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CONTRACTOR FINAL REPORT

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Final Report

DOT HS-806-059

U.S. Department
of Transportation
National Highway
Traffic Safety
Administration

Compliance Techniques for Pedestrian Protection

Feasibility Study

R. D Vergara
H B. Pritz
J T Herridge
T. W. Goodnight
C. R. Hassler

Battelle's Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

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16. Abstract

A study has been conducted to: (1) devise a compliance test methodology and criteria for the incorporation of potential injury mitigating modifications into the front end of motor vehicles; (2) design, fabricate, and test a candidate compliance test device; (3) demonstrate that the resulting methodology and test requirements generate structures which are consistent with the intent of the proposed compliance techniques and criteria.

A pedestrian safety compliance test methodology has been developed for bumper contact with the knee/leg area, and data have been obtained that: (1) represent several kinds of recent vehicle front end designs; (2) demonstrate the flexibility available to a designer in the use of foamed polymers (e.g., polyurethane); (3) characterize the velocity and temperature sensitivities that must be considered in utilizing such design concepts.

It has been shown that safety performance levels can be achieved while (1) approaching low-speed damageability capabilities; (2) using contemporary vehicle space allocation and material.

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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

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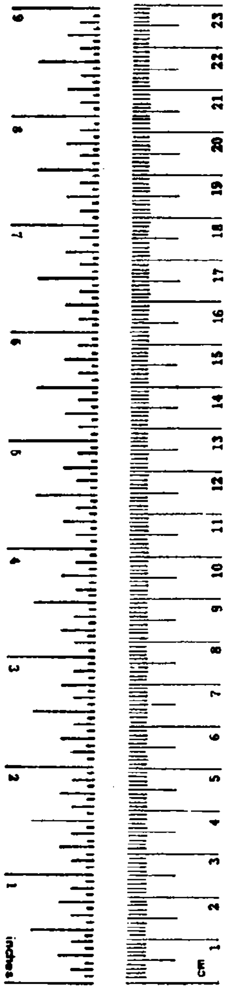
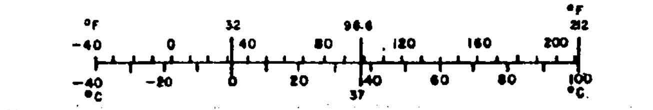
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



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



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FINAL REPORT

on

COMPLIANCE TECHNIQUES FOR PEDESTRIAN PROTECTION; FEASIBILITY STUDY

to

DEPARTMENT OF TRANSPORTATION
NATIONAL HIGHWAY TRAFFIC
SAFETY ADMINISTRATION

from

BATTELLE
Columbus Laboratories

January 30, 1981

1.0 INTRODUCTION

Pedestrian involvements in impacts by automobiles annually result in approximately 8000 fatalities and 150,000 injuries in the United States. One of several broad thrusts undertaken by the National Highway Traffic Safety Administration (NHTSA) towards reducing this accident toll is that of assessing the feasibility of developing injury mitigating concepts for vehicle exterior structural design. As part of the immediate support for that research direction, this report documents the third of a related series of research projects conducted for the NHTSA by Battelle's Columbus Laboratories (BCL); the previous two have been described in References 1 and 2*.

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* Pritz, H. B., Weis, E. B., and Herridge, J. T., "Body-Vehicle Interaction: Experimental Study", US DOT/NHTSA Report DOT-HS-361-3-745 (March 1975).

Pritz, H. B., Hassler, C. R., and Weis, E. B., "Pedestrian Impact: Baseline and Preliminary Concepts Evaluation", US DOT/NHTSA Report DOT-HS-4-00961 (May 1978).

1.1 BACKGROUND

A perspective of Battelle's research for NHTSA in the area of pedestrian injury mitigation through vehicle design is provided by the block diagram shown in Figure 1. This simplified model depicts a step process to establish a data base which could serve as a key input in the development of a Federal Motor Vehicle Safety Standard (FMVSS) for pedestrian safety. Detailed considerations for the development of such an FMVSS are presented in Reference 3*.

In regard to the definition and analysis of the pedestrian safety problem, a detailed examination of data from NHTSA's Pedestrian Injury Causation Study (PICS) is contained in Reference 3. The essential results from that analysis with respect to nonfatal injuries (i.e., at injury severity ratings of $2 \leq \text{AIS} \leq 6$) are summarized in Table 1. Within the limitations of the data, two key conclusions are:

(1) Nonfatal pedestrian injuries are divided nearly equally between vehicle and nonvehicle (e.g., ground) contact causes.

(2) Non-minor injuries (i.e., $2 \leq \text{AIS} \leq 6$) sustained from contact with a vehicle front end at estimated speeds of $V \leq 25$ mph comprise a substantial segment of total pedestrian injuries and, therefore, should benefit significantly from potentially practicable countermeasures. Lower extremity contact with the bumper appears to be an appropriate initial focus for countermeasure effort.

In the area of countermeasure concepts screening and development, NHTSA's research program elements have resulted in:

(1) Development of a test methodology for studying the biomechanics of pedestrian-vehicle impact phenomena.

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* Daniel, S. Jr., Eppinger, R. H., and Cohen, D., "Considerations in the Development of a Pedestrian Safety Standard", Seventh International Technical Conference on Experimental Safety Vehicles, US DOT/NHTSA (June 1979) pp 724-738.

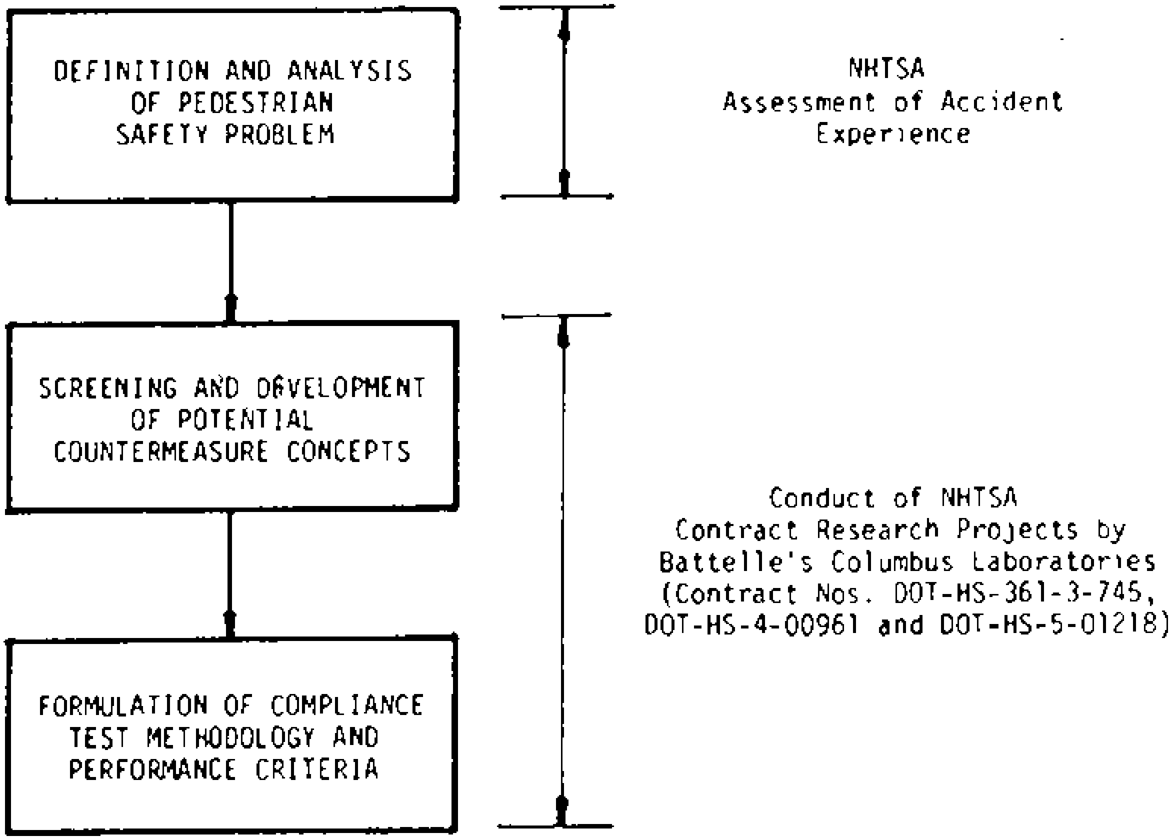

FIGURE 1. FLOWCHART OF NHTSA-SPONSORED PEDESTRIAN SAFETY RESEARCH AT BATTELLE

TABLE 1. DISTRIBUTION OF NONFATAL INJURIES TO PEDESTRIANS

Pedestrian Category (i.e., Adult/Child)	Injury Sustaining Anatomical Area	Sample Size		Percentage of Sample Involved in Injurious Contact With Designated Vehicle Component (see Note 2)							
		Partial Sample: $V \leq 25$ mph	Total Sample	Bumper	Grille	Hood Leading Edge	Hood Panel	Glazing	Roof	Underside	Non-Vehicle
Adult	Head	23	58	0/0	0/0	0/0	30/17	18/10	0/2	4/10	48/61
	Pelvis	16	25	0/0	25/24	38/32	6/4	-	-	32/36	0/4
	Lower Extremity	32	54	71/59	3/6	13/7	0/0	-	-	0/11	13/17
Child	Head	15	24	0/0	20/13	20/17	7/13	0/0	0/0	0/7	53/50
	Pelvis	0	1	0/0	0/0	0/0	0/0	-	-	100/0	0/0
	Lower Extremity	5	12	80/42	0/0	0/0	0/0	-	-	0/42	20/15
	Total	91	174								

NOTES:

1. The nonfatal injury range used here corresponds to $2 \leq \text{AIS} \leq 6$.
2. Tabular data are pairs of percentage values.
   Left value corresponds to partial sample (i.e., $V \leq 25$ mph);
   right value corresponds to total sample.

(2) Development of relationships between impact parameters and resultant pedestrian injuries.

(3) Establishment of impact tolerance levels for anatomical segments sustaining substantial proportions of non-minor injuries.

(4) Development of several potentially viable vehicle component design concepts for significantly reducing pedestrian injury severity.

The first three groups of results have been essential not only to the fourth group, which concerns countermeasure hardware conceptualization, but to the subsequent development of a compliance test methodology and performance criteria.

A necessary element of an FMVSS on pedestrian safety is a practical compliance test methodology and associated performance criteria. The development of such a methodology is the central subject of the present documentary report.

As indicated above, Battelle has performed three contract research projects for the NHTSA. In chronological order they are:

(1) Contract No. DOT-HS-361-3-745, "Body-Vehicle Interaction: Experimental Study", which is documented in Reference 1.

(2) Contract No. DOT-HS-4-00961, "Pedestrian Impact: Baseline and Preliminary Concepts Evaluation", which is documented in Reference 2.

(3) Contract No. DOT-HS-5-01218, "Compliance Techniques for Pedestrian Protection: Feasibility Study", which is documented in this report.

For ease of reference in this report, these three projects will be identified as PED I, PED II and PED III, respectively.

A broad overview of the progression of research goals and activities embodied in these three projects is presented in Table 2, which summarizes objectives, types of experiments performed and the nature of the results obtained. Some of the essential points of achievement from Table 2 are:

(1) A data base formed during the course of all three projects which characterizes the responses of various generic pedestrian surrogates to impacts with a vehicle

TABLE 2. OVERVIEW OF NHTSA/BATTELLE EXPERIMENTAL RESEARCH PROJECTS ON PEDESTRIAN SAFETY

Battelle Study	Objectives	Experiments	Results	Results Publ. in Ref.(s)
Ped I	• Establish preliminary impact tolerance levels of legs and abdomen of pedestrian struck by automobile • Explore capabilities of geometric and mechanical compliance modifications to vehicle impact surfaces to increase tolerance levels of impact velocities	• 15 Sled tests of stylized vehicle front ends impacting anatomic specimens at velocities in the range of 10-30 mph	• Useful test technique • Exploratory human tolerance data over speed range • Indication of injury sensitivity to selected vehicle design parameters	1,4,5
Ped II	• Assess injury reduction potential of selected vehicle configurations	• 90 Sled impacts of production and conceptual vehicle front ends on anatomic specimens and anthropomorphic dummies at velocities in the range 8-30 mph (emphasis on 20-25 mph range)	• Expansion of data base on human tolerance data • Acquisition of anthropomorphic dummy performance data • Indication of performance gains available from energy absorbing vehicle front end concepts	2,6
Ped III	• Devise compliance test methodology and criteria for pedestrian injury mitigation potential of vehicle front end • Produce and evaluate compliance test apparatus • Demonstrate application of compliance test methodology to vehicle design for pedestrian injury mitigation	• 8 Sled impacts of production and modified vehicle front end on anthropomorphic dummy at 25 mph • 10 Sled impacts of Calspan RSV front end modifications on anthropomorphic dummy at 25 mph • Pneumatic impactor tests of selected vehicle front end materials and configurations	• Prototype pneumatic impactor for compliance testing • Demonstration of application of compliance apparatus and methodology to modification of production vehicle front end to achieve significant injury mitigation potential • Expansion of data base on anthropomorphic dummy performance • Velocity and temperature sensitivity data for modified front end • Low speed damageability data for modified front end	7,8,9

vehicle front end. The surrogates include (a) whole cadaveric specimens, (b) both child and adult models of anthropomorphic dummies, and (c) a stylized body form for use with a special pedestrian impactor. Extensive electronic and photographic instrumentation has been used to document the impact dynamics. The responses include dynamic motion (e.g., acceleration), HIC values, judgments of injury severity, and estimated permanent disability.

(2) Initial identification of lower body impact tolerances for the pedestrian/vehicle mode of accident.

(3) Establishment (via various experiments) that there is considerable promise that experimental vehicle front end concepts (e.g., stylized forms developed during PED II, production vehicle modifications evaluated during PED III, and Research Safety Vehicle (RSV) designs evaluated during both PED II and III) represent feasible paths for developing practical pedestrian-compatible front-end configurations.

(4) The development of simplified test apparatus and methodology during PED III which should provide a reasonable compliance test approach for vehicle front end performance in key selected types of pedestrian/vehicle impacts. The subject equipment and technique affords a simple and economical means for measuring pedestrian safety performance during the development cycle as well as evaluation for regulatory compliance.

As noted in Table 2, these accomplishments have been described in several conference papers as well as the contract final reports.

1.2 OBJECTIVES AND SCOPE

To complete the introductory section, the discussion is now focused upon the particular contract documented by this report, namely DOT-HS-5-01218, or PED III. For completeness, the objectives are restated and the scope of effort is delineated.

The basic objectives of the present study were to:

(1) Devise a compliance test methodology and criteria for the incorporation of potential injury mitigating modifications into the front end of motor vehicles.

(2) Design, fabricate, and test a candidate compliance test device (or set of devices).

(3) Demonstrate that the resulting methodology and test requirements do generate structures, which are consistent with the intent of the proposed compliance techniques and criteria.

These objectives were addressed through a scope of effort delineated by the set of tasks identified in Table 3.

As footnoted in Table 3, the logical flow of tasks was interrupted by a moratorium on whole anatomic specimen experimentation. Consequently, elements of the research strategy calling for "before and after" sets of experiments with anatomic specimens implied by the sequence of Tasks 3 through 5 were not fulfilled during the present contract. However, data from the previous Battelle studies did provide guidance on desirable performance levels to be met by a vehicle front end and established the meaningfulness of tests conducted with the NHTSA/Battelle pedestrian dummy. Thus, the design, fabrication and compliance testing of a modified production vehicle were carried out in Tasks 4 and 5 using anthropomorphic dummies. Besides pedestrian safety performance evaluations, additional tests were conducted to gain insight into the Part 581 and actual car-to-car collisions damageability performance of the modified front end.

TABLE 3. TASK LISTING FOR NHTSA CONTRACT NO. HS-5-01218

Task 1 - Development of detailed plan of work

Task 2 - Development of criteria, methodology and testing device

Task 3 - Evaluation of production vehicle performance in whole anatomic specimen experiments(a)

Task 4 - Development of production vehicle modification

Task 5 - Experimental evaluation of modified vehicles

- Whole anatomic specimen experiments(a)
- Compliance test device experiments
- Vehicle damageability tests(b)
  (1) Part 581 barrier and pendulum impacts
  (2) Car-to-car collisions

Task 6 - Analysis of results

Task 7 - Experimental evaluation of Calspan RSV with compliance testing device(b)

Task 8 - Experimental evaluation of Calspan RSV with anthropomorphic dummies(b)

(a) As a result of a general moratorium on whole anatomic specimen testing imposed in November 1977, this set of experiments was stopped after the conduct of a single pre-moratorium test.

(b) Tasks not included in the original scope of effort; see text.

2.0 EXPERIMENTAL EQUIPMENT AND PROCEDURES

Three categories of experimental equipment and their associated procedures were employed during the present study: (1) prototypical pedestrian safety performance compliance test apparatus; (2) impulsively accelerated sled type equipment; and (3) vehicle damageability test facilities. Although the development of the compliance test equipment was a key task of the study, important complementary data were obtained using well established facilities such as a HYGE impulse sled and pendulum type impactor.

2.1 DEVELOPMENT OF COMPLIANCE TEST APPARATUS AND METHODOLOGY

Results obtained from Battelle's preceding research program for NHTSA (i.e., Contract No. DOT-HS-361-3-745, "Body-Vehicle Interaction Experimental Study") provided evidence that trauma and resulting disability could be related to an experimentally measurable quantity such as acceleration resulting from vehicle impact on the affected anatomical segment. Consequently, NHTSA's Request for Proposal (RFP) scoping the present study sought to use this evidence as a basis for developing a dynamic testing device especially suited to compliance work. Six initial requirements of the desired device and its methodology were itemized in the RFP.

(1) Demonstrate results consistent with the previous tests conducted by Battelle and tests to be conducted under another task*
(2) Demonstrate repeatability of output under similar conditions
(3) Be of minimum mechanical complexity
(4) Be maneuverable and easily positioned in front of a test vehicle
(5) Require a minimum of instrumentation and be easily calibrated
(6) Be insensitive to environmental factors such as temperature and humidity.

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* Task 5; see Table 3.

In its proposal response, Battelle's conceptualization efforts were reasoned along the following lines. In attempting to envision a pedestrian impact compliance methodology and test device, it would have been possible to consider the spectrum from simple pendulum type devices capable of localized impact to complete simulations of the total collision sequence. If the event is to be totally simulated in a fashion patterned after the occupant protection standard (FMVSS 208), all of the interacting dynamic impact events would need to be reproduced. Such a methodology would be quite complex and would probably require the development and validation of more sophisticated pedestrian anthropomorphic dummies. It was anticipated that (1) such an approach would be quite complex and expensive to execute and (2) that simpler criteria and methodology could be developed that would adequately address the intent of an initial pedestrian impact safety standard.

Battelle originally considered pursuing the development of two distinct dynamic test devices: (1) a device for evaluating the initial impact involving the pedestrian and the leading edges of the bumper, hood and/or fenders and (2) another device for evaluating the impact of the pedestrian with the upper surfaces of the hood, fender, glazing, and/or windshield header. A suggested initial consideration for the first device was to (1) utilize a body block, which represents the legs and/or pelvic region of a pedestrian (similar to the body block specified in SAE Recommended Practice J944a for testing steering wheel and column assemblies), and (2) propel this body form by means of an accelerator device (e.g., a bungee cord launcher or a commercially available pneumatic velocity generator) into the stationary front of the test vehicle. Another alternative included the use of complete anthropomorphic dummies and the use of a driving or towing system (such as used with an SAE J850 type barrier facility) to propel the vehicle into the pedestrian surrogate at speeds up to approximately 30 mph. While this more complex approach should provide representative ground reactions and pedestrian/vehicle dynamics, it was tentatively rejected in favor of the more repeatable, straightforward, and less expensive approaches.

For the second type of simplified approach identified, the leading configuration suggested comprised a head form (similar to that specified in SAE J984 for use in impact tests of instrument panels in accordance with SAE J921a) mounted on the end of an accelerated pivoting arm which could be readily positioned to provide localized impact at any selected area on the vehicle hood, fenders, glazing or windshield header.

For both of the simplified devices initially considered, it was planned that the dynamic response of the body form would provide a measure of impact tolerance at the test velocity. It was also planned that it would be possible to monitor the rebound velocity of the body form to gain insight into the amount of undesirable stored impact energy available to propel the struck pedestrian away from the vehicle after the "first impact" event.

2.1.1 Selection of Approach to Test Apparatus

Two basic issues were crucial to the selection of an approach to the design of a compliance test apparatus: (1) the configurational representation of both the pedestrian and the vehicle, and (2) the method of generating the relative velocity between the colliding masses prior to impact. The first issue concerned the choice of whole or partial representation of the pedestrian and/or the vehicle. The second issue dealt with a controllable and repeatable method of velocity generation.

A matrix of possibilities for the above issues is shown in Table 4. From a regulatory viewpoint, whole vehicle representation is the most logical choice for a test article. From a vehicle design development standpoint, the matrix column labelled "Partial Vehicle" is also of interest. That column could be further subdivided into "Whole Front-End Assembly" and "Partial Front-End Assembly". The latter subcategory would allow screening of materials and geometric configurations at a convenient and economical scale.

