a number of well known biases. Although we have applied the best available adjustments (Reference 4) to the data, other data bases, such as the NCSS files, should allow future studies to be even more realistic.

Traffic Environment Projections

Our study used traffic environment projections which were provided by the NHTSA (Reference 25), or which were derived from References 24, 26, 27, 28, 29 and 30. Between 1977 and 1990, total auto sales were projected to rise by 27 percent (a compounded rate of 1.9 percent per year), the number of autos on the road to rise by 22.8 percent, and the exposure of these vehicles to accidents to rise 23.5 percent. The market shares of sales showed a slight shift away from large cars (intermediate and full-size) toward small cars (minis, subcompacts and compacts): the small/large sales mix changed from 0.497/0.503 in 1977 to 0.514/0.486 in 1990. However, the weights of vehicles in all classes showed a remarkable decline by 1990 (due primarily to fuel economy pressures). The percentage changes in vehicle weights and accident exposures, by vehicle class, are shown in Table 12-2.

*This study was conducted in 1977.

TABLE 12-2. RELATIVE CHANGES BETWEEN 1977 AND 1990 BY CAR CLASS (PERCENT)

Auto Class	Weight of New Vehicles Sold	Exposure-Weighted Mean Weight for Car Population	Accident Exposure Rate
Mini	-3.30	-4.67	+350.00
Subcompact	-17.40	-6.56	+24.36
Compact	-17.38	-9.90	-10.50
Intermediate	-22.27	-17.44	+24.60
Full-size	-14.09	-16.60	-48.41

Implementation Schemes

We evaluated the benefits that would arise from the following hypothetical rule:

1. Passive driver restraints installed in all full-size cars in 1981
2. Full front (driver and passenger) passive protection in all minis in 1981
3. Passive driver restraints in all cars in 1982
4. Full front (driver and passenger) passive protection in all cars in 1983.*

Between 1977 and 1990 there might be any number of different restraint system designs that satisfy this rule. To make the problem manageable, we subdivided the designs into six categories. These categories were coded 0 through 5, as follows:

*The Department of Transportation eventually ruled that all cars manufactured after September 1, 1983 must have full front passive protection.

Code

0 Base three-point harness system (employed in current automobiles). Usage rates and performances of such systems are expected to remain at the 1976 levels. This is the only system that does not satisfy the passive restraint requirement.

1. 1972 GM Air Cushion Restraint System (ACRS), which was engineered for limited mass production and built into 10,000 full-size General Motors cars between 1974 and 1976. This system would be the easiest to design into existing cars, and thus would represent the earliest air cushion systems used by manufacturers.

2. Modified 1972 GM ACRS is the same as Item 1, but also includes recent technological developments that can be incorporated without extensive redesign.

3. Advanced ACRS uses near state-of-the-art technology, which could be designed into cars with sufficient lead time (presumably at model changes). Minicars has demonstrated that air cushions can provide occupant protection (as defined by FMVSS 208) at speeds in excess of 40 mph in most automobile classes.

4. Passive belt system, as used in the Volkswagen Rabbit. We expect that in the near term most manufacturers will use similar systems in small cars.

5. Advanced passive belt system uses near state-of-the-art passive restraint technology. Minicars has demonstrated that occupant protection is possible at speeds in excess of 30 mph.

We refer to Systems 1, 2 and 4 as "prior technology" systems, even though they may now be in production. Systems 3 and 5 are "current technology" (1977) systems, even though they are not yet in production. "Advanced technology" systems with still higher performance levels were not considered in this analysis, although the RSV Program has already demonstrated their feasibility.

Performance estimates for each of these systems were obtained through a combination of experimental (car crash) results, computer simulations and engineering judgment (Reference 31). The latter two were needed because crash data for existing systems did not cover the required velocity range, and because certain systems have not yet been engineered into all of the vehicle classes.

Estimates were made for three classes of vehicles: mini, compact/subcompact and intermediate/full-size. The expected performance (measured in chest acceleration levels) of the "prior technology" and "current technology" air cushion systems is shown in Figure 12-8.

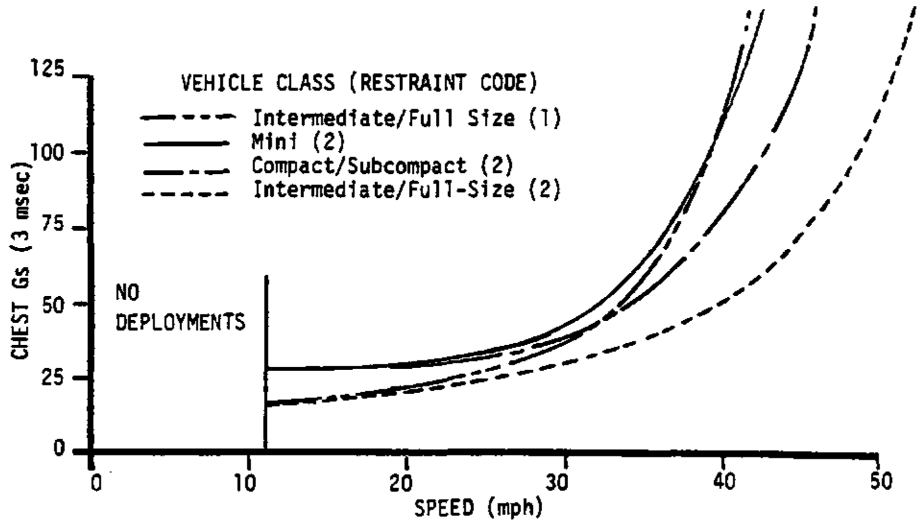
Because costs and benefits vary significantly between systems, it is important to know which ones the automakers will use to satisfy the passive restraint mandate. Unfortunately, the manufacturers themselves did not know which systems will go into their cars in the mid-1980s. Therefore, in addition to evaluating different passive restraint mandates, we also evaluated different responses to those mandates (Reference 31).

We first formulated a "prior technology" implementation scheme. This scheme is based on the assumption that manufacturers will use prior technology restraint systems (Systems 1, 2 and 4) to comply with the mandate, but, once the mandate is satisfied, will choose not to incorporate more advanced systems into later models.

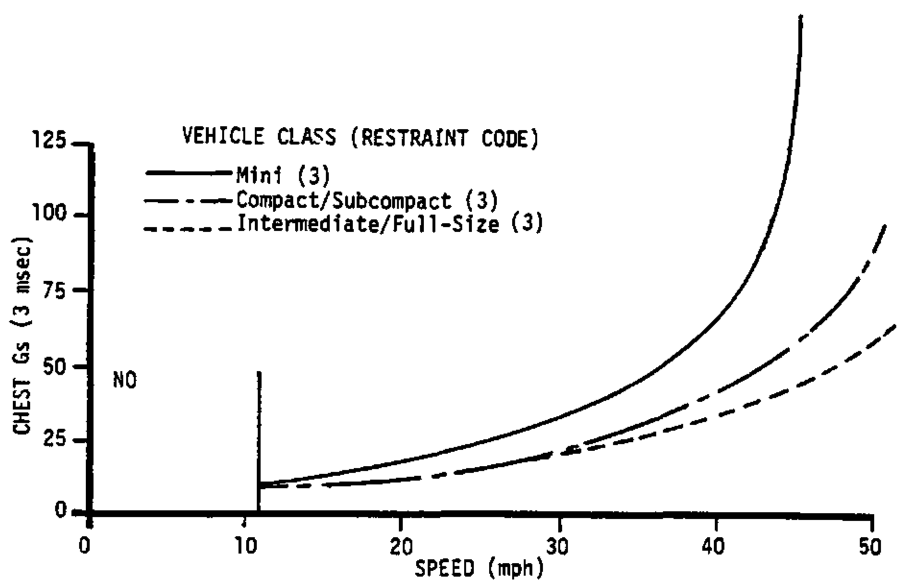
The second scheme was a more ambitious "current technology" approach. This scenario is similar to the first scheme in the mandate's early years, but later the manufacturers turn to systems with higher performance levels (using Systems 3 and 5). For instance, industry might choose, on their own initiative, to upgrade performance to provide their customers with greater value or reduced costs. Alternatively, they might be forced to do so by a revised passive restraint mandate.

The third implementation scheme was based on System 1. Here, the manufacturers would comply with the mandate simply by installing, in all automobiles, systems with the characteristics of the 1972 General Motors ACRS. This scheme was formulated in order to compare the predictions of benefits with other estimates that have been made.

The three implementation schemes are illustrated for the driver side only in Table 12-3. The schemes for the passenger restraint systems are identical to those for the driver, except for the short delay in implementation allowed by the rule. Some of the considerations affecting the formulation of the schemes were:



(a) "Prior Technology" Air Cushion System



(b) "Current Technology" Air Cushion System

FIGURE 12-8. AIR CUSHION SYSTEM PERFORMANCE

TABLE 12-3. DRIVER RESTRAINT IMPLEMENTATION SCHEMES

	Current Technology							Continuously Upgraded							1972 GM Passive Restraint						
	1977 -1980	1981	1982	1983	1984	1985	1986 -1990	1977 -1980	1981	1982	1983	1984	1985	1986 -1990	1977 -1980	1981	1982	1983	1984	1985	1986 -1990
<u>GM</u>																					
Mini	0	4	4	4	4	2	2	0	4	4	4	4	3	3	0	1	1	1	1	1	1
Subcompact	0	0	2	2	2	2	2	0	0	2	2	2	3	3	0	0	1	1	1	1	1
Compact	0	0	1	1	2	2	2	0	0	1	1	3	3	3	0	0	1	1	1	1	1
Intermediate	0	0	1	2	2	2	2	0	0	1	3	3	3	3	0	0	1	1	1	1	1
Full	0	1	2	2	2	2	2	0	1	2	2	2	2	3	0	1	1	1	1	1	1
<u>Ford</u>																					
Mini	0	4	4	4	2	2	2	0	4	4	4	4	4	3	0	1	1	1	1	1	1
Subcompact	0	0	4	4	2	2	2	0	0	4	4	3	3	3	0	0	1	1	1	1	1
Compact	0	0	1	2	2	2	2	0	0	1	2	2	2	3	0	0	1	1	1	1	1
Intermediate	0	0	2	2	2	2	2	0	0	2	2	2	2	3	0	0	1	1	1	1	1
Full	0	1	2	2	2	2	2	0	1	1	1	1	3	3	0	1	1	1	1	1	1
<u>Chrysler</u>																					
Mini	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subcompact	0	0	4	4	4	4	4	0	0	4	4	4	4	5	0	0	1	1	1	1	1
Compact	0	0	4	4	4	4	4	0	0	4	4	4	3	3	0	0	1	1	1	1	1
Intermediate	0	0	1	1	1	1	2	0	0	1	1	1	1	3	0	0	1	1	1	1	1
Full	0	1	1	1	1	1	2	0	1	1	1	1	1	3	0	1	1	1	1	1	1
<u>AMC</u>																					
Mini	0	4	4	4	4	4	4	0	4	4	4	4	4	5	0	1	1	1	1	1	1
Subcompact	0	0	4	4	4	4	4	0	0	4	4	4	4	5	0	0	1	1	1	1	1
Compact	0	0	1	2	2	2	2	0	0	1	1	1	3	3	0	0	1	1	1	1	1
Intermediate	0	0	1	1	1	1	2	0	0	1	1	1	1	3	0	0	1	1	1	1	1
Full	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<u>Foreign</u>																					
Mini	0	4	4	4	4	4	4	0	4	4	4	4	4	5	0	1	1	1	1	1	1
Subcompact	0	0	4	4	4	4	4	0	0	4	4	4	4	5	0	0	1	1	1	1	1
Compact	0	0	2	2	2	2	2	0	0	3	3	3	3	3	0	0	1	1	1	1	1
Intermediate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
Full	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

<u>Legend:</u>

0 = Base three-point harness
1 = 1972 GM Air Cushion Restraint System (ACRS)
2 = Modified GM ACRS
3 = Advanced ACRS
4 = Current passive belt system
5 = Advanced passive belt system

- Whenever possible, the manufacturers will phase in new restraint systems at model changes. Our estimates of the timing of model changes are, of course, highly subjective.
- The larger manufacturers will be the first to bring more advanced technologies into production.
- The low seat belt usage rates and the public's rejection of the seat belt/ignition interlock rule suggest that the public may reject passive belts as well. This concern will cause industry to favor air cushion systems, despite their higher costs. We also feel that the price elasticity of federally mandated safety systems will be low, as has been observed with emissions systems. This consideration will likewise tend to negate the cost advantages of belts.
- Foreign automakers will tend to favor belts over airbags because belt systems will already be designed for the cars they sell outside the United States.

The benefits of passive restraints are measured by the reduction of injuries and fatalities that would occur if they were implemented into the automotive fleet. Accordingly, it is necessary to know how many injuries and fatalities would occur without a passive restraint mandate. We therefore specified a baseline implementation scheme in which the current three-point harnesses (System 0) are retained in all vehicle classes indefinitely. Of course, the baseline does not correspond to current injury and fatality levels, because these levels will continue to change (as functions of total sales, market shares, vehicle weights and vehicle usage).

Benefit Calculations

Our results for the three schemes are shown in Figures 12-9, 12-10 and 12-11. The widths of the bands represent uncertainties in relating dummy injury measurements to the probability of human injury severities. (These uncertainties are partially due to differences in torso load distribution between unrestrained occupants, belted occupants and airbag protected occupants.) The cumulative (1977 to 1990) reductions in injuries and fatalities are shown to the right of each curve.