As noted earlier, those techniques involving a moving vehicle were judged more complicated, expensive and perhaps less repeatable than necessary for initial pedestrian compliance testing. Thus, development efforts were directed toward techniques that would involve the acceleration of a pedestrian

TABLE 4. BASIC POSSIBILITIES FOR COMPLIANCE TEST APPARATUS

Pedestrian Representation	Vehicle Representation and Motion Combination	
	Whole Vehicle	Partial Vehicle
Whole Body	Moving Body/Stationary Vehicle Stationary Body/Moving Vehicle	Moving Body/Stationary Vehicle Stationary Body/Moving Vehicle
Body Segment	Moving Body/Stationary Vehicle Stationary Body/Moving Vehicle	Moving Body/Stationary Vehicle Stationary Body/Moving Vehicle

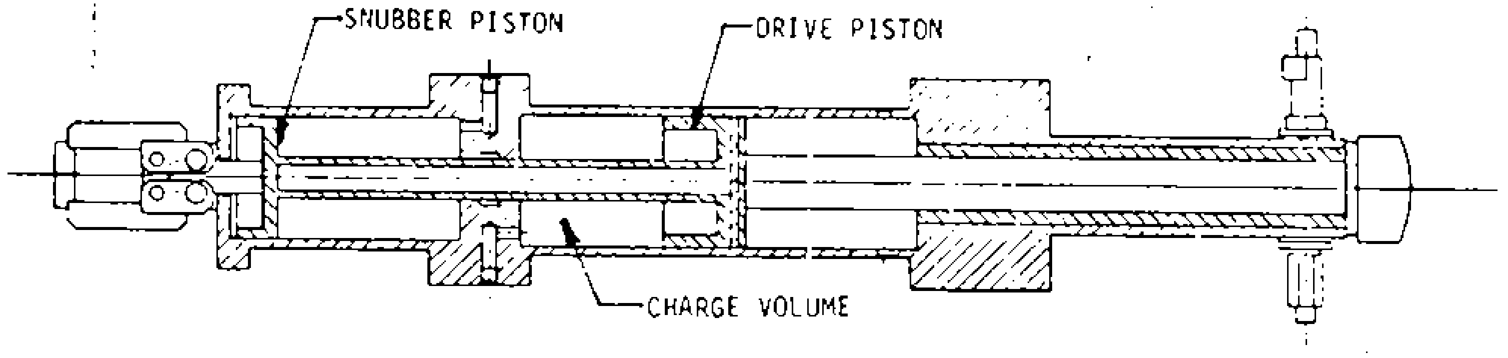
representation into a stationary vehicle representation. It became apparent that a major tradeoff would be required in choosing to accelerate a whole body versus a body segment. Larger test device and higher stored energy levels necessary to accelerate a whole body could be traded off for a considerably smaller, lower energy, more repeatable body segment approach in exchange for (1) the theoretical problem of determining an appropriate size and mass for the body segment and (2) the necessity for a compliance test battery employing several body segment forms (e.g., leg, pelvis, and head). This tradeoff to a body segment approach was made, and a segment velocity generator was designed and built. The resulting device has been identified as a "pneumatic impactor", and is described in the following Subsection 2.1.2. The development of a body form, or "striker", is detailed in Subsection 2.1.3.

2.1.2 Description of NHTSA/Battelle Pneumatic Impactor

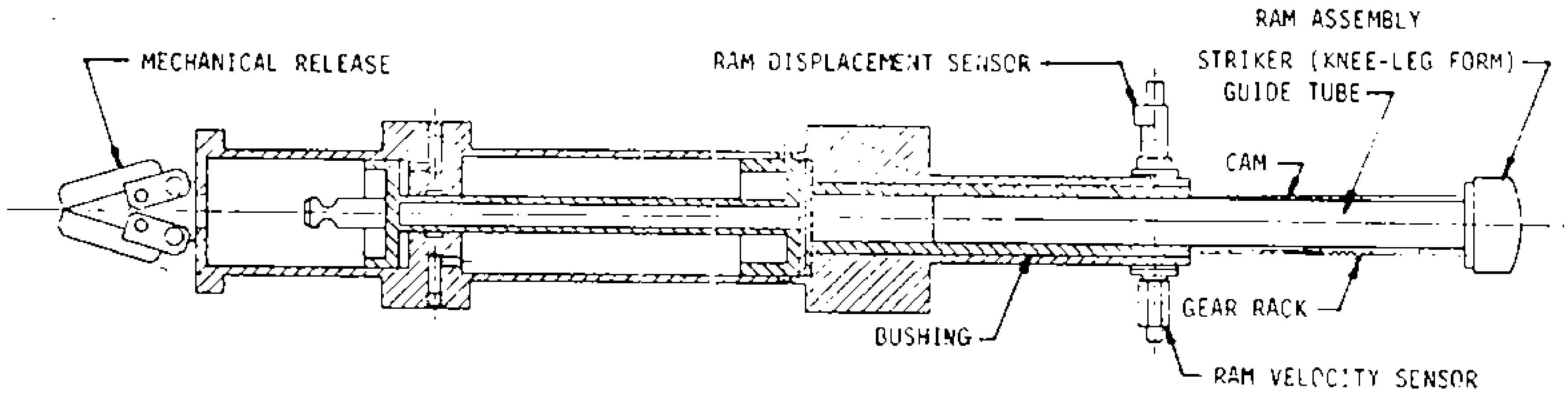
As developed in the present study, a complete system for compliance testing consists of four major subsystems: (1) the pneumatic impactor device itself, (2) a gas supply and control subsystem, (3) a data acquisition subsystem, and (4) a test article.

The basic features of the pneumatic impactor can be described with reference to the sketch in Figure 2 and the photograph in Figure 3. The outer cylindrical housing contains two moving assemblies: (1) a tandem piston assembly comprising a drive piston and a trailing snubber piston, and (2) a ram assembly consisting of a striker (i.e., a body segment form or simulator) and a guide tube. The outer housing is trunnion mounted on a frame that allows vertical positioning by a fork lift. Such an arrangement allows a 90-degree range of angular positioning of the impactor, as indicated in Figure 4.

With regard to test articles, the previously mentioned fork lift mobility of the pneumatic impactor could readily accommodate evaluation of a whole vehicle. For partial vehicle testing, in particular a bumper assembly or a sample of energy absorbing material, it was found more convenient to mount the article on a test fixture such as shown in Figure 5. The test fixture was designed with considerable rigidity (without resorting to a massive concrete block) to minimize masking effects of fixture flexibility on impact test data.



(A) INITIAL POSITION OF PISTON AND RAM ASSEMBLIES



(B) AFTER PISTON ASSEMBLY RELEASE

FIGURE 2. OPERATING FEATURES OF PNEUMATIC IMPACTOR

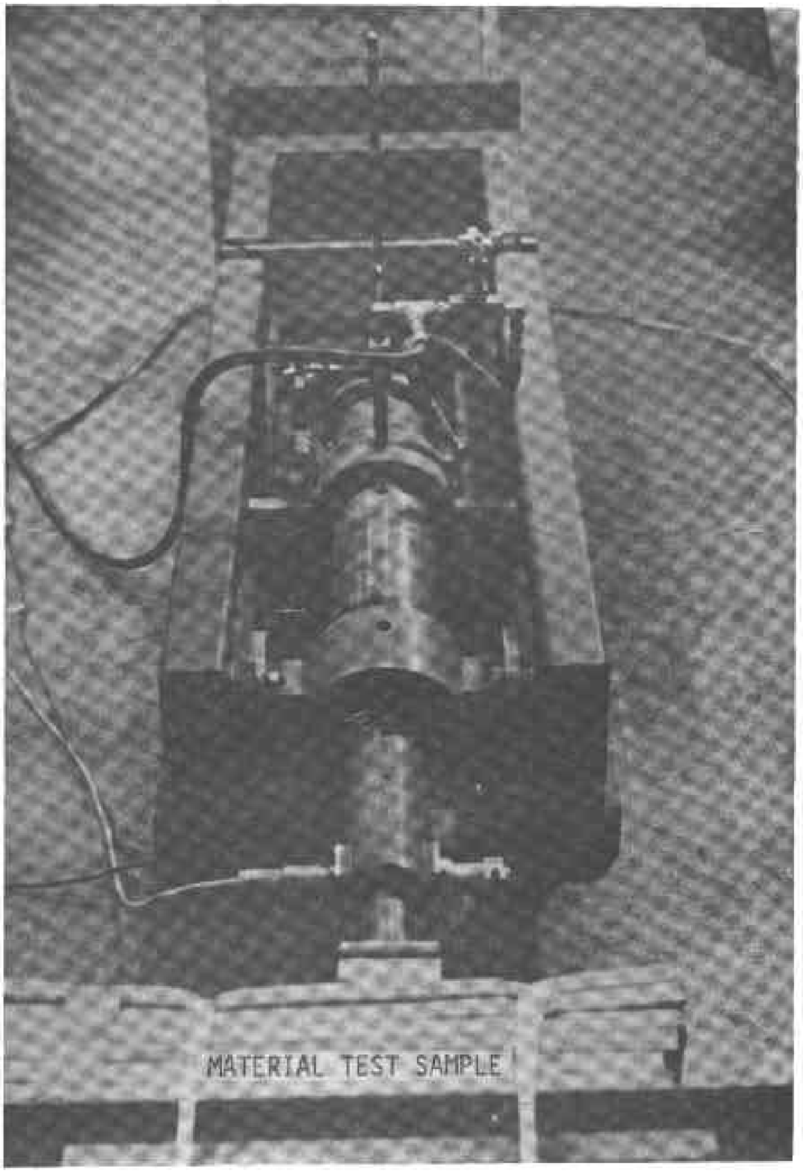


FIGURE 3. PHOTOGRAPH OF PNEUMATIC IMPACTOR

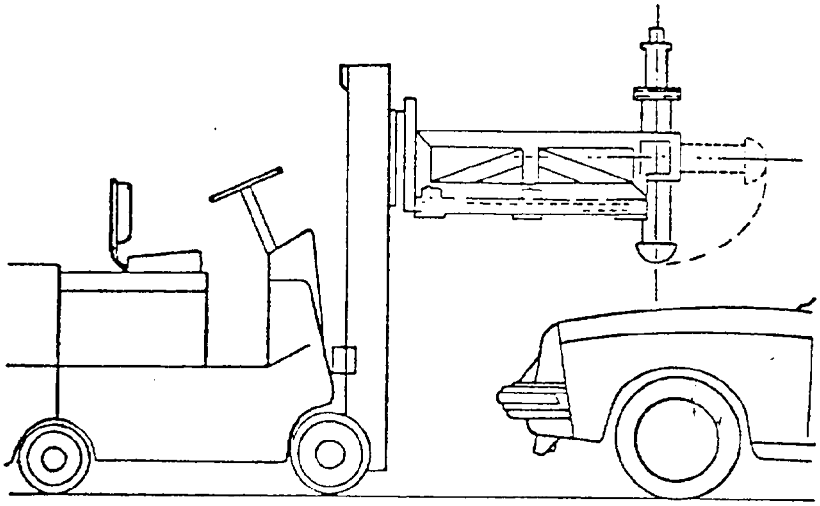


Illustration of application to hood impact

FIGURE 4. CAPABILITY OF PNEUMATIC
IMPACTOR ELEVATED BY FORKLIFT

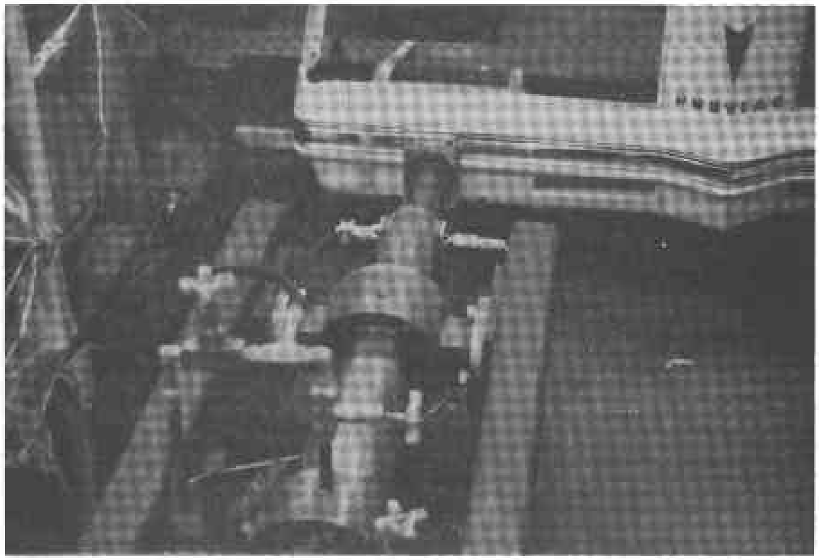


FIGURE 5. PARTIAL VEHICLE TEST ARTICLE
MOUNTED ON FIXTURE

The gas source and control subsystem schematic is shown in Figure 6. The corresponding operational procedure is summarized in Table 5. Briefly, the operational cycle is described as follows. Dry nitrogen is used to charge the driver gas volume behind the drive piston, when the front face of the drive piston is initially in contact with the trailing edge of the guide tube. Actuation of the mechanical release results in acceleration of the piston and ram assemblies. The piston assembly is decelerated by the snubber piston compression of a trapped volume of air; consequently, the ram assembly continues an essentially "constant velocity-free flight" until the striker impacts a test item.

Basic data acquisition consists of: (1) transducers for independent sensing of ram displacement, velocity and acceleration, (2) signal conditioning equipment, and (3) recording equipment. The ram displacement is measured by a stationary linear variable differential transformer (LVDT), which senses the height of a linearly tapered cam attached to the guide tube of the ram assembly. Ram velocity is measured by a stationary magnetic pickup, which senses the passage of rack gear teeth (also attached to the guide tube) as a pulse frequency. Ram acceleration is measured by a uniaxial variable capacitance accelerometer, which is fastened directly to the mounting plate of the striker.

Signal conditioning is provided by an amplifier-filtering circuit. In the case of velocity sensing the pulse frequency must first be converted to an analog voltage. Two-point calibration of the ram displacement sensor is readily provided by selection of two physically measurable positions of the ram (fully retracted is one; fully extended can be another, although it is often more convenient to use the test sample impact point). Single point, preset, calibration signals for velocity (20 mph) and acceleration (100 g) are provided with the circuitry.

Recording is accomplished on a direct-writing oscillograph, which is matched to the signal conditioning equipment by a tailored galvanometer driver circuit.

Salient features of the data acquisition system are summarized in Table 6.

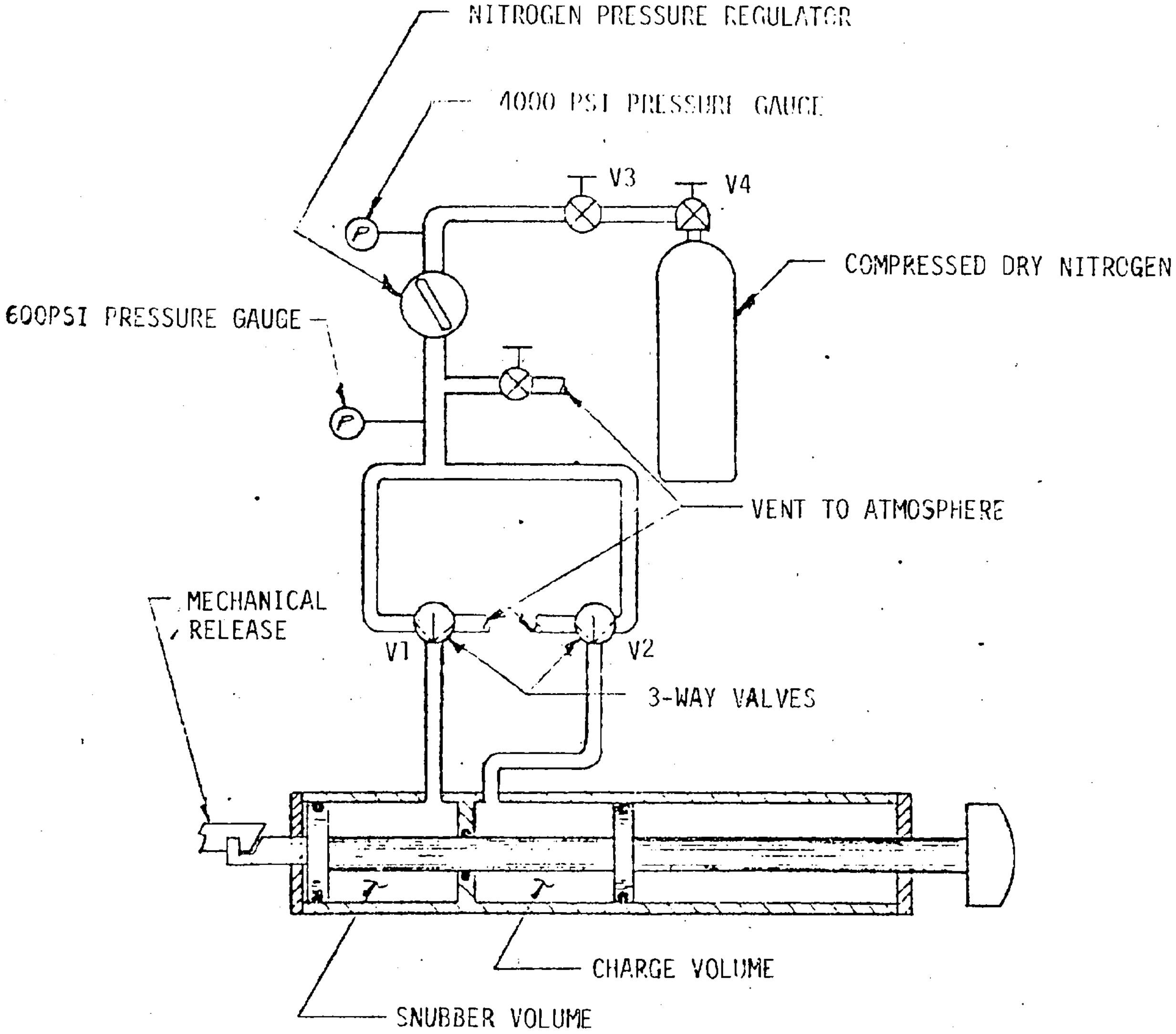


FIGURE 6. GAS SUPPLY AND CONTROL SUBSYSTEM FOR PNEUMATIC IMPACTOR

TABLE 5. OPERATING PROCEDURE FOR NHTSA/BCL PNEUMATIC IMPACTOR

(1) Close pressure regulator Valve A (i.e., set to 0 psi).

(2) Open Valve 3 slightly and Valve 4 fully. Valve 3 serves as a safety metering valve to control the gas flow from the supply tank.

(3) Set Valve 1 to the fully closed position (i.e., all three lines isolated).

(4) Set Valve 2 so that exhaust opening is closed but the other two lines are connected.

(5) Set pressure regulator Valve A to the desired pressure. This will pressurize the charge volume. A particular set pressure in the charge volume corresponds to a particular ram velocity with a given striker mass.

(6) Actuate mechanical release to launch the ram.

(7) To return the ram to its original position, set Valve 2 to open the charge volume to atmosphere; set Valve 1 so that snubber volume will be pressurized. After ram has returned, drain excess pressurized gas in snubber volume to atmosphere.

(8) Relatch mechanical release.

Always observe the following safety precautions:

(1) Remain clear of ram whenever charge volume is pressurized.

(2) Close Valves 3 and 4 and bleed gas pressure from system before working on ram or after testing is complete.

TABLE 6. DATA ACQUISITION SYSTEM FOR PNEUMATIC IMPACTOR EXPERIMENTS

Striker Parameter	Sensor and Sensed Variable	Oscillograph Galvanometer Frequency, kHz
Displacement	Linear variable differential transformer (Trans Tek Model 241-000) and proximity of linear cam (ramp)	1 (Channel Class 600)
Speed	Magnetic pickup (Airpax Model 4-0002) and linear gear tooth position	1 (Channel Class 600)
Acceleration	Variable capacitance accelerometer (Setra Systems Model 114) and seismic disc motion	1 (Channel Class 600)

Note: Signal conditioning and galvanometer driver circuit are tailored for the specific equipment used. The present filtering results in a frequency response of 3 db, down, at 150 Hz.

See Society of Automotive Engineers Standard J211B for channel classification.

2.1.3 Development of Test Procedures

Development of procedures for the use of the pneumatic impactor in compliance testing necessarily involved two considerations: (1) selection of a striker (i.e., a representation of a body segment) and (2) selection of impact locations on the test article. From a review of the kinematic behavior of pedestrian surrogates reported in previous Battelle studies, it was clear that the major involvements of pedestrian anatomy depended upon pedestrian stature (discriminating only the size difference between an adult and child) and vehicle front end configuration.

Predominant combinations of interest are shown in Table 7. The observations for the adult are entirely consistent with the accident data previously given in Table 1. However, an apparent discrepancy in body segment contact with hood leading edge and hood panel for the child (e.g., accident data indicate significant head contact with the hood leading edge, whereas, 6-year-old child dummy kinematics observed in Battelle tests suggest thorax involvement with the hood leading edge). This discrepancy has not been satisfactorily resolved, owing to the absence of kinematic data for the child at the cadaveric surrogate level to validate or upgrade the kinematic performance of the child anthropomorphic dummy.

During the present program, exploratory trials using the pneumatic impactor were conducted with a variety of body form concepts to represent the adult knee/leg area, pelvis/upper leg area and head. The development highlights are summarized in Table 8. By mutual agreement, the main thrust of the Battelle development efforts to date have been concentrated upon using an empirical approach to devise and develop the striker configuration for the adult knee/leg anatomical segment.