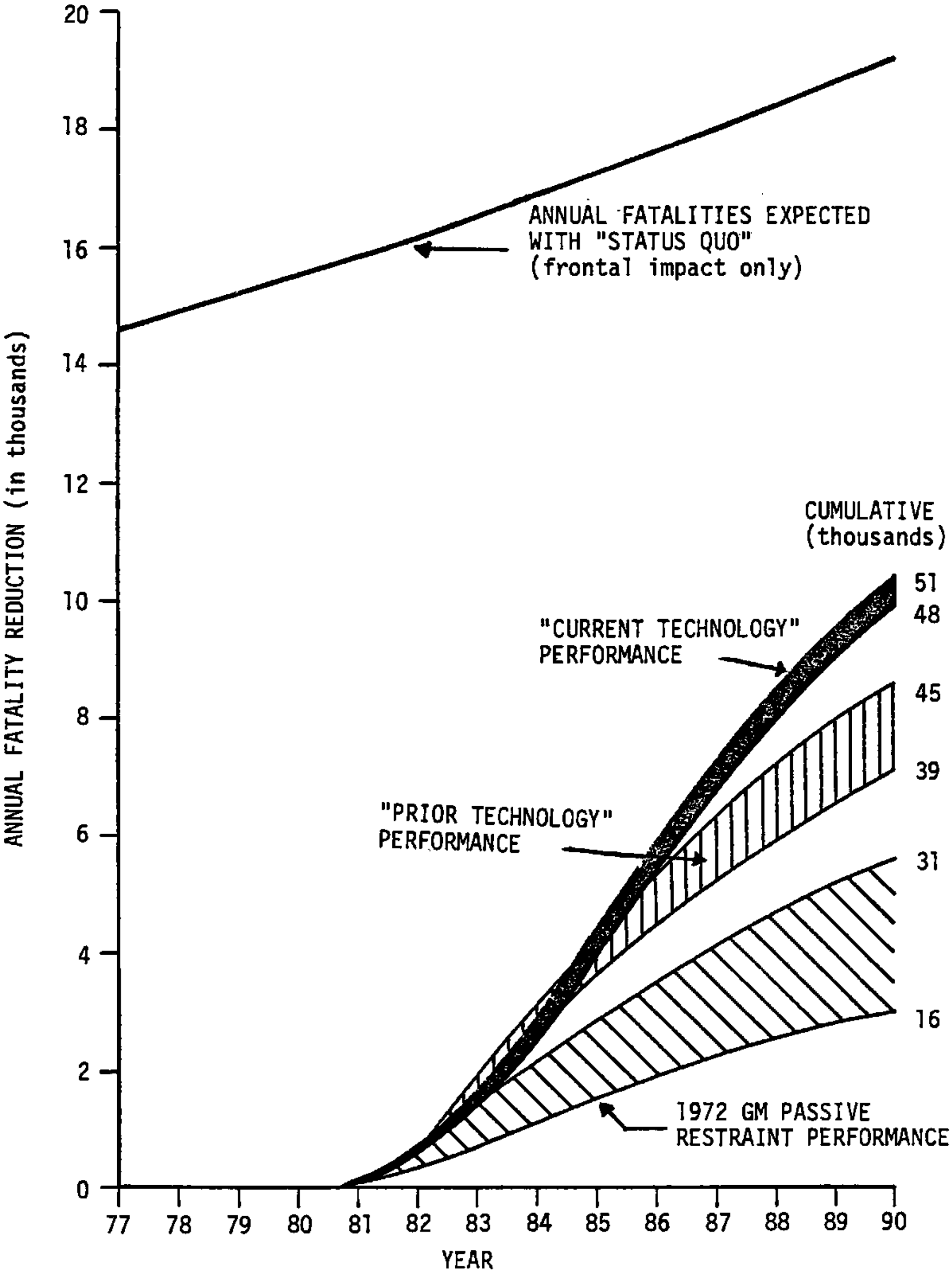


FIGURE 12-9. FATALITY REDUCTIONS

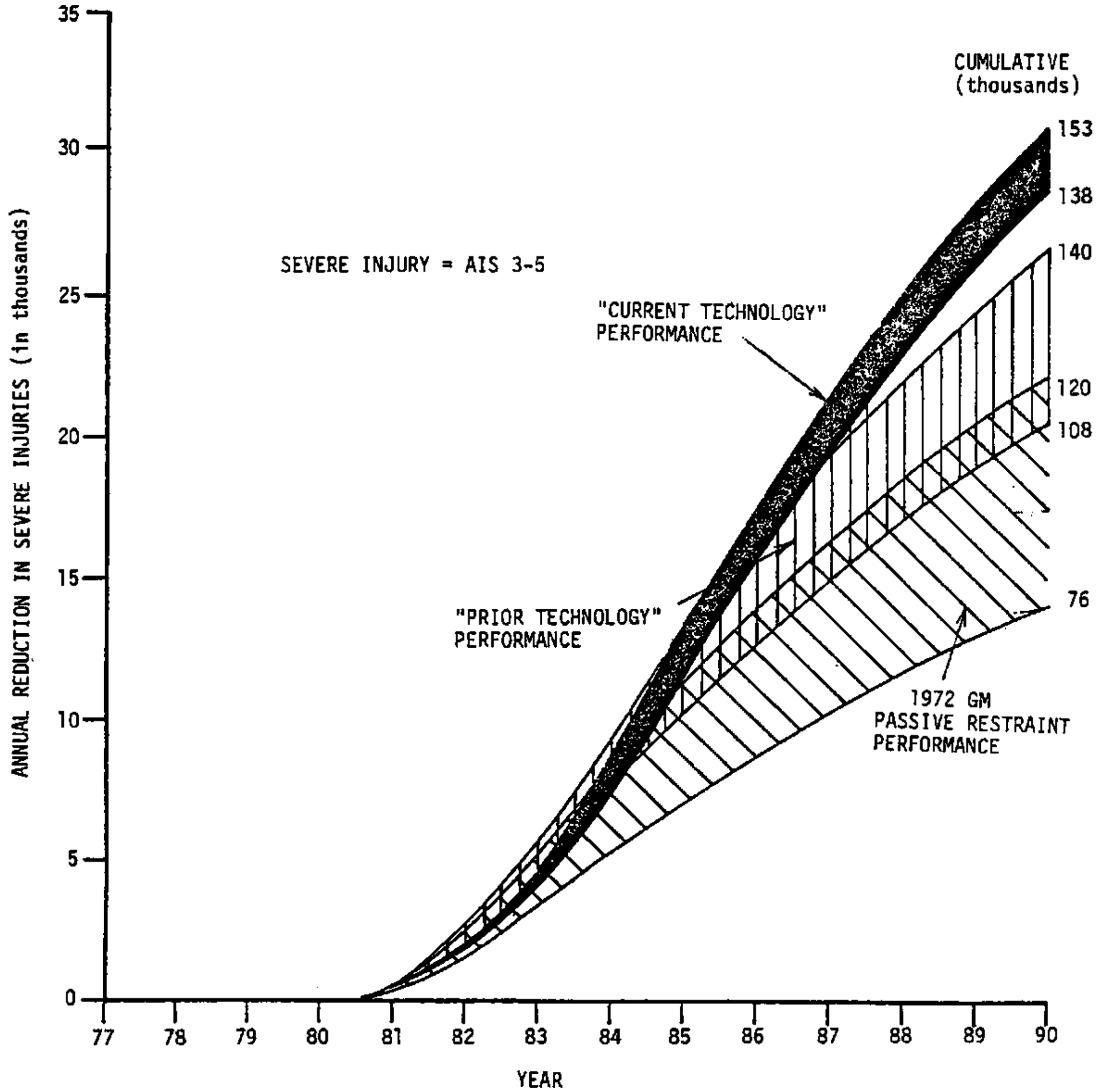


FIGURE 12-10. SEVERE INJURY REDUCTIONS

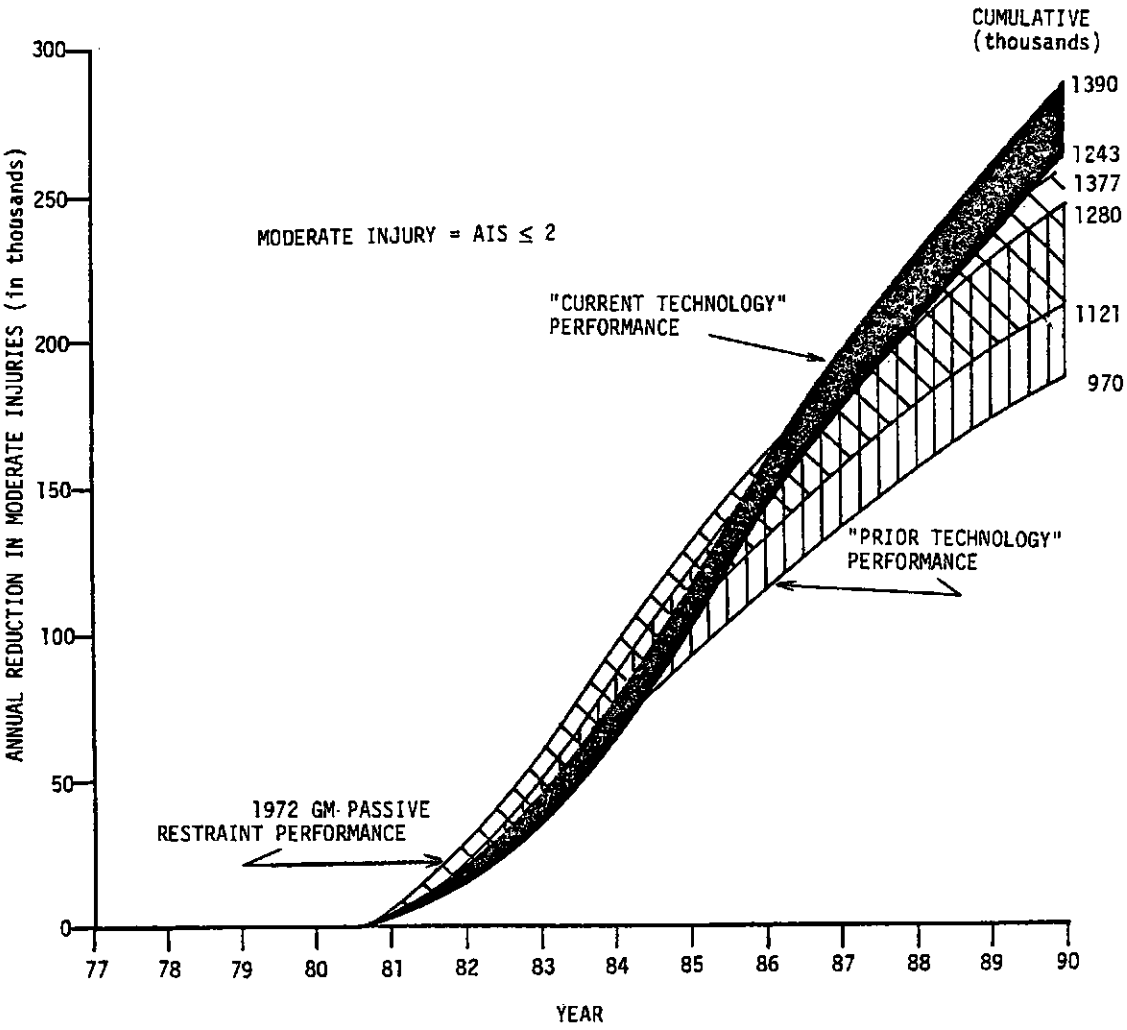


FIGURE 12-11. MODERATE INJURY REDUCTIONS

We would like to point out that these calculations are based on 1976 statistics, which show 1.4 million automotive injured.

It is important to note that none of the benefits – fatality, severe injury or minor injury reductions – reaches a steady-state condition by 1990. Even if vehicle sales, market shares and weights were static after 1985, the benefits would not reach a steady-state condition until at least the year 2000, because of the time required to move old vehicles out of the vehicle population. (The scrappage of any given model year actually extends over a 25 year period.) Obviously, the steady-state benefits (as estimated in other studies) should exceed the transient benefits calculated in this study.

It should also be noted that the benefits calculated here were wholly for front impacts; no benefits were calculated for side impacts, rear impacts or rollovers.

SECTION 13
RSV PROTOTYPE PRODUCTION

The RSV prototype production differed considerably from high volume production. The RSV prototypes were virtually hand built, and the investment in equipment and tooling was minimal. Consequently, it took approximately 3000 labor hours to complete an RSV from the ground up (and that does not include the manufacture of the engine, transmission, suspension and other Original Equipment Manufactured (OEM) parts).

The Budd Company and Response Motors conducted high volume production studies of the RSV. Both showed that the RSV production methodology already incorporated a number of innovative features that would be easily adaptable to high volume production: the extensive use of straight sheet metal sections in the body in white, the use of sheetmetal that is primarily of a single gauge, the metal-foam integral structure, and the reaction injection molded body glove parts (including the front and rear fenders and fascias).

On the other hand, some designs caused considerable difficulties in prototype production. The best example is the gullwing door. This door still has to be thoroughly production engineered to improve its producibility.

The RSV prototype production consisted of five major operations:

Body in white manufacture and assembly
Foaming and priming operations
Subsystem fabrication and assembly
Painting operations
Quality control inspections.

The first four operations took place sequentially. The fifth was conducted throughout the manufacturing process. Then, after each RSV was complete, it went through a final road test and inspection before being presented for acceptance to the NHTSA. All of the production procedures and quality control tests and results were checked and accepted by an on-site NHTSA representative.

13.1 BODY IN WHITE MANUFACTURE AND ASSEMBLY

The body in white is composed of 335 semi-finished metal parts, formed primarily by press brake. These parts may be divided into underbody members, body subassemblies, and roof sections. The body in white is carefully inspected after each of its assembly stages, and, when the structure is complete, it is fully primed and sent on to the foaming process.

13.1.1 Underbody

First the floor pan is fabricated from sheet steel. To this pan are welded hat section stiffeners running longitudinally along the bottom of the pan. The forward tunnel, rear tunnel, front seat riser, rear seat riser, transmission control mounting bracket and fuel cell cover are then fabricated separately (with doubling and reinforcement panels installed) and welded together to form a "spider" of sections that compose the upper surfaces of the floor pan. This spider is aligned with the floor pan using jigs, squared, then riveted in place and welded.

The floor pan serves as the foundation for the remaining parts of the body in white. The vehicle is built up, more or less vertically, from the floor pan to the roofline. The first parts to be welded to it are the firewall, the rear suspension forward mounts, the various brackets and mounts for the fuel pump, the rear seat restraint, the battery compartment, etc. After the forward bulkhead assembly is fabricated, it also is jigged to the floor pan, riveted and welded to the front of the pan. Then come the vertical side rails, which run from the front of the bulkhead through to the rear suspension rear mounts, and the upper section of the rear seat riser, which ties the side rails together laterally.

13.1.2 Body Subassemblies

To the rear end of the side rails is attached the rear subassembly, which both stabilizes the ends of the side rails and begins the structure that will enclose the engine. The hatch crossmember is then welded (through four vertical posts) to the top of the subassembly, the rear quarter panels fabricated and welded to the side rails, the subassembly and the hatch crossmember, and the rear seat upper welded between the quarter panels, thus closing the sides of the engine compartment.

Before the rear quarter panels are attached, the rocker panels and A and C pillars are fabricated and welded to the outsides of the side rails. The rear quarter panels then have forward attachment points on the C pillars, thus forming the rear interior compartment walls.

In the front, the floor of the trunk is first welded to the side rails and other front bulkhead members, the front spring well and the vertical wheelhouse panel are fabricated and welded to the outside edges of the trunk floor and side rails, and finally a close out panel on the front of the section closes the compartments so that they may be foam filled. The vertical wheelhouse panels link the A pillars to the firewall, thus starting the integration of the front section of the interior compartment. Horizontal flat panels are then welded to the edges of the spring wells and the outsides of the vertical wheelwell panels to form the tops of the wheelwells. To these panels are attached two three-panel sections forming trapezoidal boxes above the wheel houses. These boxes will also be foam filled, to form the upper loading members that provide protection in front crashes.

With these assemblies, the main body sections of the body in white are complete. The remaining panels and parts are brackets and close out panels, the latter being used primarily to finish the box sections that will contain the crushable foam.

The front nose assembly is fabricated as a separate bolt on section (bolted on so that it may be removed easily when damaged in 10 to 20 mph crashes). This assembly is composed of four closed compartments (again, for foam filling) that surround the radiator. The radiator brackets and the mounting plates for bolting the nose to the vehicle are attached, but the nose is not bolted on until after the vehicle is painted, near the end of the car's production. In the meantime it is treated as a separate part of the car, being foam filled, primed, painted and detailed when the rest of the car goes through these processes.

13.1.3 Roof Sections

Before any of the roof panels or upper pillars are installed, the entire body is mounted in a jig specifically constructed for precisely locating the door openings. In this jig the inner and outer panels of first the A pillars (and their headers), then the B pillars (and their headers), and finally the C pillars (and the hatch opening frame) are welded on the body.

The basic roof structure is constructed as a subassembly with side rails, hat sections and door hinge plates. The subassembly is welded to the pillars while they are still in the positioning jig. The roof structure is covered with the roof skin only after an inspection shows that the structure matches the design. The jig may then be removed.

The body in white is completed by welding on the windshield and rear window fences and pillar covers.

13.2 FOAMING AND PRIMING OPERATIONS

13.2.1 Foaming

When the body inspection is complete, it is sent to the foaming facility. There the crushable compartments in the structure are filled with energy absorbing foam. The foam used throughout the RSV body structure has a density of 2 pounds per cubic foot.

The chemicals are mixed in a specialized foam production machine. The machine delivers liquid foam per unit of time, not volume or weight, so the volumes of the compartments to be filled are carefully calculated and the times needed to fill them are precisely measured during the foaming operations. The mixing process is quite temperature and humidity sensitive. Thus our procedure is to conduct pour tests immediately before a car is foamed and to use those tests to determine the density and rise characteristics of the foam under the prevailing conditions. Usually the conditions in the plant vary only minimally, but for large compartments there can be significant differences in the time required to fill without overfilling.

The foam is produced by an exothermic reaction between isocyanate-papi-27 and six part resin that causes the mixture to rise. The foam mixing machine used at Minicars is an Admiral Equipment Company Model K500 2p equipped with an ATC Model 4000 control/delivery head. The machine is calibrated for the correct mixture before each foaming operation. The chemicals are delivered unmixed but in the correct proportion (143.8:120 resin:ISO) from the delivery head. The pour times are calculated from a flow rate of 159 to 161 grams per second (a 3 second pour produces about 3 ounces of foam). Immediately after filling we cover the entry hole with tape and check the sight holes and bend relief holes for foam.

The major problem with the process is the leakage of foam from the compartments. Bend relief holes at or near the bottoms of voids are certain to leak, as are most spot welded seams (especially improper welds containing even very tiny penetration holes). Most of these areas have to be caulked (and sometimes taped) before foaming. The caulking is done with a standard caulking gun and fast drying vinyl or latex compound. The caulk is allowed to dry 60 minutes before taping. The foaming process can start immediately thereafter.

All foaming procedures are conducted under carefully regulated safety conditions. The workers are fully covered in protective suits, including hoods with filtration masks. It is a special precaution that all vapors are fully filtered before anyone is allowed to smoke a cigarette in the area. (When isocyanate vapors pass through a burning cigarette, cyanide gas is created.)

In full production manufacturing there would be no need to inject the foam directly into the vehicle structure. The liquid foaming process was employed in the Minicars prototype production chiefly for the convenience of research and experimentation. It allowed, for instance, the foam densities in different parts of the car to be readily varied for specific tests. As it turned out, however, the advantages of varying densities were minimal, and a constant 2 pounds per cubic foot was determined to be optimal throughout the RSV.

Further, optimal energy management during crashes does not require a bond between the foam and the metal, nor does it require that every nook and cranny of every compartment be filled. Consequently, the foam could be preshaped from any of various externally gassed foams (such as styrene foam), and the whole procedure of filling the compartments of the car with liquid foam could be avoided.

13.2.2 Priming

The priming process starts with a metal etching of all of the surfaces of the body with a dilute acid solution and a wipe down with an abrasive to give good primer adhesion. The entire body is then covered with a nonsanding sealer, followed by three coats of catalyzed enamel. The enamel is color coded to the final color of the particular car. After the third coat the body receives a full inspection of the paint quality and coverage. Any deficient areas are thoroughly redone. Before the body in white returns to the manufacturing process, its lower sections receive a complete undercoat with an antirust tar-based undercoater.