The basic approach used was to seek a match with the deceleration waveforms observed in the test series involving cadaveric specimens conducted in the previous Battelle projects. In particular, it was sought to match the peak deceleration and the rise time to that peak. Given the velocity generation and piston stroke capability of the pneumatic impactor, the principal variables available for manipulation were striker shape, size and

TABLE 7. DOMINANT INVOLVEMENTS OF PEDESTRIAN ANATOMY AND VEHICLE FRONT END AREA

Pedestrian	Vehicle Area Bumper	 Hood/Fender Leading Edge	 Hood/Fender/Glazing
Adult	Knee/Lower Leg	Pelvis	Head
Child	Pelvis/Upper Leg	Thorax	Head

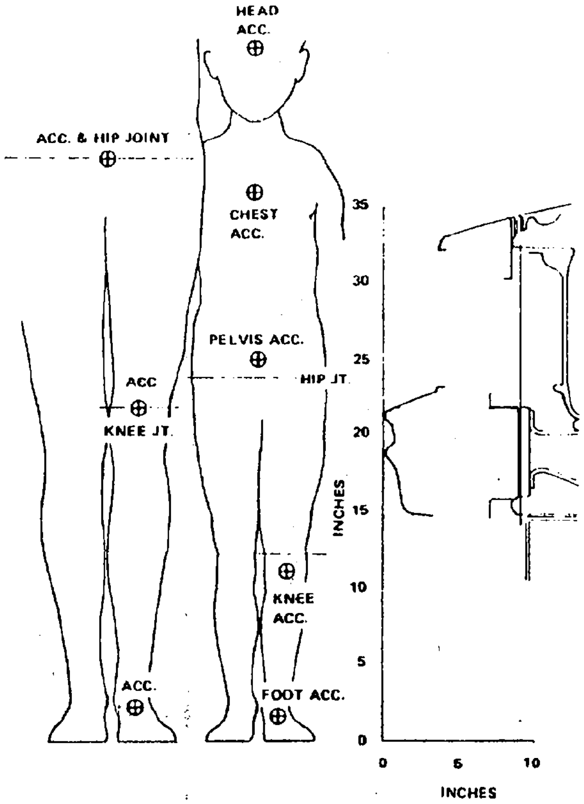


TABLE 8. SUMMARY OF EXPLORATORY STRIKER CONFIGURATIONS USED WITH PNEUMATIC IMPACTOR

Body Form	Configuration	Striker Description
Knee-leg	1	● 1-in. thick Ensolite foam layer 2-in. radius x 5-in. long wooden cylinder 2-in. thick x 4-in. x 4-in. aluminum honeycomb
	2	● 3.5-in. x 5.0-in. area layers: - 2-in. thick Ensolite AIV foam layer - 2-in. thick wood slab - 2-in. thick aluminum honeycomb
	3	● 4-in. x 6-in. frontal area - 2.5-in. thick x 8-in. radius of curvature wood block - 4-in. thick floral styrafoam - 0.375-in. thick steel ballast plate
	4	● Like configuration 3, except styrafoam omitted
Pelvis-leg	5	● 6-in. x 8-in. frontal area - 1.5-in. thick x 8-in. radius of curvature wood block - Steel ballast plate
Head	6	● Front half of Part 572 anthropomorphic dummy head

materials and the total mass of the ram assembly (i.e., striker and guide tube). After considerable experimentation, a striker configuration (Configuration 1 in Table 8) was found that would produce a response much like the initial part of the waveform observed for rigid bumper impacts upon the knee area of cadaveric specimens. This configuration was subsequently modified into Configuration 2 after additional tests with both rigid and soft bumper configurations. Efforts to obtain further simplification of the striker resulted in Configuration 3. Eventually, Configuration 4, shown in Figure 7, was adopted as a tentative "standard configuration" for soft bumper experiments, because it was discovered that the styrafoam layer was only needed as a mechanical fuse device when unacceptably hard surfaces were being evaluated. Initial waveform data (peak force and rise time) generated by a developmental striker configuration for the knee-leg body form are compared in Figure 8 with data obtained in Ped I experiments with cadaveric specimens.

A parallel analysis of Battelle data conducted by NHTSA indicated that the weight of the equivalent mass for the knee-leg segment should be approximately 7 lb, a value remarkably close to the experimentally derived 7.25 lb. This analytical development is documented in Reference 8*; it was based upon a sinusoidal waveform approximation to the experimental deceleration-time histories and the use of the impulse-momentum theorem of mechanics. Since that time, NHTSA has continued efforts to generalize the procedure (e.g., removing the assumption of a sinusoidal deceleration waveform and normalizing the peak deceleration and associated injury severity to total body weight. This analytical approach still indicates the appropriate mass is about 6.4 lb.

Because the initial application of the pedestrian pneumatic impactor is for knee-leg compliance test usage, there are three basic aspects of test procedure that must be addressed: (1) impact location on the bumper; (2) criterion for compliance; (3) repeatability of the technique. The test apparatus, in its present configuration, is conceived to apply its stroke parallel to the vehicle centerline and at any lateral location on the bumper. If the local orientation of the bumper face is such as to produce a substantial rake angle (i.e., so that the bumper surface is not normal to the vehicle centerline

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* Eppinger, R. H., and Pritz, H. B., "Development of a Simplified Vehicle Performance Requirement for Pedestrian Injury Mitigation", Seventh International Technical Conference on Experimental Safety Vehicles, US DOT/NHTSA (June 1979) pp 713-724.

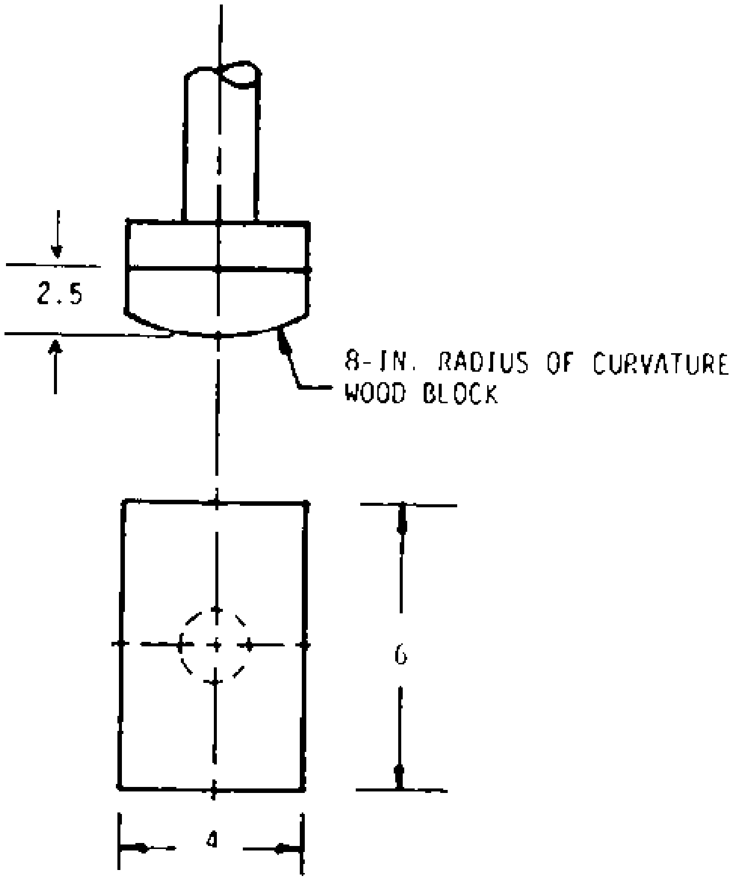


FIGURE 7. "TENTATIVE STANDARD" KNEE-LEG FORM STRIKER FOR USE WITH PNEUMATIC IMPACTOR

Notes:

1. Ratios are striker-to-cadaveric response.
2. Open symbols denote rigid bumper; filled symbols denote soft bumper
3. Cadaveric response data from Ped I; pneumatic impactor striker data from Ped III. See Table 2 of Reference 8.

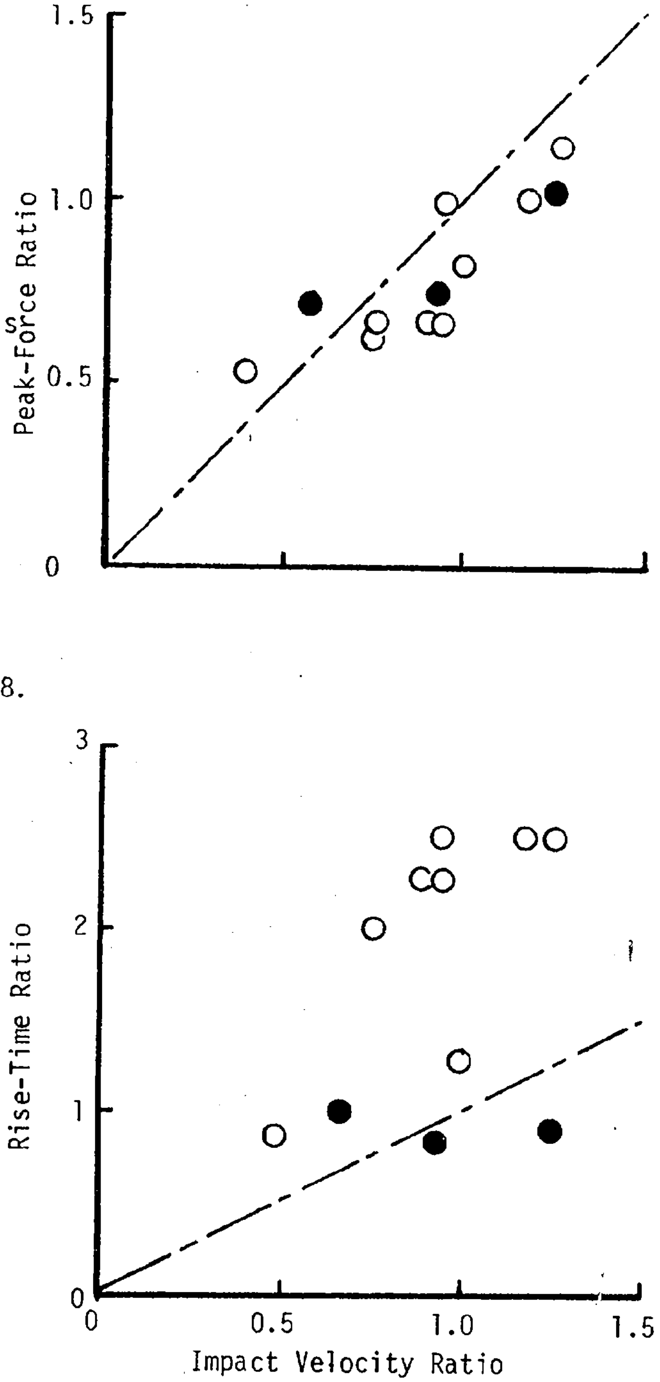


FIGURE 8. COMPARISON OF PNEUMATIC IMPACTOR STRIKER WITH CADAVERIC KNEE-LEG RESPONSES OBTAINED FROM SLED TESTS

and therefore the stroke of the impactor), it may be desirable to impact the surface in a perpendicular direction with a corrected velocity of $V/\cos\theta$, where θ is the angle of the impactor stroke with respect to vehicle centerline.

In regard to an appropriate criterion for compliance, the key concept focused upon relating the degree of impairment or disability associated with an impact injury with an observable experiment (e.g., acceleration). A regression analysis conducted on previous Battelle-generated experimental data involving cadaveric specimens indicated that indeed, independently adjudged disability could be correlated with peak deceleration of the knee-leg body segment. In Reference 8, a tentative criterion suggested by the data for significant injury mitigation for the adult knee-leg area was selected to be 100 g. This value has been used as a figure of merit for other experiments conducted during the present project.

The important subject of run-to-run repeatability has been addressed at various times throughout the present project. By run-to-run repeatability is meant the ability to repeat critical results for repeated application of a given set of inputs. Based upon the preceding discussion, the most critical result is peak deceleration of the striker. Less crucial but clearly a desirable confirming attribute is deceleration waveform (at least during the rise to peak deceleration). Satisfactory repeatability with the prototype impactor has been noted at Battelle on various occasions when test runs have been repeated. Also, a separate investigation by NHTSA's Vehicle Test and Research Laboratory on a second generation pneumatic impactor has indicated reasonable reproducibility between impactors.

2.2 SLED TEST FACILITIES AND PROCEDURES

2.2.1 Sled Test Facility and Equipment

The sled test facility used for this and previously reported Battelle projects on pedestrian safety is the 24-inch Hyge crash simulator located at The Transportation Research Center of Ohio (TRC). Photographs showing one of the test vehicles employed in the present project (the Calspan Phase IV Research Safety Vehicle) mounted on the sled are presented in Figure 9.

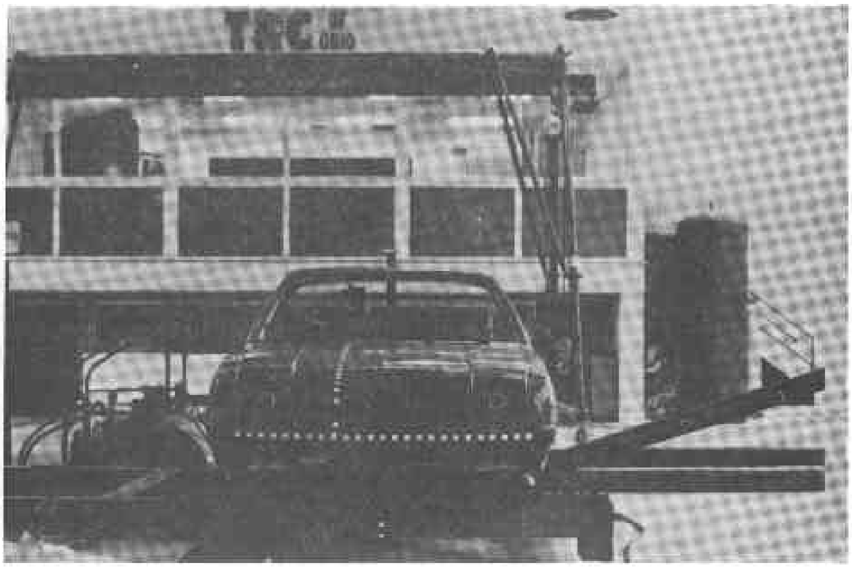
The pedestrian surrogates were instrumented with accelerometers as discussed in Subsection 2.2.2. Ground reaction forces were determined by an instrumented ground reaction platform. The sled is instrumented with an accelerometer to provide evidence that the sled-mounted test vehicle was at constant velocity prior to impact with the pedestrian surrogate. Sled velocity was obtained from an optical system.

All sensors were connected via cable to signal conditioning equipment. Outputs from the signal conditioners were either multiplexed or individually frequency modulated and recorded on magnetic tape recorders. During the test cycle, selected data channels were recorded on a direct writing oscillograph for "quick look" evaluation. The data acquisition system is shown in block diagram form in Figure 10.

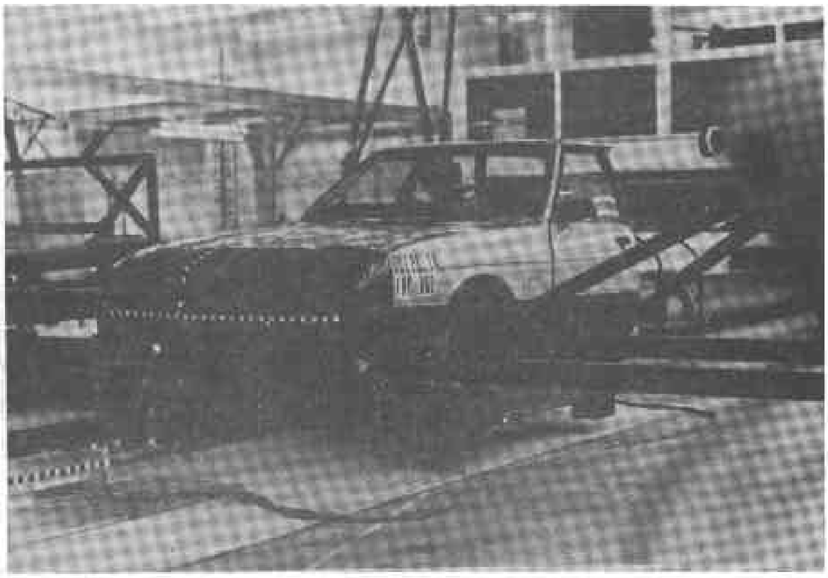
Experimental impacts were extensively photographed with high-speed cameras. Six cameras were located as follows: one onboard lateral viewing camera on each side of the test vehicle; one onboard frontal viewing (through the vehicle windshield) camera; and three offboard cameras (one overhead and one on each side of the sled track to provide oblique viewing. All cameras operated with 16-mm color film at 1000 frames per second. One millisecond long timing marks were recorded at 10 millisecond intervals on each film.

2.2.2 Anthropomorphic Dummies and Associated Instrumentation

Two anthropomorphic dummies were used as pedestrian surrogates during the present project: a 50th percentile adult male representation,



(A) FRONT VIEW



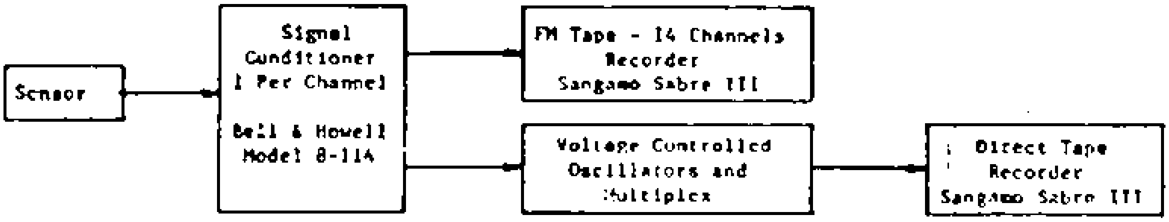
(B) FRONT QUARTER VIEW

FIGURE 9. PHOTOGRAPHS OF PARTIAL VEHICLE TEST BUCK INSTALLATION IN 24-INCH HYGE SLED FACILITY

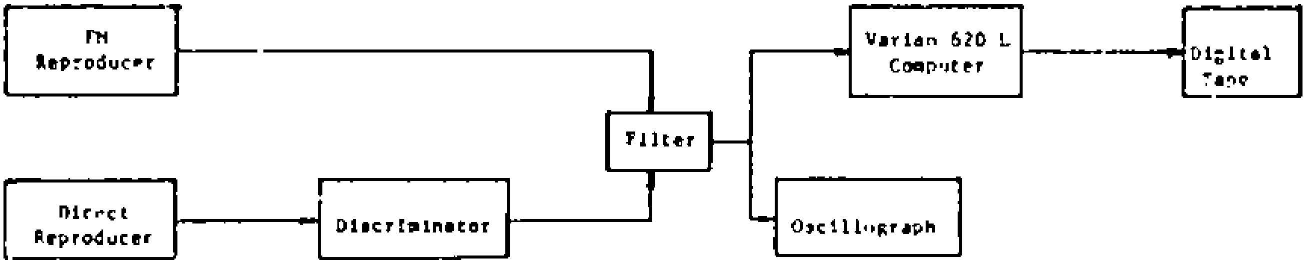
(C) REAR QUARTER VIEW

(D) REAR VIEW

FIGURE 9. (CONTINUED)



(A) DATA RECORDING SUBSYSTEM



(B) DATA REDUCTION SUBSYSTEM

FIGURE 10. DATA ACQUISITION SYSTEM FOR SLED EXPERIMENTS

and a 6-year-old child representation. The adult dummy is a specialized design based upon Part 572 dummy components and modified to include the following features.

(1) Head attitude adjusted for a walking/standing position by shimming at the base of the neck.

(2) Lower spine stiffened to maintain the upper body in an erect posture (stiffness is approximately twice that specified for the Part 572 spine).

(3) Pelvic thigh molding modified for compatibility with standing posture.

(4) Knees constructed of steel weldments to replace the more easily damaged aluminum castings and upper leg modified to provide representative lateral compliance.

(5) Ankles constructed to provide lateral rotation.

Standing capability and realistic lateral compliance of the legs were achieved in the following manner. Repeatable standing posture was assured with the use of very low resistance shear pins in each hip joint, fully extending the knees, and locking of the ankles. With the exception of the ankles, all joints were adjusted to 1 g torque resistance. The shear pins were just strong enough to maintain initial standing position and yet easily break upon impact. The shear pins also functioned to assure repeatable positioning of the hip joints. The child dummy did not require shear pins to maintain standing posture. As with the adult dummy, (1) the child dummy's knees were fully extended and (2) all joints were torqued for 1 g resistance, except for the ankles which were essentially locked. It should be noted that the ankles of the child dummy's ankles do not have lateral rotation capability.

For a given experiment, the dummy was positioned on a ground platform having a surface with a representative coefficient of friction and containing a built-in scale. The unloaded (right) leg was positioned off the scale. The dummy's ankles were adjusted until at least 80 percent of the weight was on the scale and a stable posture was achieved. The adult dummy was fitted with conventional rubber-soled shoes, and the child dummy was fitted with tennis shoes.

Realistic dynamic response in lateral impacts was achieved and damage to the knees and legs of the dummies was minimized by incorporating appropriate lateral compliance into each leg. This degree of mechanical compliance was simulated by inserting a short length of 1/2-inch diameter threaded rod directly below the knee of the adult dummy. This lateral compliance had been previously established by statically bending two cadaver legs in a lateral direction. Taking strain rate sensitivity into account, it has been concluded that the simulation was quite good. Because no data was located for establishing the lateral compliance of the child dummy's legs, the femur load link of the child dummy was replaced with a short section of the same threaded rod as used in the adult dummy.

Instrumentation for the dummies consisted of triaxial accelerometers installed in the foot, knee and pelvis. Separate uniaxial accelerometers were assembled in the chest and head. Key instrumentation and scaling information is summarized in Table 9.

2.2.3 Sled Test Procedures

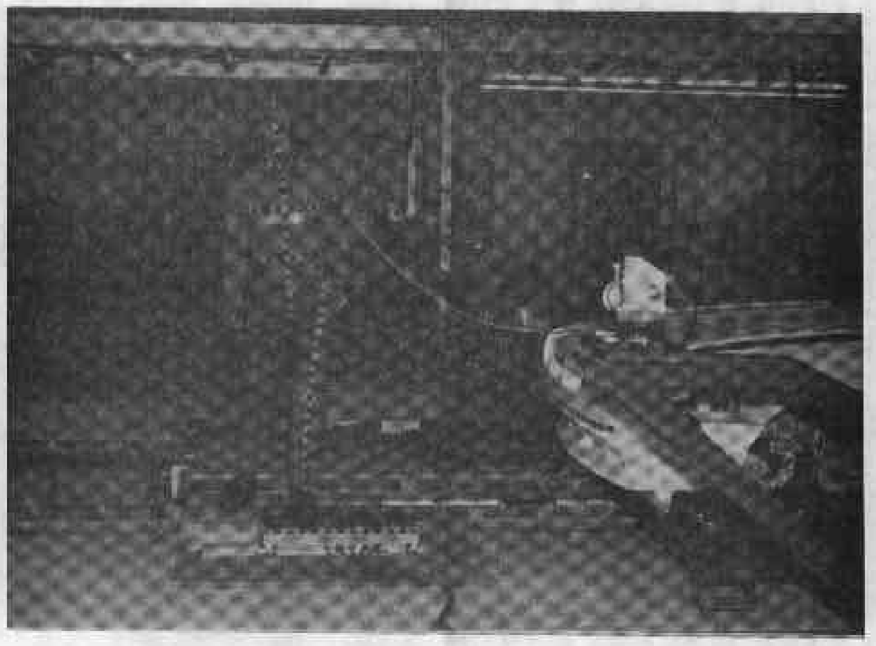
The pedestrian surrogates (all surrogates used were dummies with the exception of one Task 3 test involving a cadaveric specimen) were positioned in the desired stance 4 feet in front of the vehicle as illustrated in Figure 11. Upon firing the Hyge impulse tube, the sled rapidly accelerated to the desired impact speed in the 4-ft distance between the test vehicle and the dummy, traveled at constant speed during the collision event, and finally decelerated to a stop at a preselected braking rate (0.5 g).