13.3 SUBSYSTEM FABRICATION AND ASSEMBLY

Suspension and Rack and Pinion Steering

Once the vehicle is primed, the suspension and lower steering components are mounted. First the front struts are bolted in the shock towers, the attachment brackets mounted on the underside of the car, and the strut and control arms bolted to the brackets. None of the bolts are torqued at this time; torquing to specification occurs later in the assembly sequence.

The procedure with the rear suspension is much the same. The brackets are mounted and the struts bolted, but not torqued, in place. The passenger side A-arms are not attached until the engine is installed.

The rack and pinion oil level is checked (it requires 8 ounces of 90 weight gear oil), and then the rack and pinion is bolted to its bracket assembly. The assembly is then passed into the steering tunnel (a box compartment formed through the foam-filled compartments in the front structure) and bolted down. The tie rods are attached to the front pillars, but the steering linkage is left unfinished until the steering column is installed.

Radiator Assembly

The coolant tubes are installed (using 'adel' clamps) along the left and right undersides of the vehicle and hoses are clamped to the pipes at the engine compartment ends of the tubes. The nose section can then be bolted to the vehicle and the radiator installed, or the radiator installed in it independently. In either case the procedure is to first install the lower radiator brackets, then mount the radiator on them, and finally attach the upper brackets to both the radiator and the nose. The fan assembly and wiring harness must be installed after the radiator is mounted. When the nose is attached to the vehicle, the front radiator hoses can then be cut to size and attached.

Parking Brake

First the brake pulley mount is installed at the end of the central tunnel of the RSV body. Blind nuts are welded in the body in white for this pulley. After the brake indicator lamp switch is mounted on the brake handle assembly, the assembly is installed on the body in white. Finally, the cable assembly is attached between the pulley and the rear brake calipers and the connector cable between the handle and the pulley.

Brake Master Cylinder and Booster

The master cylinder is attached to the vacuum booster, the booster to the mounting bracket, and the bracket, in turn, to the firewall. Care must be taken that the tubing inserts in the brackets are aligned and that the top bracket is adjusted for steering shaft clearance. The front bracket is then attached between the booster and the trunk floor.

The pedal assembly is installed and adjusted so that the pedal and the bell crank do not touch the firewall at the end of the pedal stroke. The brake lines are individually measured and attached from the wheel ends back toward the master cylinder. These lines are only flared after they are firmly attached and matched to the appropriate brake line hoses. The two rear lines attach to a T fitting at the engine end of the central spine. The single line then runs up the spine on the pasenger side of the shift mechanism, through the firewall and meets the front brake line at the proportioning valve.

After the brake lines are installed, the vacuum line must be run back to the engine and attached at the base of the carburetor. When all of the lines are firmly mounted, the brake reservoirs may be filled, the brakes bled and the brake pedal travel adjusted.

Fuel System

The lower cover of the fuel cell is aligned with the floor pan and the mounting holes are match drilled into the pan. After a thorough inspection, the fuel cell is installed and the filler tube, gas line and vent line are attached.

Gear Shift and Accelerator Pedal

The shift assembly and gas pedal are slightly modified OEM parts that are directly mounted on the body in white. The cables connecting them to the transmission and engine are routed through the central tunnel. Because the RSV is a rear engine car, all of the cable connections from the front to the rear of the car had to be specially designed and manufactured. At times this required a sizeable amount of research and experimentation, especially when it came to the requirement that the gear shift lever have good, firm control. The resulting cable mechanism is clearly superior (in this application) to even rod-and-balljoint designs.

Steering Column Support, Clutch Cylinder and Pedal Assembly

The column support is temporarily bolted to four welded tube inserts in the top of the cowl. The pedal assembly bracket is then bolted to the firewall and to the brake booster brackets attached to the forward side of the firewall. After the pedal assembly is modified and aligned in position, the access hole to the front compartment is marked and cut in the firewall. The rod end of the pedal assembly will pass through this hole. After the pedal assembly support is bolted to the assembly, the mounting holes are marked on the steering column support. The column support is then removed, the holes drilled, blind nuts welded on, the impact slides attached and the unit reinstalled. The impact slides must be inclined at 9 degrees from horizontal.

Heater Hoses, Antenna Cable and Speedometer Drive Cable

The heater hoses are routed from the engine compartment through the center tunnel to the heating-ventilation-air conditioner (HVAC) unit under the dash. The feed hose, which has the inline water valve for temperature control, is connected to the engine on the output side of the water pump. The return hose, which has an inline T fitting installed to allow coolant to be added to the surge tank, is connected to the input side of the water pump.

The antenna cable reaches from a lead off the antenna (mounted in the right rear fender) through the engine compartment and central tunnel to the back of the radio in the dash.

The speedometer cable also passes through the tunnel to a 90 degree adaptor attached to the speedometer. A small spring cup holds the other end of the cable in the transmission.

Wiring Harnesses

The engine compartment harness is a large Y with one long leg. The base of the Y ties into the passenger compartment harness in the central tunnel and branches left (shorter leg) to all of the electrical equipment on the driver's side of the engine compartment. The right side connects to the tail and rear marker light assemblies. All electrical components are color coded and have connectors that mate to the harness.

The passenger compartment wiring runs from the engine compartment harness in the tunnel to the firewall, where it attaches to the luggage compartment harness, connecting to the instrument panel and steering column harnesses along the way. The luggage compartment harness connects to the front marker lights on both sides of the car. The radiator shroud must be installed when the luggage compartment wiring is attached, because the harness passes through the shroud.

The restraint harness leads from the comparator circuit in the left front strut tower to the front and side impact sensors. One leg of the restraint harness leads through the firewall to the steering column wiring and another to the passenger airbag diffuser.

Engine Compartment Components

The fuel pump, fuel pump cover plate, fuel filter, charcoal cannister, backup warning buzzer, coolant surge tank, emissions control box, voltage regulator and ignition coil and resistor are all mounted on appropriate brackets in the engine compartment before the engine is installed.

Rubrics and Bumpers

Sections are cut out of the foam bumpers to house the rubrics, which are laminated devices that stiffen the bumpers sufficiently to prevent damage in low speed (up to 8 to 10 mph) accidents. The rubrics (two front, two rear) are bolted directly to the removable nose and to the rear subassembly, and the bumpers are mounted over them.

Horns, Parking Lights and Other Electrical Accessories

The horns, lights, radiator relays, wiper drive, washer, etc. are all installed on appropriate brackets mounted on the body in white.

HVAC, Hood Latch Control

After the control bracket is installed on the top of the cowl, the HVAC unit and the heater hoses, heat control valve, control cables, defroster diffuser and ducts are all installed, in that order. Before the dash can be mounted, the door ajar warning buzzer must be mounted on the control bracket.

Fuse Block, Side Impact Sensor, Comparator Circuit

The fuse block is installed in the trunk compartment and the side impact sensor in the left front strut tower. The restraints diagnostic warning light emitting diode (LED) is installed in the center console of the passenger compartment.

Restraints

First the column mount is bolted to the firewall, then the steering column is attached to its mount, with the heads of its bolts passing through the shear capsules. The knee restraint reaction pans are installed at 45 degrees and the foam knee restraints inserted over them. On the passenger side the knee restraints are installed after the air bag mounts are attached, then the air bag assembly itself is attached (with its diffuser precisely 15 degrees below horizontal). The air bag is hand folded and secured in place by tape.

The steering column is a specially designed, specially fabricated energy absorbing column that is described in the Occupant Protection section of this Final Report.

Engine, Axles and Exhaust

The engine is assembled and bench tested before installation. The RSV requires the engine to sit at a different angle than the angle for which the engine (a Honda) was designed. We therefore install an aluminum wedge between the carburetor and the intake manifold to level the float bowls in the carburetor. That and the exhaust system (because a front engine is now moved to the rear) are the primary engine modifications required.

Before installation, the engine cradle is mounted and torqued on the engine, the carburetor removed, the transaxle attached, and the package finally installed through the right rear side of the engine compartment. The right rear A arm and strut can be installed only after the engine is in place. The hoses, wires and carburetor are then attached.

After the engine is mounted, the axles can be assembled and installed. The passenger side axle is installed first and checked to make sure the half shaft snaps into its retainer clip (else an oil leak will result). The passenger side tire and wheel can now be installed. For the driver side, the left rear pillar must first be detached from the shock assembly and A arm. Otherwise the installation procedure is the same as the left side.

The exhaust is assembled and then bolted to the support brackets. The clearance with the fuel pump cover plate and the engine cradle must be checked carefully.