In terms of data acquisition, prerun procedure involved a continuity check of data channels, electrical balancing, and calibration by shunt resistor insertion. Postrun procedure for "quick look" involved playback of calibration levels and test run data from the tape recorders, filtering and re-recording on a direct writing oscillograph. For digital data reduction, the procedure was repeated and the filtered data was sampled by an analog-to-digital converter under the control of a minicomputer (Varian 620L/100). Each data channel for the dummy head was sampled at a rate of 8,000 samples per second. All other data channels were sampled at 4,000 samples per second.

TABLE 9. ACCELEROMETER ASSIGNMENTS FOR PEDESTRIAN DUMMIES

Pedestrian Dummy Anthropomorphic Region	Accelerometer			
	Coordinate Axis Orientation	Full-Scale Range, g	Digital Data Printout Mnemonic	
			Adult Dummy	Child Dummy
Head	X	400	HGX1	HGX2
	Y		HGY1	HGY2
	Z		HGZ1	HGZ2
	X		HX11	
	Z		XZ11	
	Y		HY21	
	Z		HZ21	
	X		HX31	
	Y		HY31	
Chest	X	400	CGX1	CGX2
	Y		CGY1	CGY2
	Z		CGZ1	CGZ2
Pelvis	X	400	PGX1	PGX2
	Y		PGY1	PGY2
	Z		PGZ1	PGY2
Knee (left)	X	700	KLX1	KLX2
	Y		KLY1	KLY2
	Z		KLZ1	KLZ2
Foot (left)	X	400	FLX1	FLX2
	Y		FLY1	FLY2
	Z		FLZ1	FLZ2

FIGURE 11. PHOTOGRAPHS ILLUSTRATING INITIAL POSITION OF ANTHROPOMORPHIC DUMMIES RELATIVE TO TEST VEHICLE



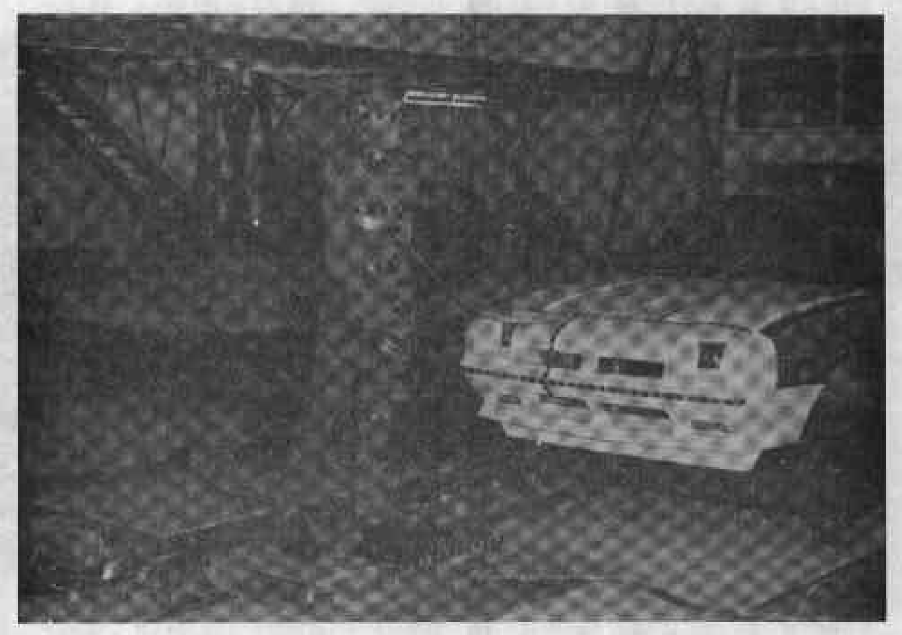


FIGURE 11. (CONTINUED)

The computer algorithm scaled the data consistent with the calibration values determined during sensor calibration. In addition to individual sensor outputs, calculations of appropriate resultants and severity indices were made. Computer generated plots of acceleration (individual and resultant) and severity indices vs. time and load vs. time for the ground reaction platform were produced. Additionally, tabular data for each of the data channels were provided. Following computer processing, the digital data was recorded on tape for permanent storage.

2.3 DAMAGEABILITY EXPERIMENTAL EQUIPMENT AND PROCEDURES

An experimental front end concept that shows promise of significant pedestrian injury mitigation should also be examined with regard to the requirements of existing regulations. One such consideration is compatibility of experimental bumpers with the provisions of Part 581.

In this section the experimental equipment and procedures used to test an experimental front end concept (mounted on a whole vehicle) in accordance with the pendulum impact and low-speed barrier impact test requirements of Part 581, are described. In addition, equipment and procedures for a related test (presently not a Part 581 requirement), viz., low-speed car-to-car impact, also are described.

2.3.1 Pendulum Impact Experimental Equipment and Procedures

The evaluation of an experimental front-end structure by means of FMVSR Part 581 pendulum impact procedure was conducted at the Davidson Rubber Company's test facility in Dover, New Hampshire. In addition to the conventional room temperature tests presently associated with Part 581, Davidson's capability for hot and cold environmental conditioning of the test vehicle front end was also utilized.

Davidson's linear impactor apparatus and environmental conditioning equpment are described in Reference 10* and are shown in Figure 12. The

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* Weller, P. A., and Scrivo, T. V., "Linear Impact Sled for Automotive Bumper Testing", SAE Paper 740063 (February 1974).

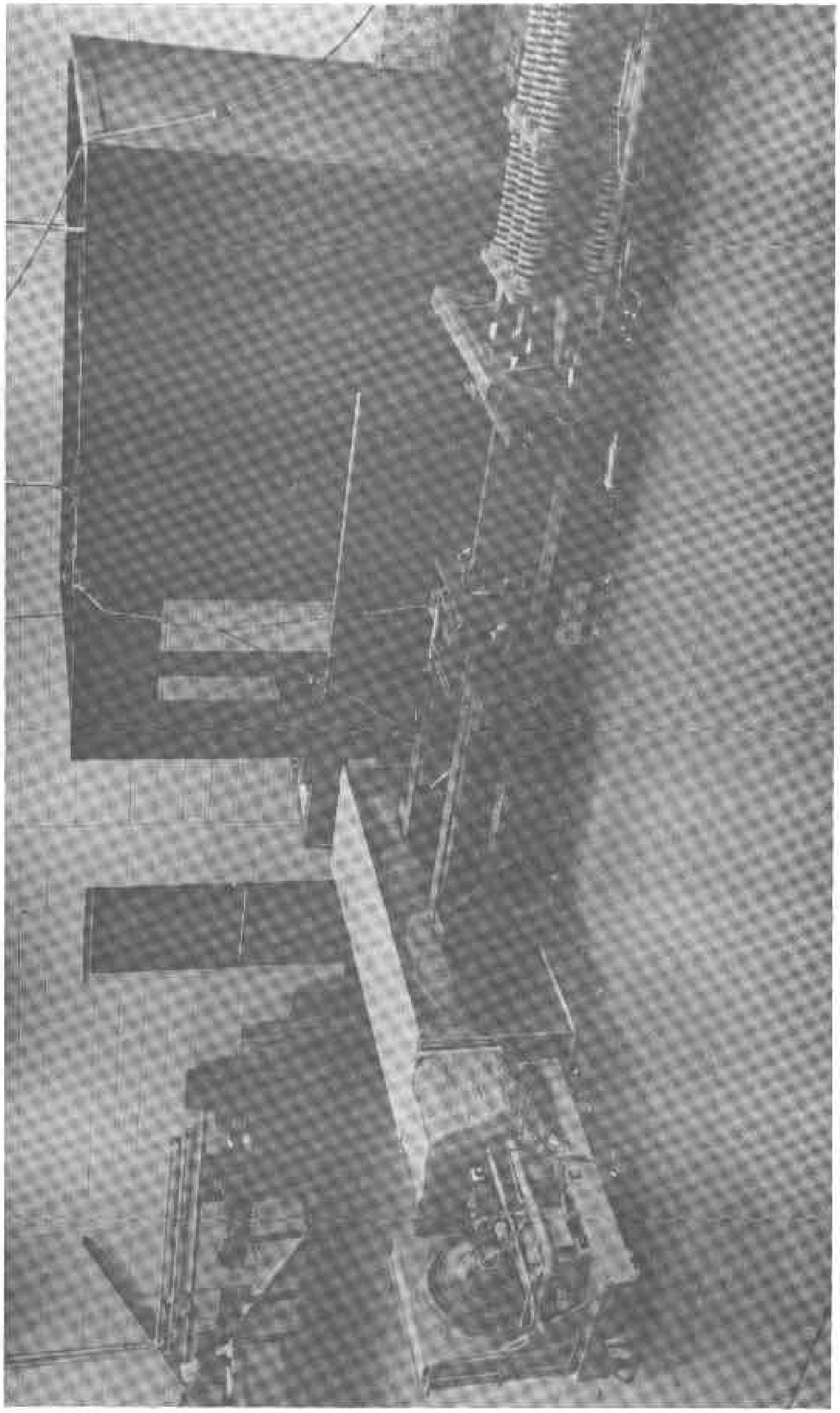

FIGURE 12. LINEAR IMPACT APPARATUS
FOR EQUIVALENT PENDULUM TEST

striker portion meets the requirements specified in Part 581. Additional photographs depicting the 1978 LeMans' test vehicle (described in Subsection 3.1) are shown in Figure 13. As discussed in Reference 10, a sled carrying a striker and ballast weight is driven by an air-cylinder-compressed spring array to simulate the kinetics of a conventional pendulum facility. A 1000-5000 lb impacting mass range capability is available.

Instrumentation capabilities are summarized in Table 10. In general, the data acquired for a given test run included: (1) impact velocity, (2) maximum force, and (3) bumper system deflection. General kinematics were recorded by high-speed movies (300 frames per second). Additionally, in many of the room temperature tests, clay posts* were placed between the bumper backbar and the main frame crossmember to record maximum backbar deflection (significance of such a deflection is discussed in Subsection 3.5.1).

TABLE 10. INSTRUMENTATION FOR PENDULUM IMPACT TESTS

Measurement	Sensor	Remarks
Velocity	Optical system	
Force	Quartz crystal force washer	
Linear displacement	Linear potentiometer	
Linear displacement	Clay posts	Witness device for maximum displacement

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* Sticks of modeling clay.

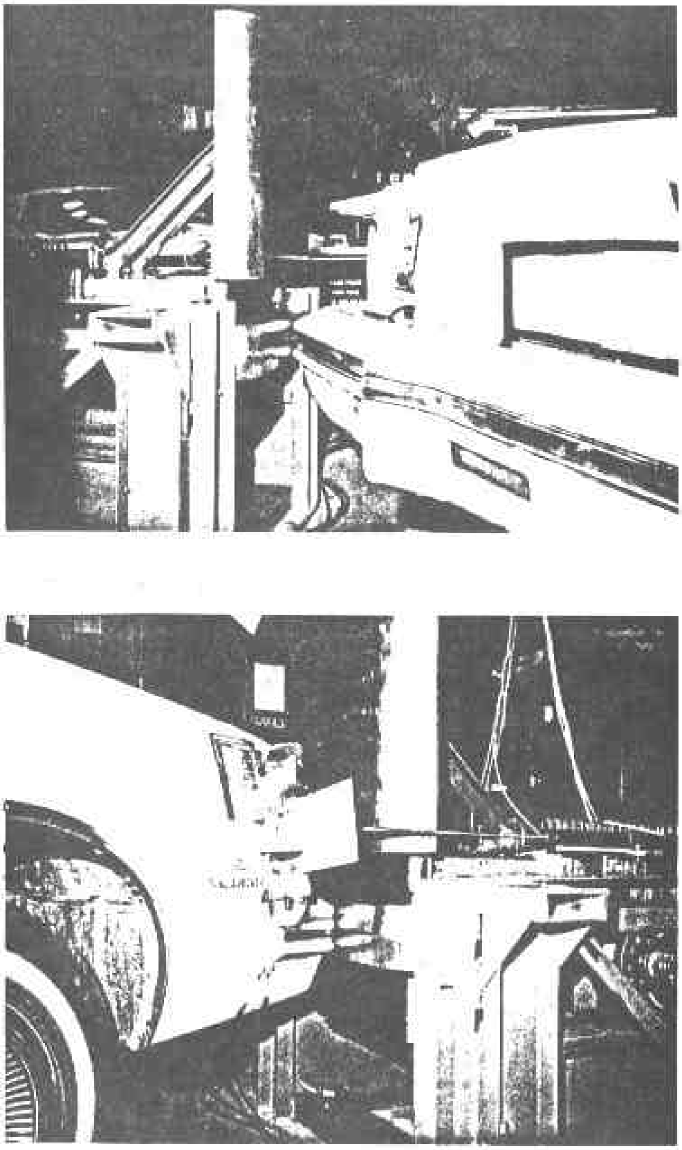

FIGURE 13. PENDULUM APPARATUS ORIENTATION FOR CORNER IMPACT

The basic parameters of the test series were impact speed, lateral position of impact on the bumper, and bumper temperature. There were two basic departures from Part 581 testing procedure. First, unlike Part 581, which involves a pass/fail outcome at the 5 mph compliance value, the initial speed for a given nominal temperature was deliberately chosen to be a lower value and cautiously incremented upward until it was judged that damage would occur on a succeeding impact. Second, unlike Part 581, which is only conducted at room temperature, 0 and 100 F conditions were included to evaluate performance sensitivity to temperature.

For hot (100 F) and cold (0 F) testing, the front end of the test vehicle was thermally soaked in the environmental chamber until a thermocouple embedded in the bumper foam registered the desired temperature. The environmental conditioning chamber was kept in place until just before impact. Sample temperatures were monitored until the impact sequence was performed.

The basic experimental data obtained at a given impact speed were maximum bumper deflection and peak impact force as functions of impact location on the bumper and temperature of the bumper. For selected test conditions, force-deflection time histories were obtained.

2.3.2 Low-Speed Barrier Impact Experimental Equipment and Procedure

A test series of four low-speed (i.e., 5 mph) barrier impacts, using a 1978 Pontiac LeMans with an experimental bumper configuration, was conducted at Battelle. For two of the impacts a flat-faced barrier surface was used. In two other tests, a protruding 6-inch high x 4-inch deep wooden member was mounted on the barrier surface at bumper height to act as the impact target for the bumper.

Two types of data were recorded during a given test: (1) speed and acceleration of the impacting vehicle as measured by a fifth wheel and a frame-mounted accelerometer, respectively; and (2) kinematics of the impact event as recorded by (a) high-speed movies (1000 frames per second), viewed from ground level and focused upon the impact area of the barrier, and (b) a front-fender-mounted telescoping tube arranged to measure maximum bumper deflection.

Specific results from those tests are described in Section 3.5.2 and integrated into the assessment of overall damageability performance in Section 4.3.

2.3.3 Low-Speed Car-to-Car Impact Experimental Equipment and Procedure

A series of low-speed car-to-car collisions using a pair of 1979 Pontiac LeMans was conducted at the Transportation Research Center of Ohio (TRC) in East Liberty, Ohio. The particular facility chosen by TRC's test conductor was the Vehicle Dynamics Area (VDA), a 50-acre bituminous-concrete test surface having a 1 percent slope. During the test periods (two separate occasions) the surface was clear and dry.

In staging the test collisions, a target vehicle was positioned to be stationary and present the appropriate target area (front, side, or rear) to the moving striker vehicle. After reviewing alternative techniques for guidance and control of the striker vehicle, TRC elected to use a manual control procedure used successfully in a previous program.

Target areas for front-to-front and front-to-rear collisions were defined by specifying impacts to be symmetric about vehicle centerlines. For side impact, the target area was specified to involve only the door panels (i.e., without involving quarter panels).

The target car was positioned with engine inoperative, transmission set in neutral position and parking brakes released. The striker car was accelerated to the desired speed, and the transmission was manually shifted into neutral position just prior to impact. Brakes were not applied during the collision event.

Two basic types of data were acquired during a given test: (1) speed of the striker vehicle as measured by a fifth wheel (digital display for the test driver and calibrated analog record); and (2) kinematics of the test vehicles as recorded by (a) high-speed movies (1000 frames per second), viewed from ground level and focused upon the impact area of the target vehicle, and (b) documentary movies (24 frames per second) of the overall test scene viewed from ground level and from an elevated position.

Vehicle test weights were obtained prior to each of the two occasions of testing. These test weights were close approximations to the nominal curb weight. Tires were inflated to recommended pressures for nominal curb weight. Weight data are included in the discussion of test results.

The basic test plan was designed around three collision modes: (1) front-to-front at 10 mph relative velocity; (2) front-to-side at 5 mph; and (3) front-to-rear at 5 mph. Because both an unmodified and a modified front bumper system were to be used on the striker vehicle, a total of 6 collisions were planned.

As required by the program Statement of Work, collision induced damage and cost to repair were assessed by professional estimators. Assessments were made by three estimators associated with different Pontiac dealerships having body repair capability.

Specific results from these tests are desdribed in Section 3.5.3 and integrated into the assessment of overall damageability performance in Section 4.3.

3.0 EXPERIMENTAL RESULTS

In this section, the basic results obtained from various sets of experiments are presented. The discussion is organized topically as follows.

- Application of the pneumatic impactor to vehicle front end design, in particular, the modification of a production vehicle (Pontiac LeMans)
- Temperature sensitivity of front end performance as measured by the pneumatic impactor
- Application of the pneumatic impactor to vehicle front end evaluation (in particular, the Calspan RSV and the Dodge Mirada)
- Sled experiments of vehicle front ends (in particular, the modified LeMans and the Calspan RSV) impacting upon pedestrian dummy surrogates
- Damageability experiments with the modified LeMans (in particular, pendulum impacts, low-speed barrier impacts and low-speed car-to-car collisions).

This presentation of results (1) illustrates the utility of the pneumatic impactor in both the design and evaluation aspects of vehicle front end configurations, (2) provides data to link the pneumatic impactor approach to the more sophisticated simulation afforded by the pedestrian dummy impacted by a sled-mounted vehicle, and (3) demonstrates recognition of existing and potential regulatory requirements for front end collisions with other objects.

3.1 APPLICATION OF PNEUMATIC IMPACTOR TO VEHICLE FRONT END DESIGN

One of the tasks (Task 4) of the subject project was to develop a production vehicle modification. Four design goals were established by NHTSA for such a modification (i.e., a front-end system concept).

(1) The concept had to have an inherent potential for pedestrian injury mitigation.

(2) It had to be oriented towards feasibility for mass production.

(3) It had to minimize impact on contemporary production vehicle design.

(4) It had to comply with the 5 mph frontal barrier impact no-damage requirement of Part 581.

At the time during the project when the selection of a baseline production vehicle was appropriate, an attractive candidate was the 1978 Pontiac LeMans. As illustrated in Figure 14, this vehicle's front end structure featured the following principal elements: (1) a reaction injection molded (RIM) polyurethane fascia, (2) a reinforcement assembly, and (3) a steel bumper bar.

At least two of the above mentioned design goals were supported by the choice of vehicle. First, it was thought that with removal of the rigid reinforcement assembly the soft production fascia could contribute to injury mitigation as the initial contact surface in the pedestrian impact event. Second, it appeared that there might be sufficient space between the fascia envelope and the radiator support assembly to incorporate sufficient energy absorbing capability in a way that would minimize the impact on vehicle design. Within these constraints, Battelle's approach to a practical modification was to replace the production metallic bumper elements (i.e., the reinforcement assembly and bumper bar depicted in Figure 14) and the hydraulic energy absorbers (not shown in Figure 14) with an energy absorbing (EA) configuration appropriate to pedestrian injury mitigation. It was in the development of this EA configuration that the pneumatic impactor played a pivotal role.

The point of departure for experimentation was the utilization of some of the concepts evaluated during the sled tests of the previous project (PED II, reported in Reference 2). Thus, for example, the multi-layered Ensolite arrangement featured in Concept 1 and a wide variety of styrofoam configurations (various thicknesses, solid and perforated blocks,

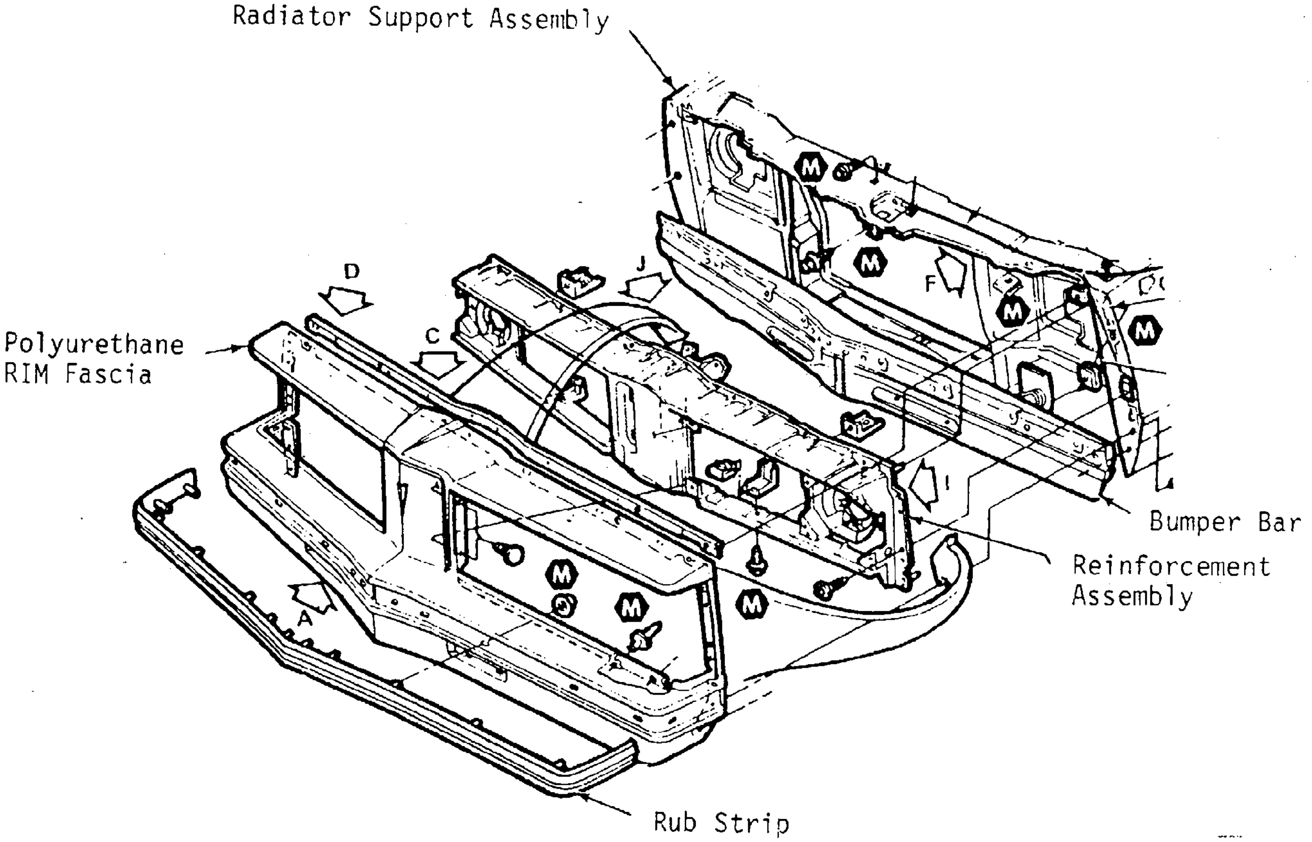

FIGURE 14. PONTIAC LEMANS FRONT END STRUCTURE

the latter being similar to Concept 3) were subjected to pneumatic impactor tests at a nominal speed of 25 mph. Although these early efforts were informative, a more promising avenue of approach, from a materials standpoint, lay in the use of polyurethane foam.

In particular, the use of microcellular polyurethane foam, as exemplified in its application to the Calspan RSV bumper, appeared to have a number of attractive features. Among them were:

(1) Shape recoverability after impact
(2) Low rebound because of highly hysteretic load-deflection behavior
(3) Wide range of stiffness achievable through controlled formulation
(4) Good load-velocity sensitivity.

Accordingly, various urethane* foam formulations were tested in block sample sizes with the pneumatic impactor to seek a desirable range of combinations of density and stiffness (as measured by a compression modulus at 50% strain).

After finding a suitable nominal formulation, the effort was focused on a geometric configuration applicable to the modification of the LeMans vehicle. A basic outcome of this work was the "Mod I" configuration depicted together with the production version on the profile sketched in Figure 15. Photographs of the modifications are shown in Figure 16. The front end modification was divided into two parts, namely, the bumper modification and the hood leading edge modification. There were two primary features of the bumper modification: (1) a hollow-cored foam insert placed behind the fascia and supported by (2) a "hat"-sectioned steel beam.

The Mod I bumper foam insert had a 4.8 pcf density and a 16 psi compression modulus. For the hood leading edge a solid insert was made from the same material. Subsequent to sled tests of the Mod I configuration, two variants in the foam inserts for that design were also subjected to comparative tests. The three designs are summarized in Table 11.

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* As customary - urethane and polyurethane are the same.

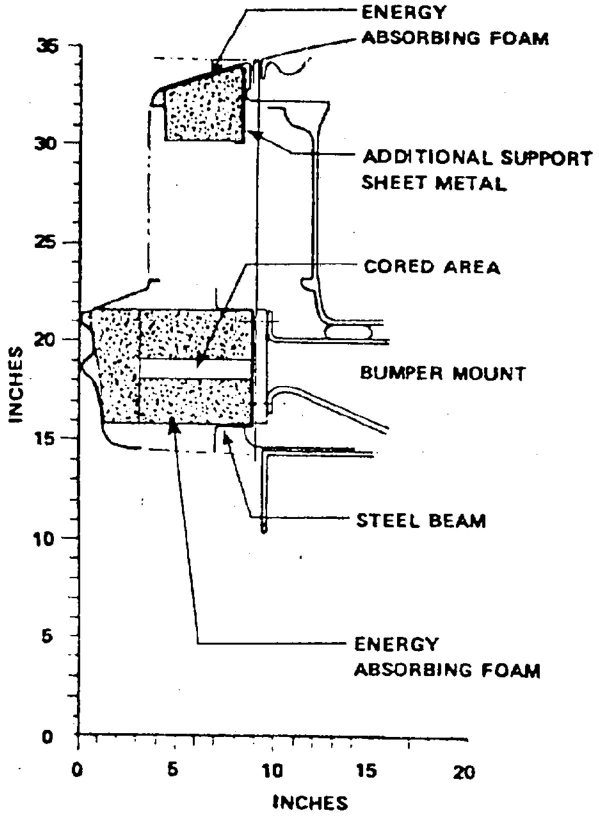
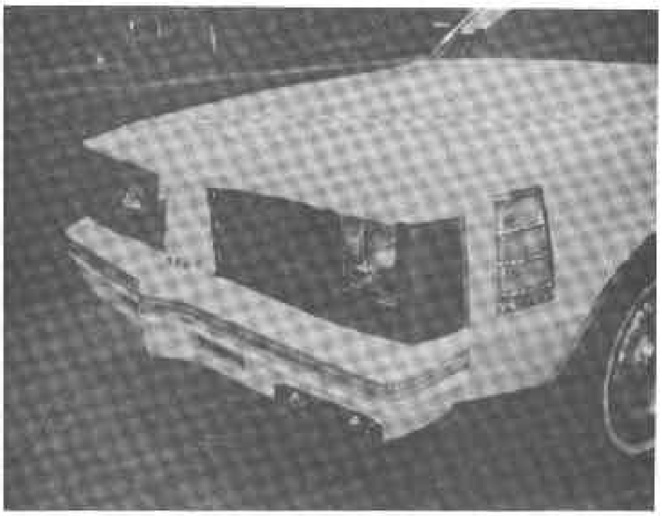
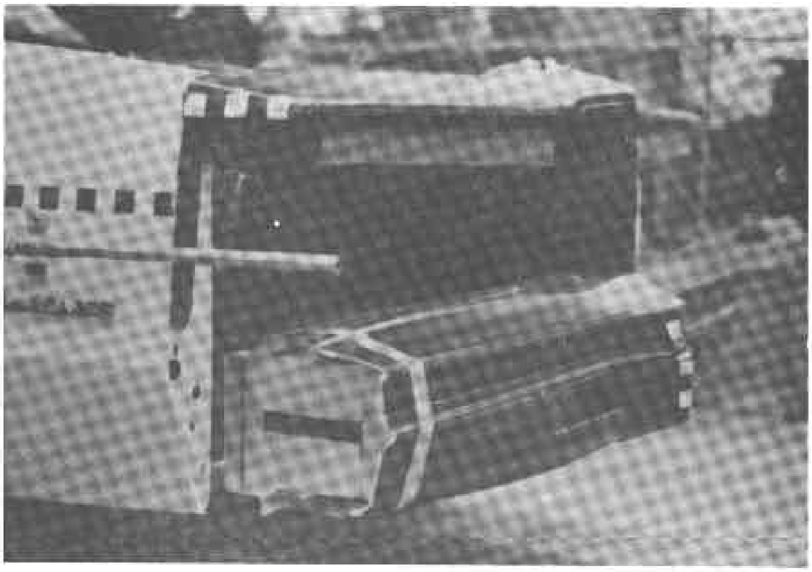


FIGURE 15. CROSS SECTION OF MODIFIED LEMANS FRONT END AT 18 INCHES FROM VEHICLE CENTERLINE



(A) COMPLETED MODIFICATION OF 1978 LEMANS



(B) RIGHT CORNER OF FASCIA REMOVED TO EXPOSE FOAM ELEMENTS

FIGURE 16. PHOTOGRAPHS OF PONTIAC LEMANS WITH MOD I FRONT END CONFIGURATION

TABLE 11. SUMMARY OF MODIFIED FRONT END CONFIGURATIONS FOR PONTIAC LEMANS

Component Modification	Mod I	Mod II	Mod III
Bumper foam insert			
Geometry	Hollow-cored	Solid	Solid
Density, pcf	4.8	4.8	4.8
Compression modulus, psi	16	16	16
Hood leading edge foam insert			
Geometry	Solid	Solid	Solid
Density, pcf	4.8	4.8	4.8
Compression modulus, psi	16	32	54

Experimental data of the Mod 1 bumper obtained with the pneumatic impactor are summarized in Table 12 and Figure 17. The key observation here is that the peak acceleration is well below the 100 g level set as a tentative goal for injury mitigation in the knee/leg area (see previous discussion in Subsection 2.1.3).

Based on its utility in developing the modified LeMans, it is clear that the pneumatic impactor can be a useful tool in developing a front end configuration that is conducive to pedestrian injury mitigation.

3.2 TEMPERATURE SENSITIVITY OF FRONT END PERFORMANCE MEASURED BY PNEUMATIC IMPACTOR

Results are summarized in Tables 13 and 14, regarding the temperature sensitivity of the Mod 1 front-end configuration (mounted on the 1978 LeMans whole vehicle) performance as measured with the pneumatic impactor. Bumper results appear in Table 13; hood leading edge data in Table 14.

Bumper results were obtained with the knee/leg striker configuration previously described. Hood leading edge data were obtained with an exploratory pelvis/leg striker geometrically similar to the knee/leg striker, i.e., the radius of curvature was the same (8-inch; see Figure 7) but the curved surface area was enlarged by increasing the boundary dimensions from 4 x 6-in. to 6 x 8-in. The total ram assembly mass was increased from 7.25 to 9.25 lb.

Behavior of the front end (i.e., both bumper and hood leading edge) performance parameters over the temperature range employed conformed to general expectations. That is, for a given impact speed,

1. (1) The maximum deceleration at a given lateral station varied inversely with temperature. (Deceleration values at 0 F were on the order of twice those at 100 F.
2. (2) The depth of penetration into the front end by the body form striker increased directly with temperature. (Penetration at 100 F was as much as 2-3 times that at 0 F.)
3. (3) The rebound velocity ratio showed only minor sensitivity to temperature variation.

These three observations suggest that although the force-deflection behavior is altered by temperature, the amount of energy absorbed remains essentially constant.

TABLE 12. TEST RESULTS FOR LEMANS MOD I FRONT BUMPER OBTAINED WITH NHTSA/BATTELLE PNEUMATIC IMPACTOR

Data obtained at nominal room temperature

Impact Lateral Location From Centerline, in.	Striker Weight, lb	Impact Velocity, mph	Maximum Deceleration, g	Bumper Penetration, in.	Rebound Velocity Ratio
0	6.8	25.0	108	4.9	0.42
11	6.8	25.2	93	4.5	0.38
11	6.8	25.5	95	4.2	0.40
11	6.8	25.3	87	4.7	0.40
11	6.8	25.6	85	4.9	0.40
18	6.8	26.0	88	4.2	0.37
18	6.8	25.5	87	4.5	0.37
18	8.9	22.0	63	4.8	0.43
18	11.4	22.3	57	5.7	0.43
18	14.8	23.3	70	6.7	0.42
18	18.2	23.5	96	7.2	0.40
18	21.6	24.7	123	7.4	0.35
18	25.0	25.0	180	7.4	0.35
18	6.8	20.6	75	3.3	0.42
19	6.8	24.9	87	4.2	0.39
19	6.8	25.0	84	4.3	0.37

NOTES: 1. Data corrected to impact velocity of 25 mph as necessary.

2. Dashed line indicates energy absorber bottomed out.

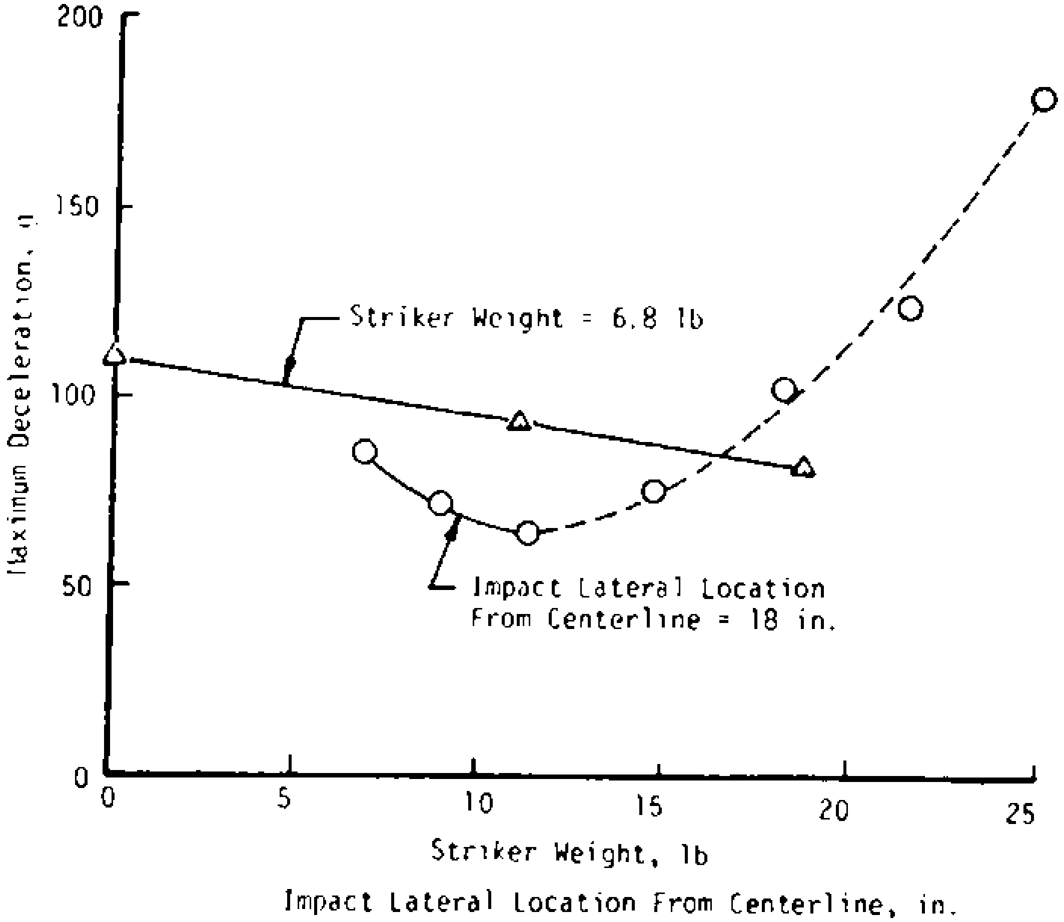


FIGURE 17. MAXIMUM DECELERATION OBTAINED FOR LEMANS MOD I BUMPER WITH PNEUMATIC IMPACTOR

TABLE 13. TEMPERATURE EFFECTS ON PERFORMANCE OF MODIFIED LEMANS BUMPER OBTAINED WITH PNEUMATIC IMPACTOR

Test Nos.	Nominal Temperature, F	Actual Temperature, F		Impact Location From Centerline, in.	Impact Velocity, mph	Maximum Deceleration, g	Bumper Penetration, in.	Rebound Velocity Ratio
		Foam	Fascia					
7	0	-4.2	- 6.4	0	21.5		1.4	0.28
12		-3.0	19.6	0	19.1		1.6	0.32
9		-3.2	19.4	11	21.0	111	2.2	0.42
10		-3.8	-10.8	11	24.6	138	2.4	0.39
8		-4.2	13.0	18	20.8	123	2.1	0.41
11		-4.4	6.8	18	21.1	126	1.8	0.42
14	68			0	20.9	106	3.0	0.40
17				0	26.2	114	4.2	0.33
13				11	21.1	64	4.0	0.41
15				11	25.2	75	4.9	0.38
12				18	20.9	65	4.1	0.43
18				18	24.7	68	5.0	0.33
16				18	22.3	70	4.1	0.37
7	100	102.7	107.0	0	17.9	75	3.1	0.34
9		101.6	99.6	11	19.8	51	4.3	0.37
12		99.8	112.9	11	25.6	61	6.4	0.36
8		102.2	100.6	18	17.9	85	3.8	0.39
11		100.2	113.0	18	25.6	60	6.4	0.35

TABLE 14. TEMPERATURE EFFECTS ON PERFORMANCE OF MODIFIED LEMANS HOOD LEADING EDGE OBTAINED WITH PNEUMATIC IMPACTOR

Test Nos.	Nominal Temperature, F	Actual Temperature, F		Impact Location From Centerline, in.	Impact Velocity, mph	Maximum Deceleration, g	Bumper Penetration, in.	Rebound Velocity Ratio
		Foam	Fascia					
1	0	-1.6	6.0	0	21.8	81	2.4	0.30
6		-3.4	18.6	0	22.6	93	3.1	0.24
3		-0.8	20.4	11	19.7	99	2.4	0.40
4		-3.8	-14.0	11	25.0	139	3.7	0.38
2		-1.6	13.2	18	20.0	75	3.5	0.36
5		-4.0	- 2.2	18	24.0	135	4.3	0.33
10	68			0	24.4	88	4.3	0.25
1				11	19.6	94	4.7	0.35
4				11	18.9	79	4.4	0.36
7				11	17.5	68	3.1	0.33
9				11	25.0	167	4.4	0.35
6				11	23.3	136	3.9	0.32
5				11	23.1	126	4.3	0.24
2				18	19.5	93	4.2	0.35
11				18	25.4	180	4.3	0.33
8				18	23.5	71	4.3	0.25
1	100	102.0	114.0	0	20.4	56	4.5	0.24
4		101.0	110.0	0	24.4	88	5.4	0.25
3		96.0	100.2	11	19.0	80	3.8	0.39
6		99.0	104.8	11	23.5	146	4.8(a)	0.39
2		100.8	100.4	18	19.6	88	3.9	0.37
5		99.6	108.0	18	24.1	175	4.4(a)	0.30

(a) Energy absorber bottomed out.

As expected, the impact speed sensitivity of the performance parameters observed in previous testing at room temperature was also noted at the other test temperatures. Furthermore, as anticipated, the impact speed sensitivity varied directly with temperature.

The explanation for the observed results and trends is clearly dependent upon a temperature sensitivity of the mechanical properties (principally the mechanical compliance) of the urethane material used to fabricate the front end. Although the fascia is RIM urethane, the behavior is expected to be dominated by the urethane foam EA inserts.

3.3 APPLICATION OF PNEUMATIC IMPACTOR TO VEHICLE FRONT END EVALUATION

In this section, attention is directed to the use of the pneumatic impactor as an evaluation tool in the context of pedestrian injury mitigation. The front-end designs used to illustrate this type of application are: (1) three independently designed experimental configurations for the Calspan Phase IV RSV*; and (2) a production front end for the 1980 Dodge Mirada. Both sets of front ends were mounted on a stiff laboratory test fixture rather than any representation of the vehicle.

3.3.1 Calspan RSV

A sketch of the basic features of the Calspan Phase IV RSV front end is shown in Figure 18. The experimental bumpers were fabricated from Phase IV RSV fascias and fitted with different density urethane foam inserts (4.1, 4.8 and 5.6 pcf, all with a nominal modulus of 16 psi). The Phase IV front end has a 5.1 pcf foam (modulus of 33 psi). Only bumper performance was measured in this test series. A typical raw data record is illustrated in Figure 19.

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* Phase IV designates the final deliverable configuration of the Research Safety Vehicle. This designation is used here to distinguish the test articles from earlier Calspan RSV prototypes that were sled tested during the PED II project.