Dash and Instrument Panel

The dash is based on a single piece of vacuum formed plastic. This material is upholstered with vinyl fabric that matches the interior of the specific car. For show purposes the passenger airbag and steering wheel hub are covered with a different material, to clearly distinguish where the restraints systems are located. In standard production, of course, these areas would typically be covered with the same upholstery as the rest of the dash, specifically to deemphasize the existence of the restraints.

The dash is attached at its front edge by four clips that catch corresponding brackets mounted on the windshield fence. The lower left and right surfaces are mounted on brackets that attach to the A pillars. The ends of the duct hoses are then pushed into place in the dash.

The holes for the gauges, lights, etc. must be cut into the instrument panel and the gauges matched to them. The Sonealert is tested before being installed in the dash. Then all of the rest of the cables and harnesses are attached.

Steering Wheel and Driver Restraint

The steering wheel is mounted with the horn buttons on the top and the tires straight. The airbag module is then mounted (with a "T" that is stamped on its back centered at the top of the steering wheel).

Hatch, Engine Cover and Rear Vent Ducts

The hinge is attached to the engine cover, the cover is attached to the rear seat riser and the hold-open latch then installed. The locking mechanism, hinges and supports are mounted on the rear hatch and the hatch also installed. Finally, the rear vent ducts are attached to the vent boxes and routed between the wheelhouse and the body glove through to the rear grills.

Rear Seat Belts and Battery

The coil force limiters are fabricated (a special tool is required for winding the force limiting tapes) and mounted on special brackets. The belts themselves are modified Honda belts.

The battery is mounted in a compartment beneath the right rear passenger seat.

Body Glove and Hood

In the rear the body glove components require largely trim and fit operations. The rear panel and fenders are primarily bolted on. The quarter panels, air scoop backplates and forward edges of the fenders are riveted in place. The light brackets are bolted in and the grilles are held on by Allen head bolts. The rear spoiler is simply aligned and screwed on.

In the front the fiberglass panel must be slotted for the headlight adjusters. Beyond that, the panels (including the complete front glove) are simply fitted and mounted with either rivets or bolts. The determining checkpoints for the body glove are its centering on the parking light assembly and on the air scoop.

The (front) trunk lid is a sandwich of 4 pound per cubic foot foam between fiberglass panels. After the panels are attached together, the hinges, latch and opening brace must be aligned with the appropriate plates on the body. The hood can then be mounted on the body.

The fiberglass wheelwell liners are fabricated specifically for the RSV, but final fitting must be done on each vehicle. Each well is riveted in place along all of its edges, and their centers are secured by special brackets.

Doors

The doors are the most complex parts of the body. They are integral parts of the side restraint systems, yet they must also be lightweight, so that they can be supported easily while fully open. The doors are composed of aluminum panels with foam filling in the lower sections and fiberglass reinforcements in the supports around the windows. The windows themselves (which are installed after the doors are mounted on the car) are bonded to the doors to provide as much strength as possible; only small central windows slide open for ventilation. The doors are supported by gas struts.

While the doors are being fabricated they are carefully matched to female jigs. The male counterparts of these jigs are used to align the door frames while the bodies in white are being constructed. These measures are made necessary not only by the required lightness of the doors (making every reinforcement critical), but also by the fact that the door designs include compound curves, making them harder than most to fabricate accurately.

Once the doors are carefully aligned with the body, the striker pins, latches, handles, locks and control linkages must be installed and adjusted. Then the rigid plastic cover panels, trim panels and pull straps are installed, and the gas springs are attached between the doors and the interior roofline. Only then can the stationary windows and slider assemblies be installed.

Lights

The head lights, tail lights, courtesy lights and Knaff light are all mounted in standard OEM assemblies and attached completely according to standard automotive manufacturing procedures.

Interior Trim and Carpeting

Ensolite is glued onto the interior metal pieces (such as the A and B pillars) and the interior upholstery then glued to the Ensolite. Welting that matches the dash cover material is attached along the sides of the instrument panel to fill any gaps. The same procedures are used for the rear interior quarter panels. The floor and side sills are fully carpeted, as are the engine cover, the surrounding deck and the floor of the luggage compartment. Finally, the headliner is installed and trim is clipped to the cover over the bases of the gas springs.

The Vehicle Identification Number plate is riveted in place approximately 1 inch forward of the left side of the windshield fence.

Window Installation

The windows are bonded in place following conventional American automotive practice. After the vehicle has been painted, the surfaces to be bonded are cleaned with a chemical cleaner. The bonding surfaces of the glass and the metal frame are then coated with a primer and a bead of urethane sealant is applied to the body using an air driven caulking gun. The glass is then installed and taped in place, and water is used as a catalyst to cure the sealant. The sealant is then allowed to dry a minimum of 24 hours.

Center Spine (Tunnel) Cover

The front and rear spine covers are single vacuum formed pieces (each much like the dash) that are covered with an upholstery appropriate to the interior of the specific vehicle. Both are installed after the carpeting is in place, but before the seats are mounted.

Seats

The seats are specially modified Dodge van seats. The modifications include reinforcements to prevent deformation in crashes and force limited clear plastic head restraints that attach to the RSV roof. The head restraints help prevent whiplash and seatback collapse in rear end collisions.

The seat tracks of the front seats are first mounted on the seats and then the seats are installed on the body structure. The upper ends of the head restraints are bolted and glued on to specially fabricated brackets.

The rear seat is fabricated specifically for the RSV using standard American automotive techniques. The back of the rear seat is aligned and installed first, then the seat bottom (after the appropriate brackets are mounted).

Wheels and Tires

The wheels and tires are Dunlop Runflat tires mounted on Dunlop Denloc rims. The wheel lug nuts are torqued to 80 foot-pounds, and the tires are inflated to 30 to 35 psi.

The front wheels are then aligned (the primary adjustment on a McPherson strut suspension is the toe-in) and the car sent out to its complete inspection and road test.

13.4 PAINTING OPERATIONS

After all of the subassemblies (including the body glove parts) are installed, the RSV undergoes its final painting. Because the doors are aluminum, they must first be painted with zinc chromate primer (required for aluminum); the standard laquer can then be applied over this primer. The fiberglass and flexible urethane parts pose different problems. Fiberglass is covered with gelcoat when it comes out of the mold, so it has to be thoroughly cleaned with grease and wax remover, then sanded, primed and sanded again, until smooth. The flexible urethane parts (including the fenders, the front glove and the rear bumper cover) have a different coating, which must be removed with methalyene chloride. These parts must also be sanded smooth (with flexible sanding blocks) before being painted. Because we were conducting only a prototype operation, all of the flexible parts were left in their natural (beige) color. In final production these parts could be impregnated with the color of the particular car, thereby significantly reducing the amount of painting effort required for the final car.

After the body parts were all thoroughly cleaned and primed, they were painted with three coats of flexible laquer. The entire bodies (including the nonflexible parts) were covered with the flexible paint because laquers will change color when flex agents are added. A flexible clear urethane coating was applied over the laquer on all of the showcars.

13.5 QUALITY CONTROL INSPECTION AND ROAD TESTING

During its construction, each RSV underwent a large number of inspections. In fact, when each vehicle was complete and fully approved, a 110 page checklist report was issued. The report included notations from all inspections and the signatures of approval at each stage of the manufacturing process.

The inspections began with a review of the conformance of the floor pan to the appropriate design drawings (and a direct check of the sizes of the cuts, bends, holes, etc. against the specifications listed in the drawings) and ended with the acceptance driving test of the fully completed vehicle. Along the way there were inspections of (and quality assurance inspection reports issued for) the

Floor pan
Firewall
Side sill subassemblies
Rear quarter panels
Stage I BIW -- after the quarter panels were installed
Stage II BIW -- after the spring towers were installed
Stage III BIW -- after the roofline was in place
Nose assembly
BIW -- complete, less doors
Foam and clean-up -- including doors
Priming -- prepaint and undercoat
Stage I assembly
Stage II assembly

Stage III assembly
Stage IV assembly
Complete vehicle non-driving acceptance test
Complete vehicle acceptance road test.

The non-driving acceptance test itself required 31 pages of checklists and testing procedures to be followed step by step and checked off as each system (from the cigarette lighter to the operation of the rear hatch) passed its tests. The acceptance driving test required another 10 pages of inspections and tests to be conducted over a prescribed on-the-road driving course.

There also were full inspections and inspection reports for the major subsystems that either were entirely fabricated or extensively modified by Minicars. These included the:

Electrical harnesses
Engine modifications
Pre-installation engine run-in
Front and Rear suspension A arm and spring modifications
Driver restraint system and steering column
Fuel cell
Seat fabrication
Door assembly.

13.6 MANUFACTURING DIFFICULTIES

The RSV prototype production difficulties can be classified into four categories: design, tooling and equipment, accessibility and serviceability, and weight increase.