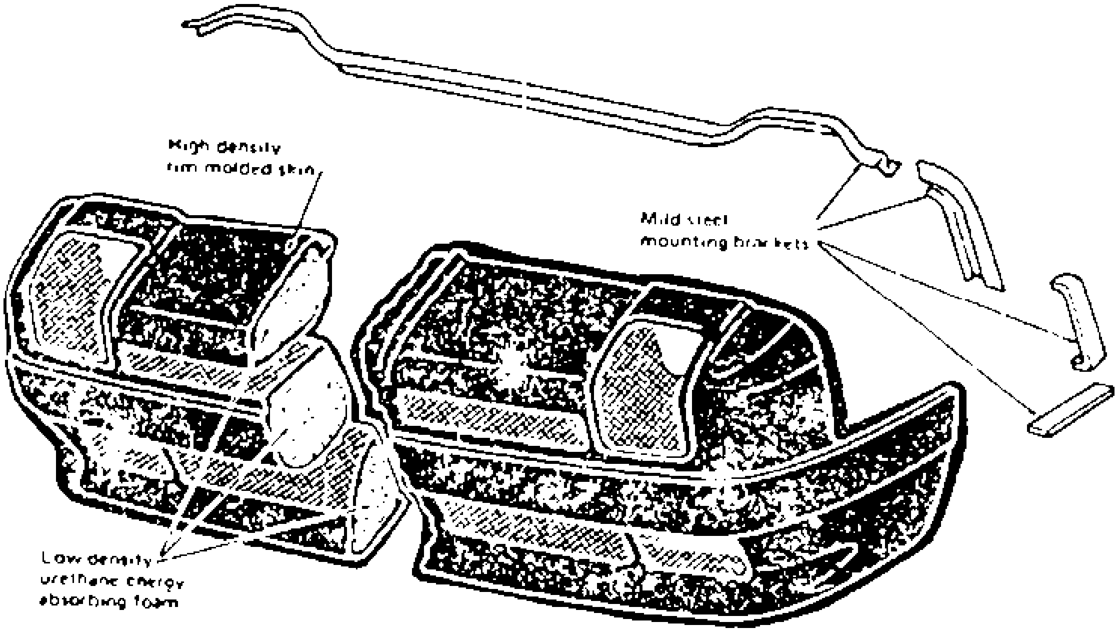

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FIGURE 18. FRONT END FEATURES OF CALSPAN PHASE IV RSV

Run No. 129
Foam Density 4.8 pcf
Nominal Impact Velocity, 25 mph
Lateral Impact Station, 7.25-in. from centerline

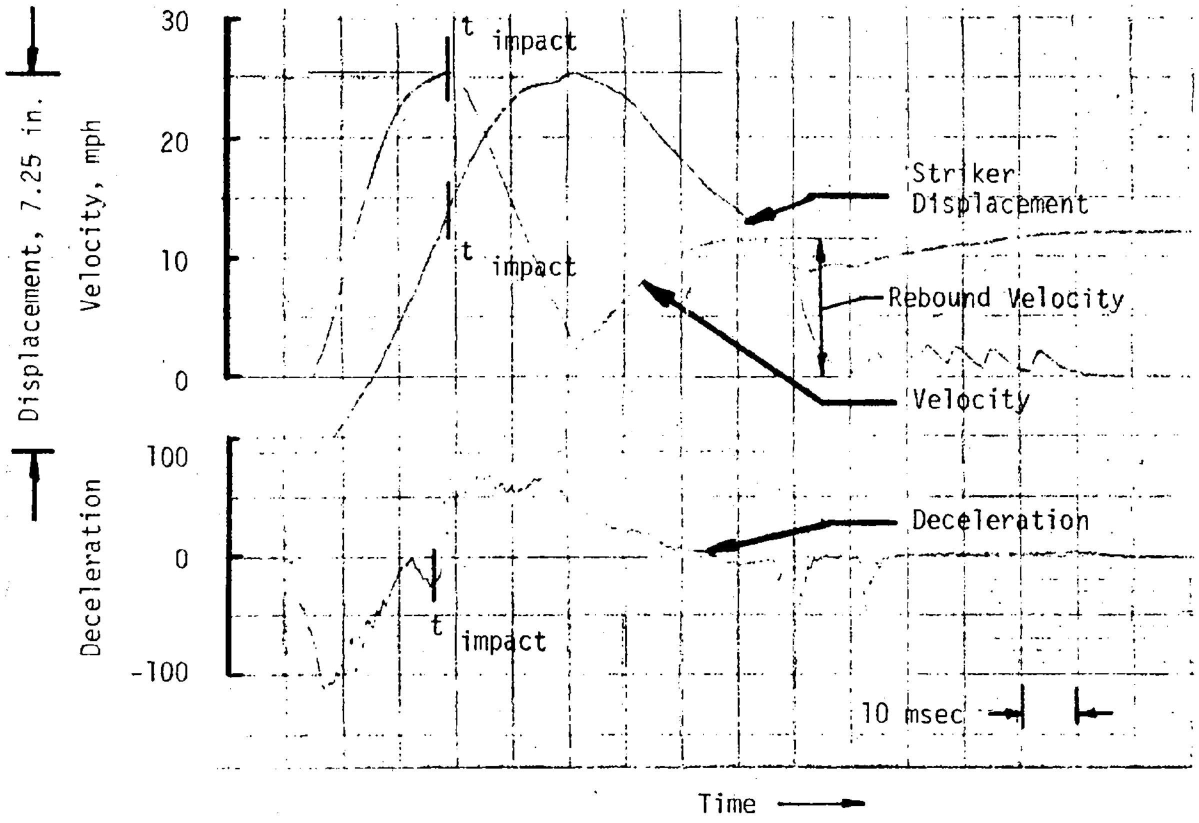

FIGURE 19. TYPICAL RAW DATA RECORD OBTAINED FOR CALSPAN RSV BUMPER WITH PNEUMATIC IMPACTOR

Pneumatic impactor data obtained at room temperature for these Calspan Phase IV RSV bumpers are summarized in Table 15. The lateral distributions of the maximum decelerations are shown in Figure 20, from which several features can be noted.

(1) The experimental bumpers exhibit relatively constant stiffness within 20 inches of centerline; stiffness appears to increase outboard from that station owing to the geometric construction in the immediate vicinity of the head lamp*.

(2) The Phase IV design bumper appears to increase in stiffness outboard from centerline.

(3) The maximum decelerations recorded for the Phase IV design bumper are significantly higher than the experimental configurations, particularly at the outboard stations.

(4) The experimental bumper having the 4.1 pcf foam limits maximum decelerations at 25 mph to values below 100 g.

3.3.2 Dodge Mirada

A photograph of the front end of a production 1980 Dodge Mirada is shown in Figure 21. This front end features a soft RIM urethane fascia. Recesses behind the bumper portion of the fascia contain a combination of metal and foam inserts.

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* It should be noted that the clear plastic lens cover for the headlamp recess was not installed for any of these tests.

TABLE 15. TEST RESULTS FOR CALSPAN RSV PHASE IV FRONT BUMPER OBTAINED WITH NHTSA/BATTELLE PNEUMATIC IMPACTOR

Run No.	Foam Density, pcf	Impact Lateral Location From Centerline, in.	Impact Velocity, mph	Maximum Deceleration, g	Bumper Penetration, in.	Rebound Velocity Ratio
104	5.6	0	24.4	76.6	6.0	0.48
105		0	24.8	79.8	6.1	0.48
116		0	26.0	82.1	4.4	0.48
130		7.25	26.0	81.6	4.2	0.48
136		15	23.7	81.8	2.9	0.44
141		20	25.0	104.0	3.1	0.51
148		24	25.5	113.3	1.0	0.46
108	4.8	0	24.3	71.3	6.0	0.48
115		0	25.6	63.2	5.2	0.45
129		7.25	24.8	63.9	4.7	0.45
135		15	23.5	86.9	2.9	0.43
142		20	25.0	96.0	3.2	0.49
149		24	25.3	105.1	3.6	0.45
109	4.1	0	25.5	63.2	3.3	0.42
128		7.25	24.7	61.0	4.8	0.41
134		15	24.2	72.7	3.7	0.38
143		20	25.6	82.8	3.7	0.45
150		24	25.6	95.9	4.1	0.44
158	5.1(a)	0	24.4	85.7	3.2	0.46
157		7.25	24.4	99.0	2.9	0.51
156		15	25.5	134.7	2.3	0.46
155		20	25.2	157.1	2.1	0.48
154		24	25.2	157.1	2.1	0.45
103	5.6	0	21.2	73.4	5.1	0.50
114		0	19.8	63.2	3.2	0.52
127		7.25	20.8	53.1	3.2	0.51
133		15	18.8	72.7	2.1	0.42
138		15	18.7	72.7	2.0	0.51
144		20	18.8	72.7	2.4	0.53
147		20	19.3	81.6	2.7	0.54
151		24	19.5	86.7	2.6	0.50

TABLE 15. (Continued)

Run No.	Foam Density, pcf	Impact Lateral Location From Centerline, in.	Impact Velocity, mph	Maximum Deceleration, g	Bumper Penetration, in.	Rebound Velocity Ratio
107	4.8	0	20.5	63.8	4.9	0.51
110		0	20.3	62.1	1.4	0.50
112		0	19.7	-	3.6	0.48
113		0	20.5	57.9	3.9	0.48
126		7.25	20.3	56.1	3.4	0.47
132		15	18.9	71.7	2.1	0.43
145		20	19.8	73.5	2.7	0.51
152		24	20.1	84.7	2.7	0.47
124	4.1	0	20.0	49.2	2.2	0.41
125		7.25	19.7	51.1	3.4	0.45
131		15	17.8	51.5	2.3	0.43
146		20	19.7	66.3	4.3	0.44
153		24	19.7	76.5	2.6	0.44

(a) Phase IV RSV reference configuration.

Symbol	Foam Density, pcf
○ ●	5.6
△ ▲	4.8
□ ■	4.1
▽	5.1 (Reference Configuration)

NOTE: Open symbols denote nominal impact velocity of 25 mph; filled symbols denote nominal impact velocity of 20 mph.

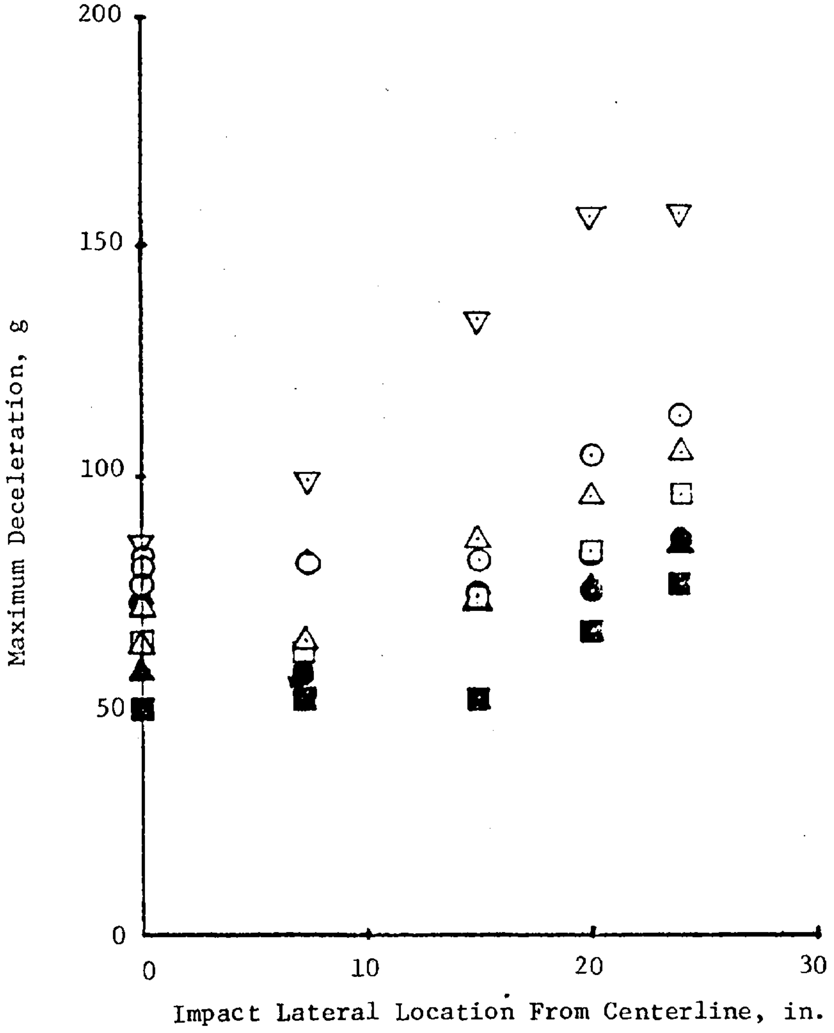


FIGURE 20. MAXIMUM DECELERATION OF KNEE-LEG STRIKER IMPACTING CALSPAN RSV BUMPER CONFIGURATIONS

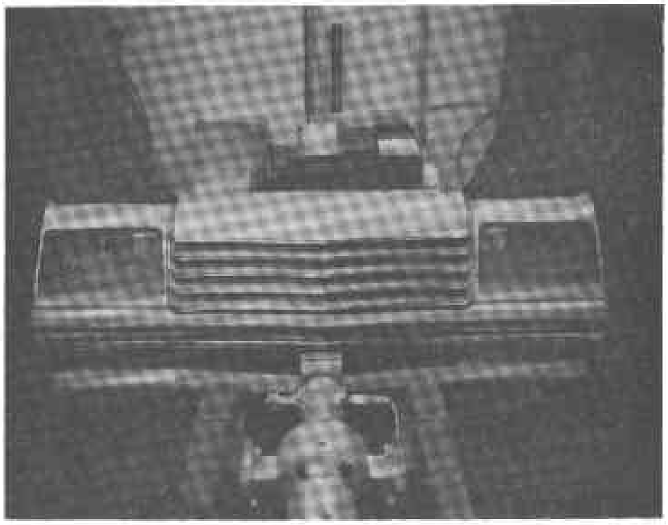


FIGURE 21. DODGE MIRADA BUMPER ASSEMBLY INSTALLED FOR TEST ON NHTSA/BATTELLE PNEUMATIC IMPACTOR

It should be noted that this bumper system was designed for present damageability requirements, not for the upcoming pedestrian requirements. Inclusion of this sample design in the test program was merely to gain additional insight into the performance of a new production "soft snout" design.

Pneumatic impactor data obtained at room temperature for the Mirada bumper are summarized in Table 16. Lateral distributions of maximum decelerations are shown in Figure 22. It can be noted that

(1) The Mirada front end appears to be very sensitive to impact speed.

(2) At a given impact speed, the lateral distribution of stiffness appears to be relatively uniform up to the vicinity of the fascia cutout for the headlamp.

(3) Maximum deceleration levels are well above the 100 g goal level.

3.4 SLED EXPERIMENT RESULTS

In this subsection, experimental results are presented for vehicle front end impacts on pedestrian surrogates (here, 6-year-old child and 50th percentile adult male dummies) obtained by sled technique. These results are divided into two groups: (1) those associated with the partial vehicle test buck version of a 1978 LeMans equipped with either a production front end or with various experimental front end designs; and (2) those associated with the Calspan Phase IV RSV partial vehicle test buck.

3.4.1 Pontiac LeMans

Figure 23 depicts the adult dummy standing in front of the vehicle. Figure 24 shows both dummies and the accelerometer locations relative to the front of the vehicle. It can be seen that the bumper impacts the knee of the adult and the mid-thigh of the 6-year-old child. The hood edge of the vehicle impacts the hip joint of the adult and the chest of the child. Data are summarized in Table 17.

TABLE 16. TEST RESULTS FOR 1980 PRODUCTION DODGE MIRADA FRONT BUMPER OBTAINED WITH NHTSA/BATTELLE PNEUMATIC IMPACTOR

Run No.	Impact Lateral Location From Centerline, in.	Impact Velocity, mph	Maximum Deceleration, g	Bumper Penetration, in.	Rebound Velocity Ratio
203	0	25.2	335	1.5	0.45
206	0	24.9	342	1.6	0.47
207	8.5	25.0	307	1.7	0.45
209	17	25.0	309	1.8	0.42
211	24.5	25.6	327	2.2	0.41
214	30	25.1	239	1.8	0.39
205	0	19.9	231	1.4	0.43
208	8.5	19.7	213	1.7	0.46
210	17	20.2	121	1.9	0.42
212	24.5	19.9	219	2.1	0.43
213	30	19.6	138	1.4	0.40

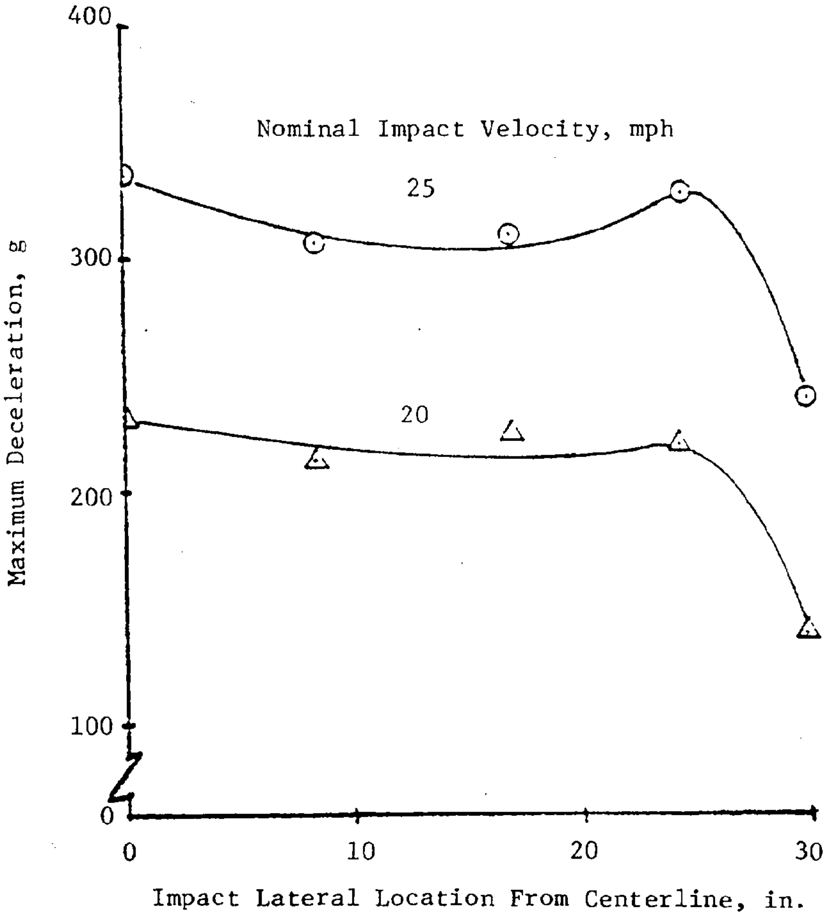


FIGURE 22. MAXIMUM DECELERATION OF KNEE-LEG STRIKER IMPACTING 1980 PRODUCTION DODGE MIRADA FRONT BUMPER

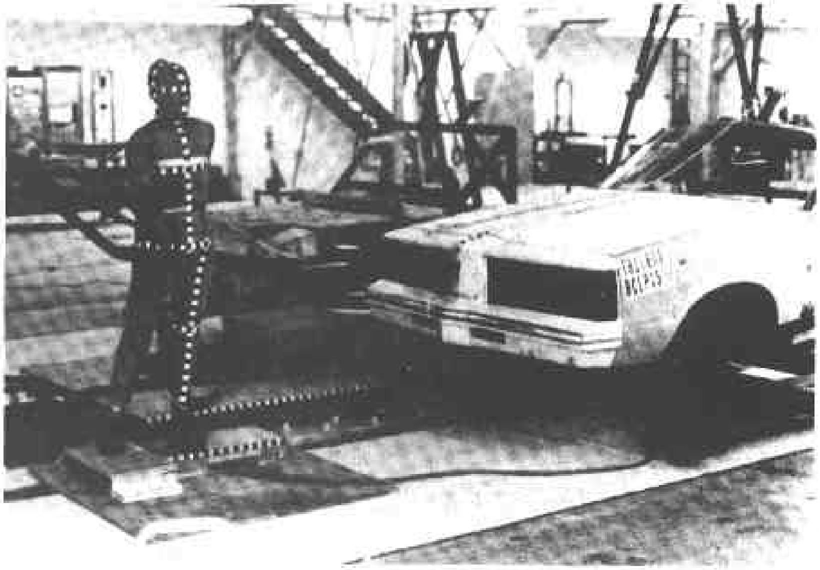


FIGURE 23. STANDING ADULT PEDESTRIAN DUMMY IN POSITION IN FRONT OF MODIFIED LEMANS

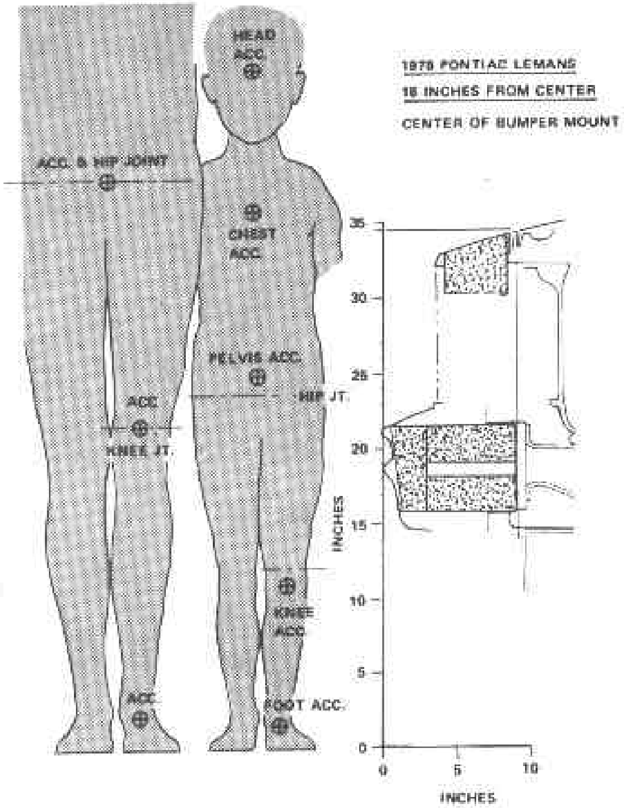


FIGURE 24. ADULT AND 6-YEAR-OLD CHILD DUMMY RELATIVE TO LEMANS VEHICLE FRONT

TABLE 17. SUMMARY OF PEDESTRIAN IMPACT PERFORMANCE FROM SLED TESTS OF PONTIAC LEMANS FRONT END CONFIGURATIONS

Experiment Number	Bumper Configuration	Impact Station, Lateral Distance From Centerline, in.	Pedestrian Surrogate	Impact Speed, mph	Peak Resultant Acceleration and Time of Occurrence After Impact										Head Severity Index
					Head		Chest		Pelvis		Knee		Foot		
					g	msec	g	msec	g	msec	g	msec	g	msec	
PC-2	Mod I[(a)]	19	Child	25.4	131	53	96	31	147	27	50	2	78	30	1200
PC-3	Mod I	19	Adult	25.0	39	78	43	126	76	24	120	25	72	28	385
PC-4	Production	19	Child	25.0	114	45	67	16	304	5	367	5	240	11	1090
PC-5	Production	20	Adult	25.0	115	109	34	121	94	9	350	4	153	8	940
PC-6	Mod II	19	Child	24.6	100	55	76	26	82	24	56	4	70	39	827
PC-7	Mod II	18	Adult	25.0	49	81	39	122	66	21	81	22	106	75	492
PC-8	Mod III	18	Child	24.7	86	55	65	26	89	23	54	3	173	39	700
PC-9	Mod III	18	Adult	24.9	81	109	35	51	56	24	33	2	Lost signal		610

(a) See Table 11

Runs PC-4 and PC-5 with the production vehicle provided a baseline for comparison. Runs PC-2 and PC-3 were made with the first modified vehicle (Mod I) with the same (16 psi) foam in both the bumper and hood edge. The bumper foam was cut out (i.e., cored out) in the rear as shown in Figure 24 These experiments with Mod I revealed that the hood edge was much too compliant and that the impact energy was absorbed primarily by the sheet metal support structure. It was also apparent that the bumper was too compliant and that the knee of the adult dummy and the pelvis of the child dummy bottomed on the supporting steel beam. The test results from which these inferences are drawn are clearly dependent upon the physical characteristics of the anthropomorphic dummies used as pedestrian surrogates. For example, the foot reactions, which partly determine kinematics, are limited by the ankle motion capabilities of the dummies (in the child dummy, ankle rotation is prevented; in the adult dummy, the ankle joints are initially very tight to aid in achieving a balanced standing posture, and thus the ankle kinematics may lack biofidelity). Also, the mass of the dummy leg may not be representative.

For the Runs PC-6 and PC-7 (Mod II) and Runs PC-8 and PC-9 (Mod III) the cored bumper foam element was replaced with a solid piece of the same 16 psi material. To explore the full possibilities of reducing the acceleration levels in the area of the hood edge, two successive levels of foam compliance, 32 psi for Mod II and 54 psi for Mod III, were used.

In general, the results indicate significant reductions in the acceleration levels - especially in the lower body region of the knee and pelvis. The adult's knee acceleration was reduced from 350 g's in experiments with the production vehicle to 60 g's in experiments with Mod III; the child's knee acceleration was reduced from 367 g's to 54 g's. Proportionate reductions were also evident for the pelvis and foot of the child.

The pelvic acceleration for the adult (approximately at the same height as the hood edge) was reduced from 94 g's in experiments with the production vehicle to 56 g's in experiments with Mod III. Some bottoming of the pelvis in the sheet metal hood edge support occurred in all cases, although the fairly stiff foam of Mod III absorbed a significant portion of the energy. Similar results were obtained for the child chest acceleration.

In each case, there was insufficient deformation space for the hood edge foam to fully absorb the energy of that portion of the body impacting the hood edge without some distortion of the supporting metal structure. Further reductions in the child chest acceleration and adult pelvic acceleration should be attainable by increasing the compliance of the hood support structure.

Reductions in peak accelerations were observed in the heads of the adult and child dummies. The peak adult head acceleration in the experiment with the production vehicle was 115 g's, which is higher than the acceleration observed in experiments with all three of the modified vehicles. This same trend was evident in the Head Severity Index for the adult; 940 in experiments with the production vehicle versus 385, 492, and 610 with the modified vehicles.

The head acceleration levels for the child were lower in experiments with the Mod III vehicle than in experiments with the production vehicle. Also, the head acceleration Severity Index (700) was below the generally accepted survival threshold level.

Although the test results are limited by the lack of biofidelity in the head-neck-shoulder complex of each dummy, the data from these experiments indicate that increased surface compliance in the bumper and hood edge of a vehicle could have a pronounced effect in minimizing head injuries of both adults and children.

3.4.2 Calspan RSV

Basic data for the front end performance of several Calspan Phase IV RSV front ends, differing in foam density, are summarized in Table 18. As previously noted, pneumatic impactor results of the three Davidson experimental foams having densities of 4.1, 4.8, and 5.6 pcf suggested the 4.1 pcf configuration as the primary candidate for dummy impact evaluation in a sled test series. Then, for that configuration, the parameters examined were (1) lateral position of the impact station on the bumper and (2) choice of child or adult pedestrian dummy.

Sled test data obtained with a 6-year-old child dummy and a 50th percentile adult male dummy are highlighted by the following results. In terms of front bumper contact with either the child pelvis or the adult knee, the data displayed in Figures 25 and 26 suggest the following observations.

TABLE 18. SUMMARY OF PEDESTRIAN IMPACT PERFORMANCE FROM SLED TESTS OF CALSPAN PHASE IV RSV FRONT END CONFIGURATIONS

Experiment Number	Front-End Foam Density, pcf	Impact Station, Lateral Distance From Centerline, in.	Pedestrian Surrogate	Impact Speed, mph	Peak Resultant Acceleration and Time of Occurrence After Impact										Head Severity Index
					Head		Chest		Pelvis		Knee		Foot		
					g	msec	g	msec	g	msec	g	msec	g	msec	
PC-14	4.1	7.25	6-year-old child	20.0	97	74.5	46	77.5	36	26.5	44	4	266	36.5	723
PC-15	4.1	7.25	Ditto	25.0	39	63	52	37	50	29	60	5	274	32	979
PC-16	4.1	15.0	"	25.0	96	65	50	39	61	16	76	4	290	34	1257
PC-17	4.1	0	"	25.0	83	69	50	33	53	30	76	4	106	11	634
PC-18	5.1[(a)]	0	"	25.0	145	59	455	50	70	4	96	3	129	21	1683
PC-19	5.1[(a)]	0	50th percentile adult	25.0	139	104	32	67	45	41	62	4	193	26	745
PC-20	4.1	15.0	Ditto	25.0	39	70	33	99	60	26	48	5	98	31	435
PC-21	4.1	7.25	"	25.0	40	161	23	46	60	27	50	7	69	44	377
PC-22	4.1	0	"	25.0	272	138	34	143	64	27	45	4	178	24	-
PC-23	4.8	0	-	25.0	42	148	28	74	43	27	Signal lost		179	22	413

(a) RSV contractor-designed or "reference" configuration; the foam has a compression modulus at 50 percent strain of 33 psi, compared with 16 psi for the experimental bumpers.

NOTES: 1. Unflagged symbols denote foam density of 4.1 pcf; flagged symbol denotes foam density of 5.1 pcf (reference configuration)

2. Open symbols denote impact velocity of 25 mph; filled symbol denotes impact velocity of 20 mph.

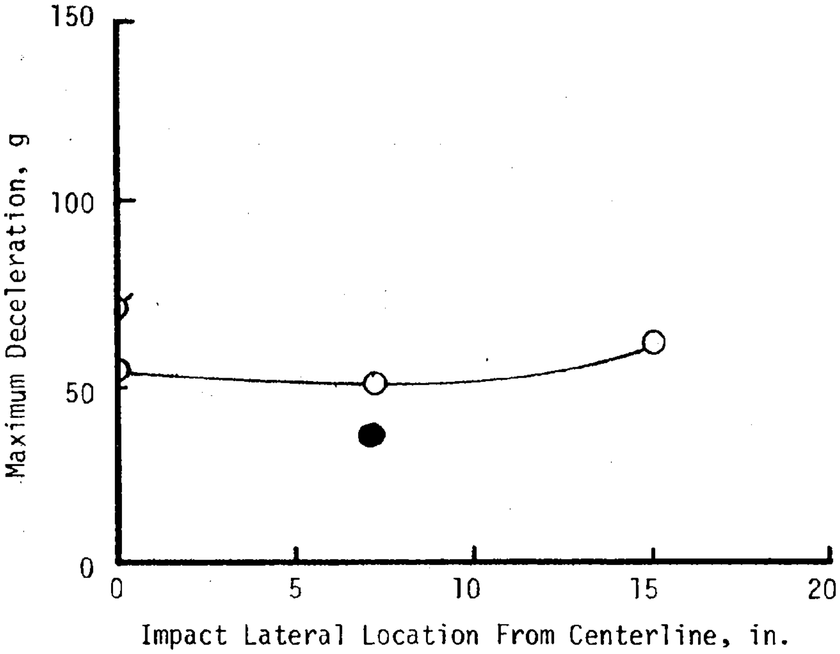


FIGURE 25. MAXIMUM DECELERATION OF CHILD DUMMY PELVIS FROM IMPACT BY CALSPAN RSV IN SLED TEST

NOTES: 1. Unflagged symbols denote foam density of 4.1 pcf; flagged symbol denotes foam density of 5.1 pcf (reference configuration)

2. Impact velocity - 25 mph

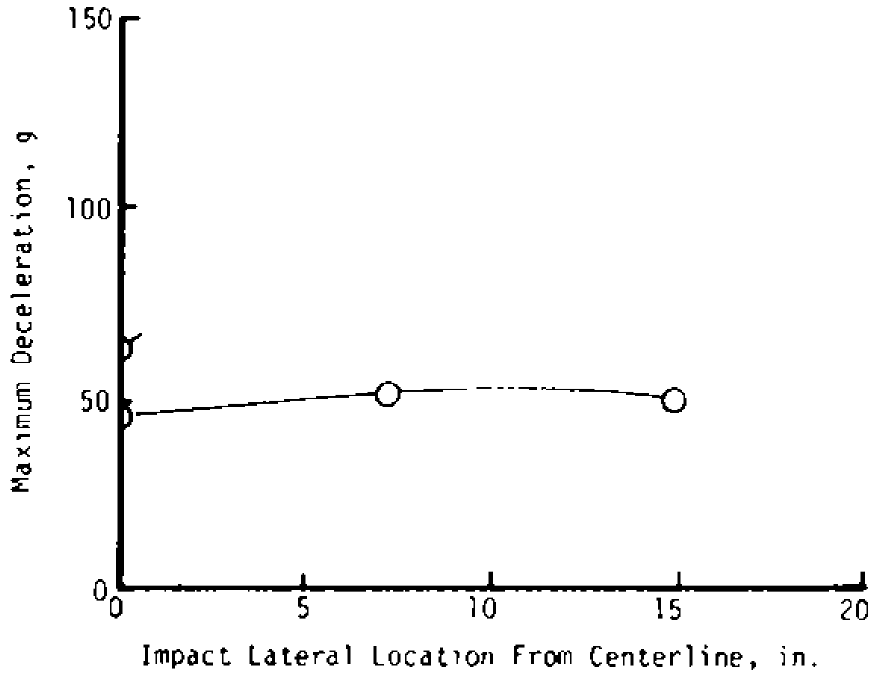


FIGURE 26. MAXIMUM DECELERATION OF ADULT DUMMY KNEE FROM IMPACT BY CALSPAN RSV IN SLED TEST

(1) For a fixed foam density of 4.1 pcf and an impact speed of 25 mph, the maximum deceleration levels recorded for the child dummy's pelvic region vary with the lateral location of bumper contact much like the trend indicated by pneumatic impactor data, i.e., peak deceleration tends to increase with increasing outboard distance from centerline. For the same test conditions as the child, the maximum deceleration levels experienced by the adult dummy's knee exhibit an unexpected behavior in that maximum deceleration levels do not vary significantly with outboard distance.

(2) At an impact speed of 25 mph on bumper centerline, the maximum deceleration recorded for the child dummy's pelvis is significantly higher for the RSV contractor-designed front end than for the experimental configuration (4.1 pcf). For the same test conditions as the child, the maximum deceleration level experienced by the adult dummy's knee is also higher for the RSV contractor-designed front end than for the experimental configuration (4.1 pcf). This result is consistent with data obtained for these bumpers by means of the pneumatic impactor.

In examining post-test damage of the Calspan RSV test buck, it was noted that in all impacts involving the adult dummy, deformation of the hood leading edge portion of the front end by the pelvic region resulted in yielding of the top horizontal cross member supporting the top of the front end fascia and foam filler assembly.

3.5 DAMAGEABILITY EXPERIMENTAL RESULTS

In this subsection results are presented from damageability experiments involving the Mod I front end concept designed for the 1978/1979 LeMans. The results are presented in three groups: (1) pendulum impact; (2) low-speed impact; and (3) low-speed car-to-car impact.

3.5.1 Pendulum Impact

Results of the pendulum impact tests performed on the Mod I bumper system are summarized in Table 19 and Figures 22 through 31. As indicated in Table 19, the test matrix included three impact sites (at the vehicle longitudinal centerline, 18 inches from the vehicle's longitudinal centerline, and at the corner) and three nominal test temperatures (0°F, 60°F, and 100°F). A striker impact line height of 20 inches was judged to be critical from the standpoint of meeting the Plane B loading requirements of Part 581 and, therefore, was utilized throughout the subject test series.

On an overall basis, the Part 581 requirements of 5 mph for frontal impacts and 3 mph for corner impacts were approached but not satisfied by the Mod I bumper system. At room temperature (note Part 581 currently only requires room temperature evaluation), the threshold no damage impact velocities are (1) approximately 3.5 mph for frontal impacts and (2) about 2.5 mph for corner impacts. Other observations are as follows.

(1) As expected, the stiffness of the Mod I elastomeric bumper system exhibits considerable temperature sensitivity, e.g., at a frontal impact velocity of 3.5 mph, the peak bumper impact force is 1.33 times greater for a 0°F impact than it is for a 60°F impact.

(2) Stiffness sensitivity to temperature at the elevated test temperature is somewhat masked by actual or near bottoming out of the elastomeric elements. However, on a relative deflection basis it can be seen from inspection of Figure 28 that for a 3 mph frontal impact, the peak deflection for a 100°F impact will be approximately 1.2 times greater than for a 60°F impact, and about 1.7 times greater than for a 0°F impact.

TABLE 19. SUMMARY OF PENDULUM TEST DATA FOR 1978 LEMANS EQUIPPED WITH MOD-I FRONT END

Davidson Run No.(a)	Nominal Test Temperature, deg F	Lateral Position of Impact on Bumper, in.	Impact Speed, mph(b)	Impact Force, lb			Bumper Deflection, in.
				Total	Plane A	Plane B	
4400	0	0	3.51*	1915	0	1210	6.40
4391	60	0	2.98	652	0	692	7.60
4393	60	0	3.44*	1250	0	1090	9.04
4394	100	0	3.00*	832	88	848	9.14
4398	0	18	3.51	2550	0	532	5.51
4401	0	18	3.49	2280	0	860	5.48
4402	0	18	4.13	2950	25	1315	6.30
4403	0	18	4.52*	3800	0	1770	6.86
4390	60	18	2.98	1328	0	980	6.96
4392	60	18	3.50*	1824	0	1580	7.66
4395	100	18	3.01	1324	24	960	N.A.
4396	100	18	3.01*	1424	24	1124	8.48
4398	0	corner	2.66*	1056	0	136	5.26
4388	60	corner	2.18	492	0	296	5.08
4389	60	corner	2.52*	1252	0	1052	6.16
4397	100	corner	2.10*	840	0	292	6.22

(a) Test Vehicle Weight - 3230 lbs.
Vertical Position of Pendulum Striker = 20 in.above the ground plane.
Pendulum Weight = 3278 lbs.

(b) Asterisk denotes maximum value of impact speed attempted.

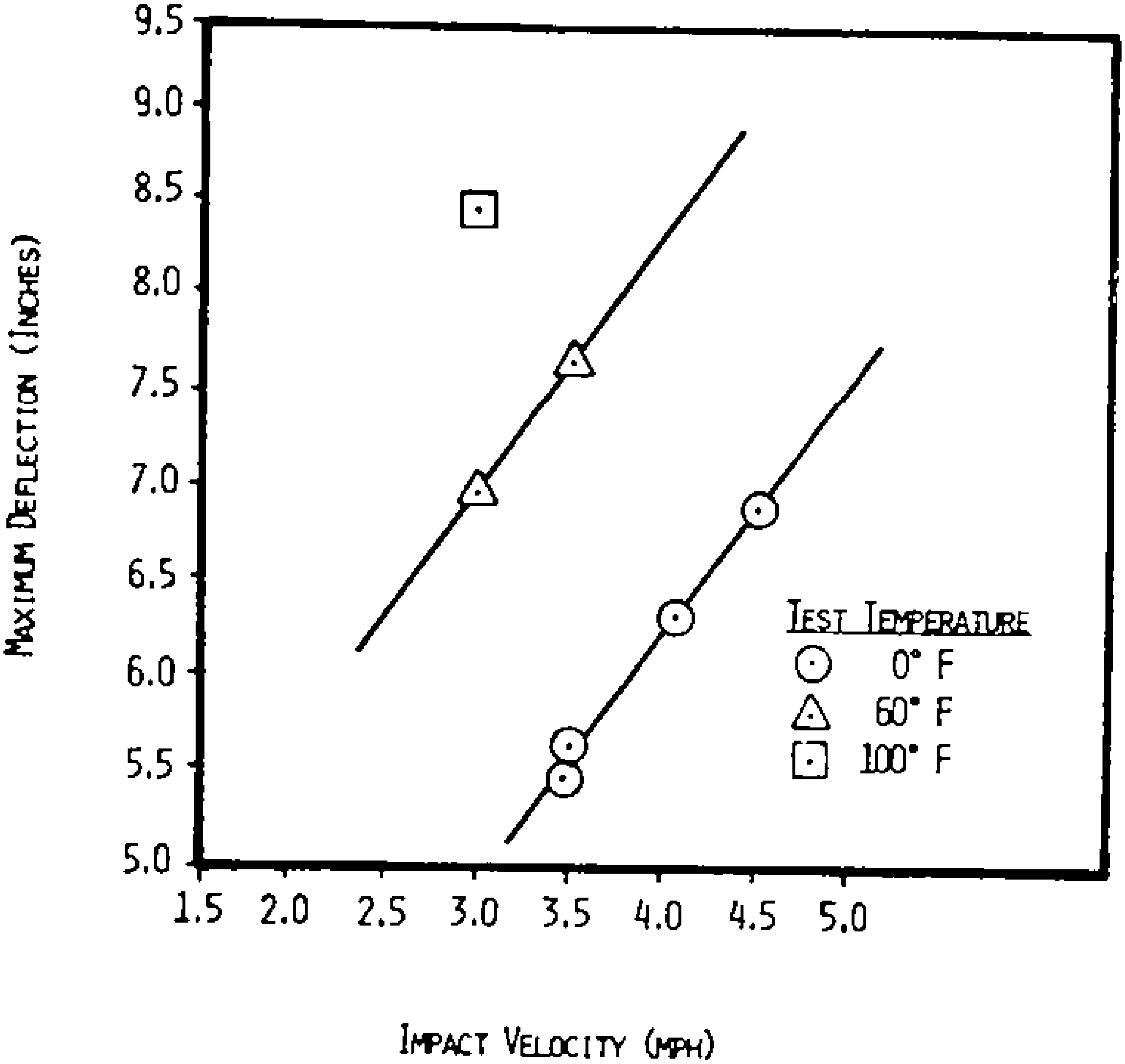


FIGURE 27. MAXIMUM DEFLECTION VS PART 581 STRIKER IMPACT VELOCITY (IMPACT SITE 18" FROM LONGITUDINAL CENTERLINE OF VEHICLE)

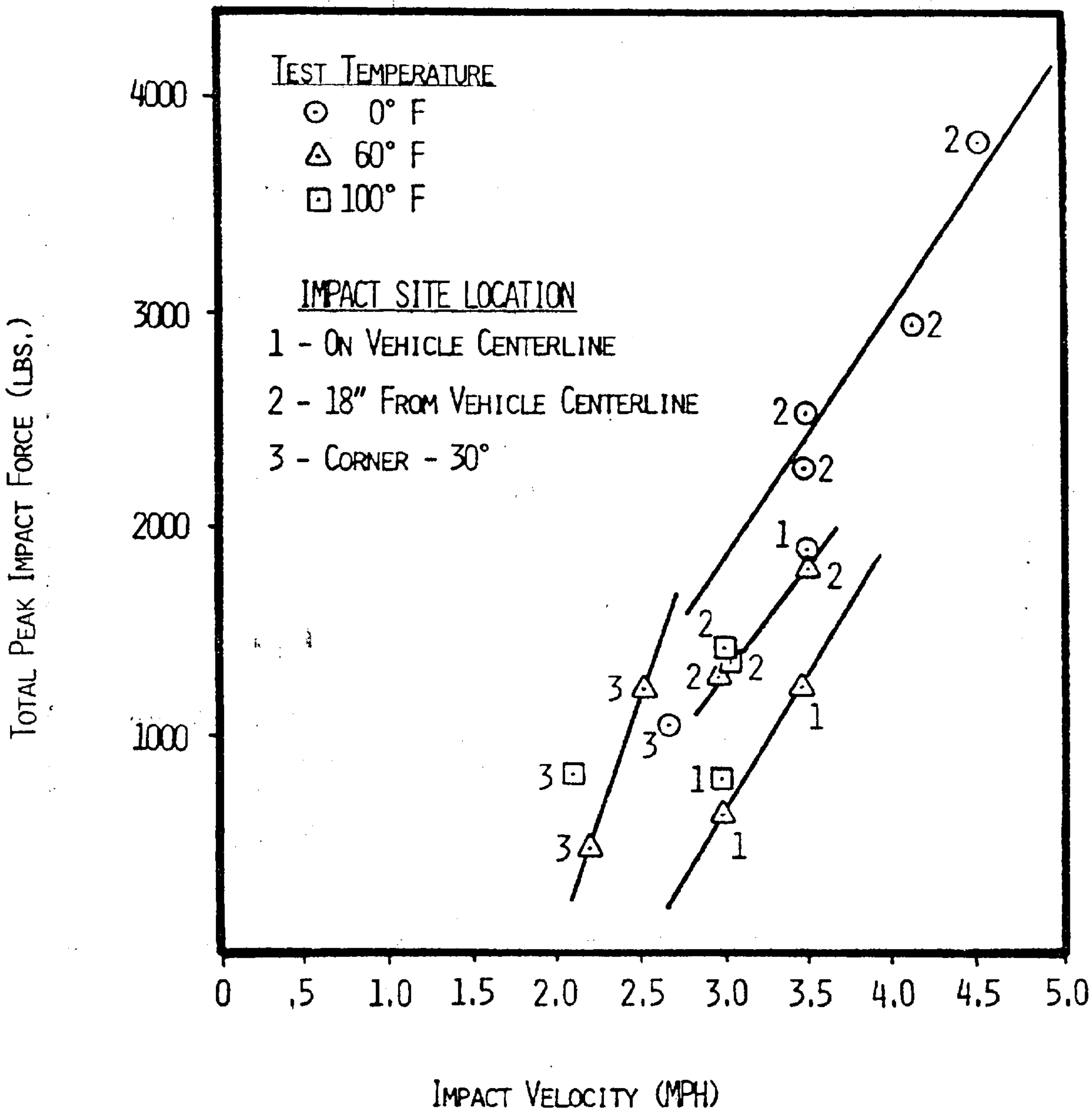


FIGURE 28. TOTAL PEAK IMPACT FORCE VS PART 581 STRIKER IMPACT VELOCITY

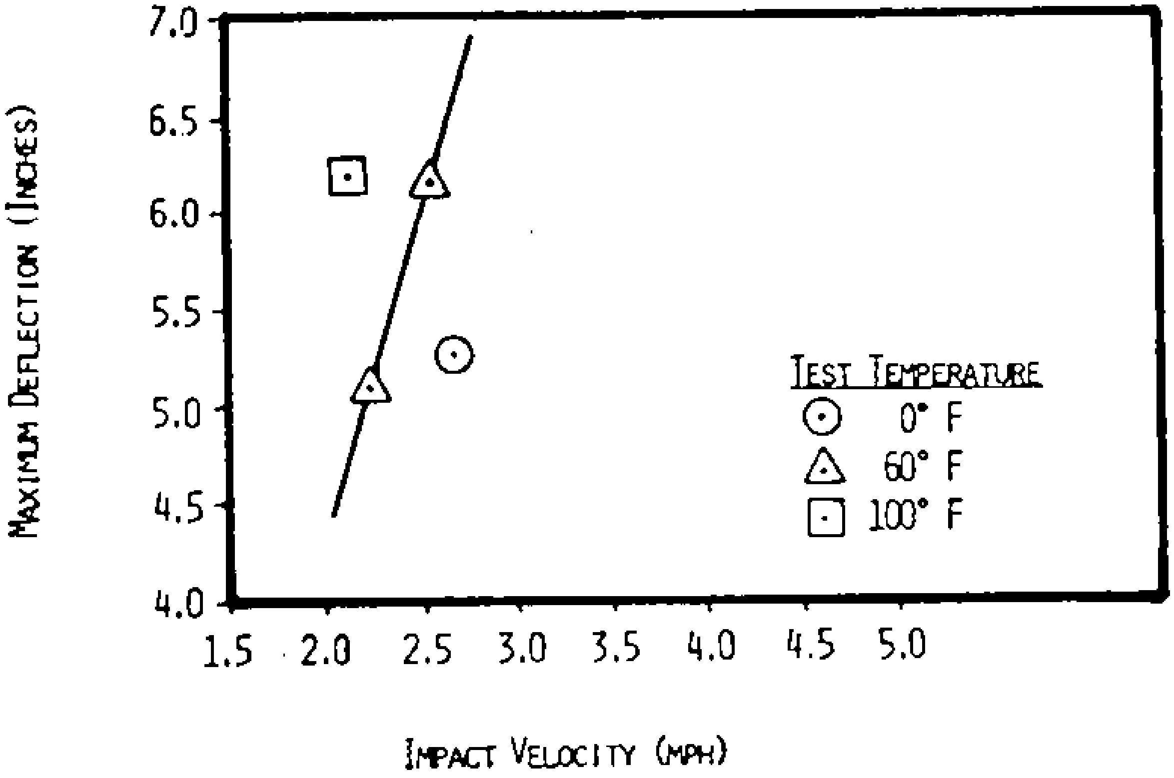


FIGURE 29. MAXIMUM DEFLECTION VS PART 581 STRIKER IMPACT VELOCITY (CORNER IMPACT - 30°)