13.6.1 Design

A straightforward production engineering of the vehicle would solve the design difficulties (as well as the problems with the accessibility and serviceability of the components and subsystems). In addition, the weight increase was a direct result of the fact that the vehicle structures were completely hand built, using minimal tooling and equipment. A fully production engineered RSV, manufactured with dedicated tooling and equipment, would not, therefore, have experienced the production difficulties described below.

Because of a buildup of tolerances in the body in white assembly, the door fit, for instance, varied from car to car. This could be prevented by the use of more extensive jigs and fixtures than were possible in the prototype construction. (The construction of such jigs would, of course, be included in the production engineering of the car.)

There were limitations imposed by the simple fact that the RSV had to be designed to accept components that were already in production. For example, because the engine used was from a front wheel drive car, the shift linkage to the transmission was mounted on the rear of the engine. When this engine is moved to the rear, the connection is still on the rear, on the opposite side of the engine from the driver. The linkage from the shift handle to the transmission thus had to pass under the engine to reach the transmission connection. Obviously production engineering would move the connection to the front of the engine and thereby eliminate the extra parts. The use of a production (though modified) steering column caused a similar problem: the steering linkage had to pass through two U-joints, when one would have been sufficient if the whole system could have been redesigned.

There were some difficulties caused by late changes made in other parts of the design. A change to Dunlop Denovo run-flat tires produced interference problems; special lock nuts, studs and spacers were required for a correct fit. Changes in the head restraints caused difficulties for their attachment to the roofline. Delays in the actual production of the cars caused the aluminum door parts to remain on the shelf too long, allowing them to age harden, and thus to become much harder to weld.

Finally, there were design difficulties that were simply discovered too late to be completely redesigned. The doors are difficult to upholster. The windows are bonded directly to the body of the car, so body flexing at times causes them to crack. (This could be solved by more flexible mountings.) The fuel inlet hose can too easily be stretched during installation, allowing it to crack under the pressure of a fuel nozzle or wear caused by vibration. The trailing arms and the suspension attachment points must be reinforced. Redesign of all of these would take a very short time in the production engineering of the car.

13.6.2 Tooling and Equipment

The manufacturing process would be greatly improved by the development of complete jigs and fixtures for the body in white greenhouse assembly, the door assembly and fitting, and the rear hatch fitting. There also were difficulties with the preciseness of the environment and mixture required for foaming, ripples in the RIM urethane components, and the matching of the paint colors and finishes on the metal, fiberglass and RIM urethane parts.

13.6.3 Accessibility and Serviceability

There also is a need to redesign to improve the accessibility and serviceability of the bumpers, front nose, radiator, wiring, heater hoses, heaters, wiper arms, battery and instrument panel. The primary problem here is that, at times, too many extra pieces have to be detached to gain access to a particular part. For instance, the wiring harnesses run down the central tunnel of the vehicle. To check these harnesses, too many cover plates and sections of upholstery must be removed.

13.6.4 Weight Increase

Because the vehicle is hand built, many weight saving measures available in full production could not be used. For instance, most of the bends in the body in white were straight angle bends, ones that could be rounded (less material, hence less weight) in production. Thus the RSV weighs much more than it would in production. This has consequences on the vehicle's acceleration, braking performance, handling -- and even the gas struts and hinges of the doors.

SECTION 14
CONCLUSIONS AND RECOMMENDATIONS

> "The objective of the RSV project is to provide research and test data applicable to the automobile safety performance requirements for the mid-1980's, and to evaluate the compatibility of these requirements with environmental policies, efficient energy utilization, and consumer economic considerations."

These words appeared in the Phase I Statement of Work, written in 1973, and have appeared in all subsequent RSV contracts. Between then and now, the nature of the future automotive environment has become much clearer. The objective has narrowed to the attempt to answer the question:

> Can small cars be made safe?

and its corollaries:

> In the drive to improve fuel economy, how safe should cars, in general, and small cars, in particular, be?
>
> What technologies will be required to make them this safe?
>
> Are these technologies feasible?
>
> Can they be, or have they been, sufficiently developed to justify their implementation in production vehicles?

The RSV Program has not, in and of itself, provided answers to all of these questions. But it has shown that it is possible to make cars much safer than they are presently. It has produced designs that are consistent, at affordable cost, with the national objectives for fuel economy and environmental protection. It has demonstrated, at least to a limited degree, that the technological findings are applicable, at varying levels, to a variety of car designs. And it has provided evidence that these findings can be wrapped in a package of considerable appeal to the public.

It must be remembered that the RSV Program did not complete the development of a car. The development process is finished only when the design is ready for production. Yet it has been estimated that the entire Minicars development of the RSV involved less than 2 percent of the cost required to bring a new design into mass production in Detroit. There simply is an enormous amount of work involved in the development of a production vehicle and much of it has little to do with the questions asked in the RSV Program. We have, in this program, demonstrated the feasibility of certain automotive concepts; what remains is for these concepts to be brought to fruition by the industry itself.

One output of Phase I efforts, which began in January 1974, was a performance specification for the RSV which reflected a detailed study of accidents and injuries and their vehicle related causitive factors. This performance specification was aimed at the threats to a small vehicle in the projected mid-1980's traffic environment which involved a significant shift in auto population by weight categories and, therefore, forecasted shifts in the distribution of crash severity probabilities. Other products of Phase I, which was completed in April 1975, were a conceptual design of the RSV to achieve the requirements of the performance specification and a program plan for RSV development in Phase II.

Phase II activities started in July 1975. In Phase II all subsystems were defined and specified, and all necessary development testing was performed to verify the design approach. These development tests included subsystems integration tests as required to assure the performance of related subsystems (e.g., structures and occupant restraints). Materials and manufacturing processes were identified, and, where necessary, their feasibility was verified.

The primary objectives of Phase III were to further develop the RSV in accord with the performance specification and to manufacture vehicles for testing and evaluation in Phase IV. It should be noted that the Government's Statement of Work said: "It is not the Government's intention that detailed production engineering, as would be required to actually bring a product to mass-production, be performed.... However, it is the goal of the Phase II and Phase III development efforts to ensure that all aspects of the RSV design are feasible;

i.e., translatable into an affordable, mass-produced product in the mid-1980's. It is not the goal of the RSV Program to actually perform the translation."

In Phase III, refinements were made in the designs of selected subsystems which had been tested in Phase II. These refinements were in some cases adviseable to achieve improvement in performance demonstrated in Phase II testing (e.g., introduction of stiffeners in torque box region to reduce compartment intrusion which had been judged marginal in Phase II offset frontal barrier crash). Other cases of design improvements were related to design deficiencies encountered during testing in Phase III (e.g., stiffening of suspension mounting brackets and improvements in steering mechanism). In Phase III, it was also necessary to introduce a brake vacuum boost assistance system in order to achieve specified limits on tolerable pedal forces during braking and to refine the parking brake rear cabling in order to eliminate excess slack which had been discovered to be the cause of the RSV's failure to achieve grade holding requirements.

Another objective of Phase III was to demonstrate the potential applicability of the RSV design for other vehicle weight classes. This objective was achieved in the development of the Large Research Safety Vehicle, a six passenger sedan which (compared to the production vehicle from which it was derived) demonstrated weight savings, improved occupant crash protection and improved fuel economy through use of foam-filled structures, air bags, and powertrain changes.

14.1 DERIVING THE PERFORMANCE REQUIREMENTS

To find out how safe cars should be, one must make a detailed study of accidents and injuries, and of how they are influenced by vehicle design changes. Such investigations were conducted throughout the RSV Program (and were discussed at length in the Final Reports of Phases I and II, as well as in Section 12 of this report). The RSV Program has done much to advance the analytical state of the art, but it can hardly be argued that the work is done.

Analytical results are still limited by shortcomings in the accident data. To assess improvements in vehicle damageability, for example, one needs better data on low-speed accidents (in which property damage is significant relative to injuries). These data could be obtained by studying non-towaway accidents and by broadening the spectrum of low-speed crash tests.

Similar data needs exist for the evaluation of improved braking systems. Impact data are not sufficient; the accident files must be upgraded to include the traveling speeds as well as impact speeds. Additional data on road surface conditions would also be useful.

In evaluating the effects of vehicle design on injuries and fatalities, one comes ultimately to the problem of relating accident file data to test results with anthropomorphic dummies. The problem of correlating dummy injury measures to human injury has been most difficult to solve, and more progress must be made if analytical results are to gain widespread acceptance.

14.2 DEVELOPING A CRASHWORTHY STRUCTURE

It is axiomatic that low weight and good fuel economy go hand in hand, and that low weight depends on an efficient structural design. Thus the vehicle structure is at the nub of the problem of providing crashworthiness and fuel economy simultaneously. Indeed, it is the core of the RSV Program.

The RSV structure employs conventional materials and common automotive fabrication processes with one significant exception – the use of foam-filling. In fact, the basic vehicle architecture is unremarkable, except for the gull-wing doors (which are not fundamental to the use of foam-filling) and the strategic placement of structural elements to provide intrusion resistance or controlled crush. Of course, foam-filling requires that the metal structure form closed box sections, which generally occupy larger volumes and employ thinner steel than conventional automotive structure. Although foam-filled structure offers reduced weight and improved crash energy management, its use has significant effects on the design process. The details of vehicle volume devoted to structure, local reinforcement of the thin sheet metal at points of concentrated load and the assembly sequence of the entire vehicle are more critical and require greater attention during design than do more conventional current mass-produced vehicles. Once the design is finished, however, the structure is readily assembled, and it is extraordinarily crashworthy.

This is not to say that the RSV's structure is ready for mass production. Significant issues that have not been thoroughly explored include durability, corrosion resistance, repairability, and assembly line foam-filling at high production rates. The scope of the RSV Program simply did not permit the investigation of all these factors in depth. But if regulations that encouraged the use of foam-filling were contemplated, we would certainly recommend further in-depth studies along these lines.

14.3 PROVIDING OCCUPANT CRASH PROTECTION

The RSV was designed to produce an approximate 75 percent reduction in the economic societal losses caused by auto accidents. Work in Phases I and II of this contract had indicated that this 75 percent societal loss reduction was achievable with a very favorable economic benefit to increased consumer purchase cost ratio. To actually express this goal in terms of physical hardware required a very painstaking and thorough analysis of the ways these losses are incurred. But the results of that analysis are quite straightforward: the greatest societal losses are due to the serious injuries and fatalities that occur to the occupants of the vehicle in question. Serious injuries and fatalities tend to occur at high impact speeds, usually to front seat occupants and usually when the vehicle is struck in the front or the side. Thus the problem of providing occupant crash protection tends to focus on these particular circumstances.

In the RSV, frontal crash protection is provided by a highly efficient energy-absorbing front structure and by two air cushion restraint systems - one each for the driver and the right front passenger. The restraint systems are designed for adult occupants who are seated in the so-called "normally seated position." Their performance is impressive: 50 mph BEV front impacts can be sustained with dummy injury measurements satisfying the FMVSS 208 injury criteria. The strategy of protecting normally seated adult drivers appears reasonable in that the driver is:

- Performing a function (driving) that requires him to be in a seated, erect posture
- Likely to be aware of an impending crash
- Provided with a proximate object (the steering wheel) with which to maintain himself in a seated, erect posture during pre-impact braking and/or evasive maneuvers.

The passenger restraint system of the RSV was designed to provide protection to a range of occupant sizes in a range of possible and reasonable positions at impact. Although development and evaluation plans existed, fully adequate evaluation through testing of adult and child passenger misspositioning was not actually performed as a result of schedule requirements and unanticipated higher costs in systems development. In retrospect it seems likely that a "hybrid" rather than a high-mount passenger restraint system would be more effective and that the present system may possess more deployment energy than ideal. By a "hybrid" system, we mean an air cushion system in which the module is mounted in the upper dash, as in a high-mount system (so that the passenger's knees can translate forward and under the inflator package), but a separate knee bag is provided for lower-body restraint, as in a low-mount system. Over the last few years such hybrid systems have been developed by Minicars under other NHTSA programs. These systems tend to be less sensitive to the occupant's pre-impact position than are RSV-type systems that rely on a fixed knee restraint. Moreover, using dual-level inflation techniques*, these systems can provide both protection for small out-of-position occupants (represented by the three- and six-year-old dummy sizes) as well as for normally seated adults.

Side impact protection is provided by generous padding in conjunction with an extraordinarily intrusion-resistant door and sill structure. This system performs impressively well, when judged in a manner consistent with its development criteria (i.e., the injury criteria presented in Section 4.5 and measured in a Part 572 dummy). Since the completion of its development, however, significant advancements have been made in the methodology of evaluating side impact protection, particularly with regard to the side impact dummy and the

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*In a dual level system the deployment energy can be changed according to either the BEV of the crash (e.g., the GM ACRS system) or the proximity of the passengers to the dash (as sensed by sonar sensors — of the type used in Polaroid cameras, for example), or some combination of these circumstances.

injury criteria. If we were conducting the development today, we would, of course, use the improved methodology. Preliminary estimates indicate that the protection levels would be approximately the same, but that the stiffness of the shoulder target would be slightly reduced.

14.4 EVALUATING VEHICLE PERFORMANCE

From the beginning the RSV Program was designed to focus on safety issues that are significant with respect to the societal losses that actually occur in accidents. It seems clear that a vehicle evaluation program should have the same emphasis as the development effort. Indeed, Minicars recommended large crash test matrices that reflected actual accidents (as seen from a societal loss point of view), for the Government to implement in its Phase IV RSV evaluation program. The cost of supplying RSV's and conducting a large number of crash tests which represent real world single vehicle and vehicle-to-vehicle crashes demanded resources (dollars and time) far beyond those available in the RSV Program. Additionally, the test dummy utilized in the RSV crash tests did not process the human biofidelity necessary to make comprehensive evaluations of projected real world human injury possible. This situation limits the value of a large crash test program.

As such it is not possible to accurately predict the real world injury performance of the RSV's, were they to be introduced into the U.S. fleet. It is possible, however, to evaluate RSV occupant crash protection in those crash environments in which it was tested. These tests were in very severe frontal and side crash modes and demonstrated that the RSV provided crash protection (as measured by FMVSS 208 injury criteria). Although these tests do not provide a measure of the benefits under more common real world milder crash conditions (or benefits due to reduced injuries), they do allow an estimate of the benefits in the crash modes tested.

An example of the shortcomings of a small number of design evaluation crash tests is the testing done on the frontal structure. Untimely delays in prototype fabrication and testing at Minicars resulted in a late detection of an unacceptable deficiency in the RSV performance in aligned frontal crash with a large production car. This deficiency was unexpected and was of particular surprise in that earlier testing of the RSV against another large car in offset frontal crash had been successful. Although the original RSV design offered protection to its own occupants, the RSV overrode the primary frontal structure of the large car shortly after engagement and posed a severe threat to the large car front seat occupants. This discovery late in the Phase III program necessitated a costly development of RSV design modifications and additional frontal aligned development and demonstration tests. This event highlights the necessity for early design demonstration of performance in all common car crash modes rather than only those which are thought to provide the greatest hazards.

Since no quantitative correlation has been established between societal benefits and handling performance, this topic did not get nearly the attention that crashworthiness did. Indeed, the Intermediate ESV handling specifications, and the RSV specifications derived from them, may be subject to criticism on various grounds, but there was no justification for doing anything but designing the vehicle to meet those specifications as they existed. RSV braking and handling tests conducted by Minicars on final vehicles did not detect deficiencies in vehicle performance relative to the RSV handling specifications. However, subsequent testing conducted under Government agreement in Japan revealed failure to achieve RSV specification requirements under some specified conditions of braking and also detected an unsatisfactory steering returnability performance to our specification. Some detail design improvements were made by Minicars on a second handling test vehicle which was then tested in Germany. The German tests confirmed improvements in handling performance relative to RSV specifications but did find this performance to be marginal under certain test conditions. Furthermore, the parking brake was again found to be inadequate relative to our performance specifications as had been previously determined in Japan. Another RSV has since been further refined to improve handling and a design deficiency in cabling to the rear parking brakes which had produced excess slack has been corrected. Minicars testing of this vehicle indicates substantial handling improvement as well as full satisfaction of the parking brake performance requirements.

14.5 LOOKING FORWARD

In our view, the RSV Program has played a key role in the NHTSA's advancement of highway safety. As an integrated vehicle program should, it has touched on nearly all areas of automotive safety, it has provided badly needed coordination between these areas, and it has advanced the state of the art on a number of fronts. It was a very involved program. It made extraordinary demands on the managerial capabilities of the NHTSA in general, and on the Contract Technical Manager, Mr. Jerome Kossar, in particular. Few persons possess Mr. Kossar's technical breadth, so important for a program of this type. Nevertheless, the RSV Program was too large to be effectively managed by one person, and we would recommend that on future programs a small staff be assigned to support the manager in the various technical disciplines.

We at Minicars are pleased to have had the opportunity to participate in such an important and far-reaching program. We are hopeful that the NHTSA will continue to pursue such efforts, and that they will in fact lead to reductions in the injuries and fatalities that are still occurring on our highways.

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