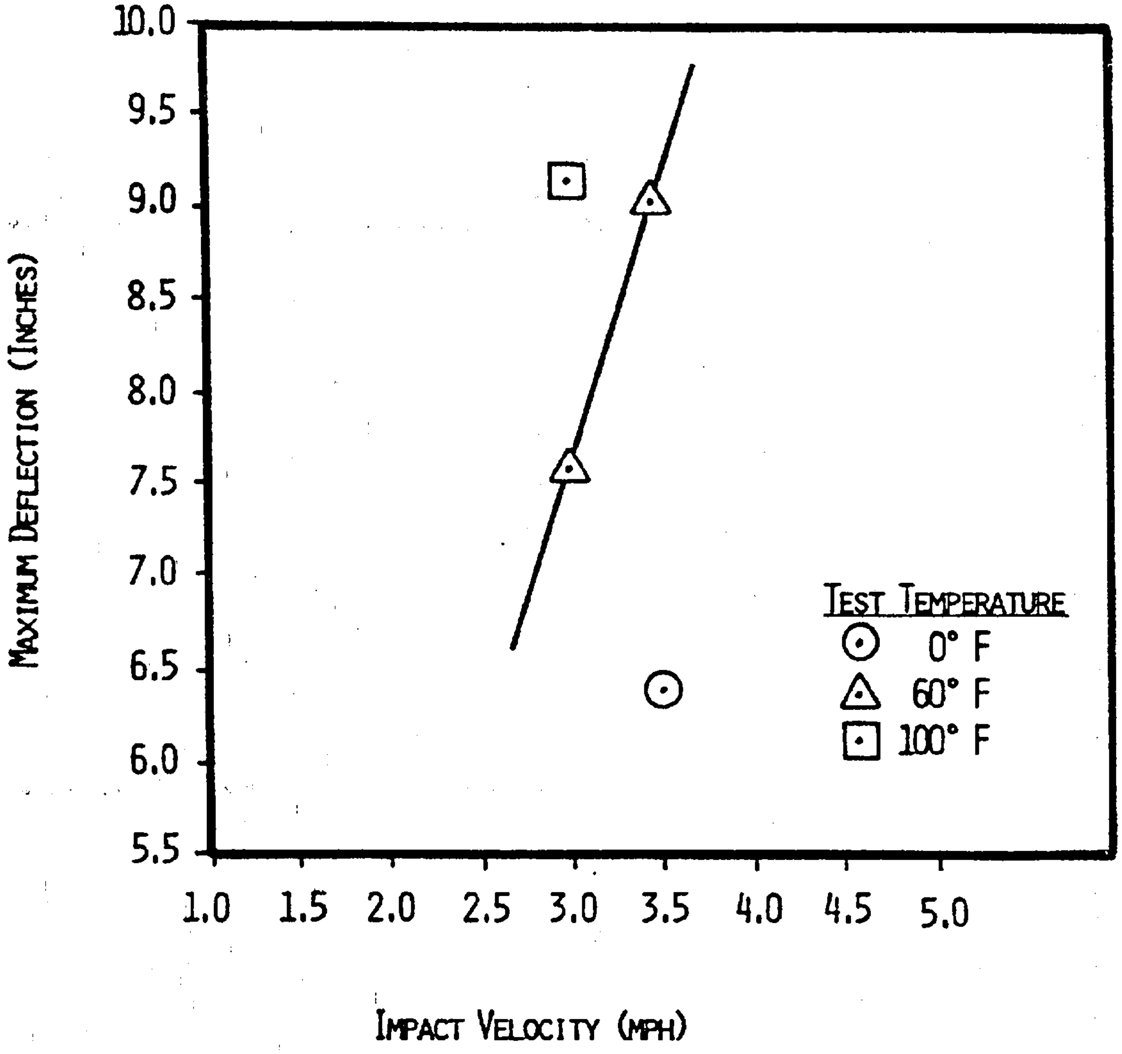
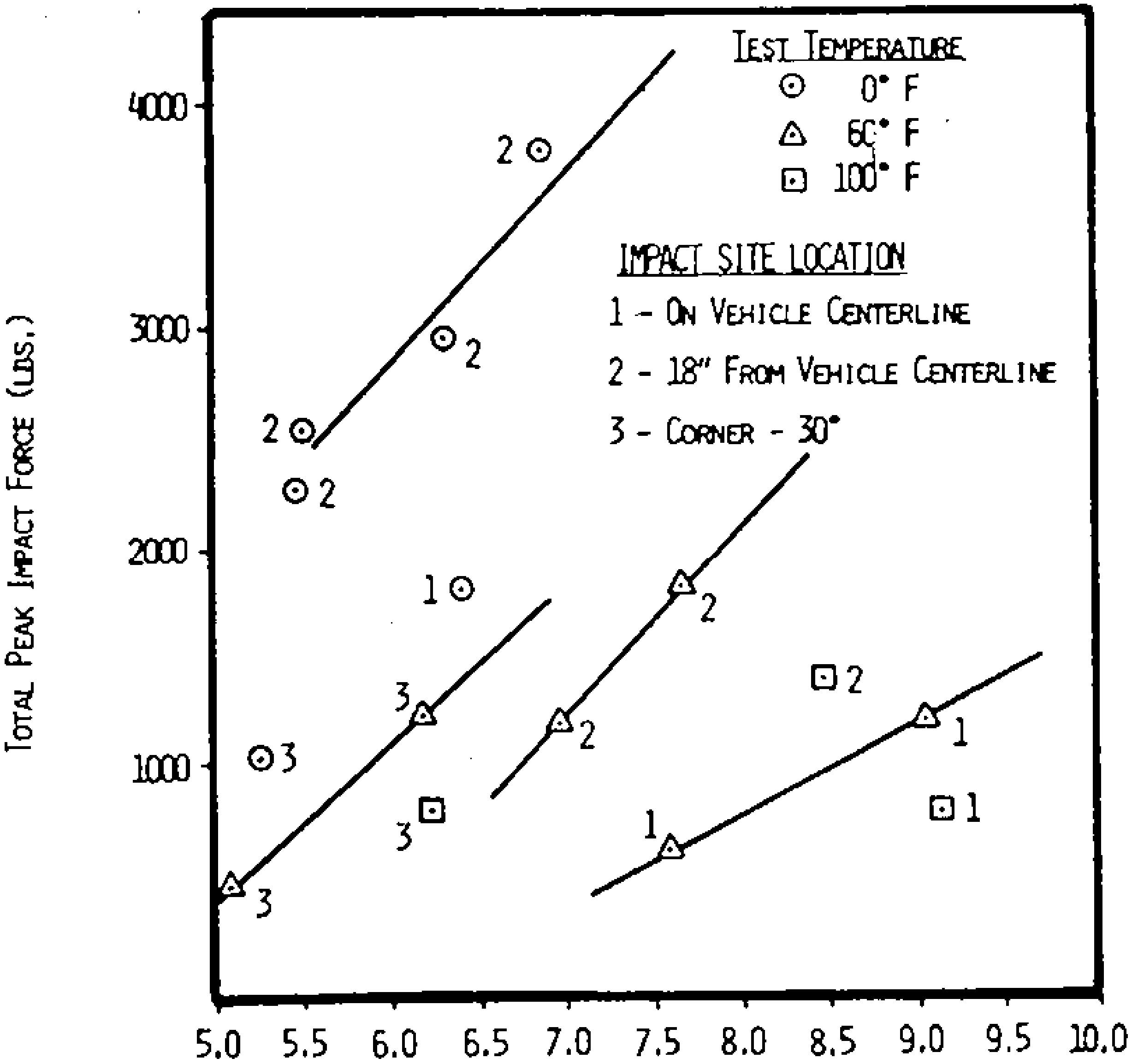


FIGURE 30. MAXIMUM DEFLECTION VS PART 581 STRIKER IMPACT VELOCITY (IMPACT SITE ON LONGITUDINAL CENTERLINE OF VEHICLE)



BUMPER DEFLECTION (INCHES)

FIGURE 31. TOTAL PEAK IMPACT FORCE VS MAXIMUM BUMPER DEFLECTION

(3) In some cases (especially the 100°F tests and the corner impacts) the impact velocity capability of the Mod I bumper system was limited by the available stroke, and in other cases (e.g., the frontal cold tests), by the Part 581 restriction of 2000 lbs, for the combination of Plane A and Plane B forces.

Considering that the Mod I configuration is only a first generation design, the results recorded above are generally encouraging. Runs 4395, 4396 and 4400 were the only runs in which appreciable damage (e.g., tearing of the fascia and shearing of the hood leading edge support plate attachments) were noted.

There are several ways of viewing the effects of ambient temperature on the pendulum impact performance of the Mod I front end configuration. The data suggest that for a given impact energy (in these tests, the same as impact speed, because the impacting areas remain constant) the bumper deformation increases in rough proportion with increasing ambient temperature. However, for a given maximum physically allowable bumper deflection, a lower ambient temperature allows a greater amount of energy absorption (i.e., higher impact speed to obtain the maximum deflection).

3.5.2 Low-Speed Barrier Impact

The 1978 LeMans, fitted with a Mod I front end (see Figure 16) was subjected to four low-speed (nominal 5 mph) barrier impacts. Test conditions and results are summarized in Table 20.

Although the no-damage result obtained for Run B-1 was encouraging, the impact speed of 3.5 mph was well below the 5 mph required by FMVSR Part 581. For the subsequent Run B-2 at 4.9 mph, no damage was observed on the bumper. However, the backbar of the hood leading edge from insert was slightly deformed, and the left front fender was dimpled in the vicinity of the bumper. No repair cost assessment was attempted for these essentially threshold level damages, because it was reasoned that they would be eliminated by a normal design optimization process.

TABLE 20. SUMMARY OF LOW-SPEED BARRIER IMPACTS

Test Run No.	Barrier Configuration	Ambient Temperature, deg F	Impact Speed V_i-mph	Maximum Bumper Deflection δ-in.	Observed Damage	High-Speed Movie
B-1	Flat concrete impact surface	30	3.5	8.2	None	Yes
B-2	Same as Test No. 1	30	4.9	8.9	Hood leading edge backbar bowed 1/8 in. on one side Fascia - scraped in immediate area on centerline Bumper - none Left front fender - dimple from bumper	Yes
B-3	Wooden member for bumper contact (see Figure 26)	27	4.6	9.5	Left front fender - lower corner deflected inward	Yes
B-4	Same as Test No. 3	27	4.8	[9.6(a)]	Left front fender buckled inboard	Yes

(a) Estimated from high-speed movie.

As noted in Table 20, and also previously mentioned in Subsection 2.3.2, the target impacted by the test vehicle front end in Runs B-3 and B-4 was a wooden beam positioned on the barrier surface to match the bumper height. This test arrangement is sketched in Figure 32. The 4-inch front-to-back depth of the target beam matched the horizontal offset between the bumper and hood leading edges. That barrier configuration can be considered to have conservatively simulated (owing to its extreme stiffness) the front end of another 1978 LeMans having a production front end. Thus, the results of Runs B-3 and B-4 were expected to provide an indication of the performance of the modified front end in a front-to-front collision with a production front end at a closure speed of 10 mph. The minimal damages observed for the modified bumper and the absence of damage to the hood leading edge were encouraging.

3.5.3 Low-Speed Car-to-Car Collision

The low-speed car-to-car collisions are identified, in the chronological order of performance, in Table 21. Actual impact speeds, resulting apparent damage, and availability of movies are indicated. Photographs of pretest car-to-car alignment and collision-induced damage are provided in the Appendix.

Program Run No. 2 was repeated as Run No. 7 because of the low impact speed on Run No. 2. Although a tolerance of ±0.2 mph was desired, Run Nos. 4 and 5 were accepted, because the speeds were on the high side. For Run No. 4, the difference was of no consequence, because no apparent damage resulted. The potential significance of the speed error for Run No. 5 can be estimated by noting that the percentage change in the energy absorbed will be approximately* twice the percentage change in speed**. In this

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* It would be exact if the striking velocity experienced no rebound. Because of the rebound, part of the speed error must be assignable to a change in rebound speed.

** From $E = 1/2\ mV^2$, logarithmic differentiation and replacement of differentials by differences yields

$$\frac{\Delta E}{E} = \frac{\Delta M}{M} + 2\frac{\Delta V}{V} .$$

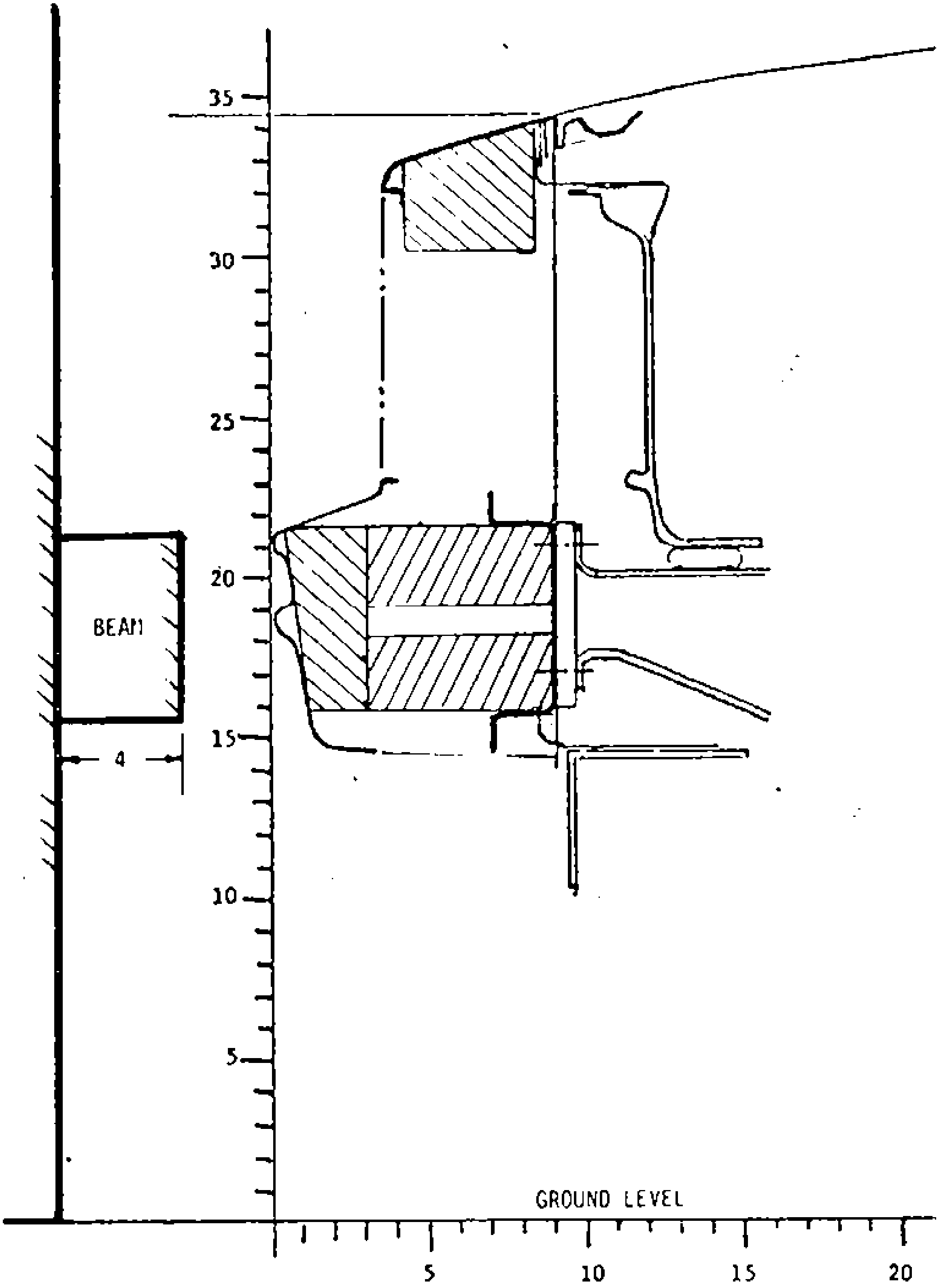

FIGURE 32. BARRIER CONFIGURATION FOR LOW SPEED IMPACT

TABLE 21. SUMMARY OF LOW-SPEED CAR-TO-CAR COLLISION TEST RESULTS

Program Run No. (a)	Vehicle Component for Test Vehicle		Stationary Target Vehicle (c)	Actual Impact Speed, mph	Areas Having Apparent Damage	Movies	
	A	B				High Speed (d)	Documentary (f)
1	Stock front	Stock rear	B	5.0	None	No[e]	Yes
2	Stock (right) side	Stock front	A	4.7	Both door panels	Yes	Yes
3	Stock front	Stock front	A	10.1	None	No[e]	Yes
4	Stock rear	Modified front	A	5.3	None	Yes	Yes
5	Stock (left) side	Modified front	A	5.3	Front door panel	Yes	Yes
6	Stock front	Modified front	A	10.1	Modified bumper beam	Yes	Yes
7[b]	Stock front	Stock (right) side	B	5.0	Front door panel front fender and rear door panel	Yes	Yes

(a) Runs 1-3 were conducted on the same day; Runs 4-7 on another.

(b) Run 7 is a repeat of Run 2.

(c) Test vehicle weights (lb) were: A = 3370; B = 3390.

(d) 1000 Frames/sec; ground level view.

(e) Timing error resulted in the collision event not being recorded.

(f) 24 Frames/sec; includes ground level and elevated level views for Runs 1-3; elevated level views for Runs 4-7.

instance the speed error is 6 percent, and an upper bound to the change in energy absorbed by the target vehicle is 12 percent. Because the consequent damage is not expected to be a linear function of energy absorbed, the percentage change in damage should tend to be greater than the percentage change in energy absorbed; damageability assessments based on the limited damage caused in Run No. 5, therefore, should be on the conservative side.

In all cases of side impact damage (Run Nos. 2, 5, and 7), the apparent damage was confined to outer panels. In no case was intrusion of the passenger compartment detected by permanent deflection of interior surfaces. Doors were readily operable and no apparent damage was sustained by lower pillars or frame.

An item of importance to be noted in Table 21 is the occurrence of damage to the modified bumper system in Run No. 6. That run was the third of three consecutive collisions involving that configuration mounted on the striker vehicle. It is believed that the damage incurred in Run No. 6 (note the higher impact speed) and is assignable to that collision, because post-run visual inspection for the other two collisions had not detected apparent damage.

Damage and cost-to-repair assessments for the production components by three estimators from three different Pontiac dealers* are summarized in Table 22. The repair methodology invoked by the estimators was generally consistent. An exception was in Run No. 2, for which estimator III chose not to reskin (see footnotes for Table 2 for explanation of terminology) the damaged front door. Estimator III also used a low cost for door panel replacement (an adjustment for this difference is indicated for Run No. 5).

It appears from the data of Table 22 that the cost of repairing vehicle side damage from impact by a modified bumper system is less than that from impact by a stock bumper system (compare average estimated cost

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* One estimator was from Bellefontaine, Ohio, where the test cars were obtained; two were from Columbus, Ohio. Estimators were not informed of the circumstances surrounding the damage.

TABLE 22. COMPARATIVE DOOR REPAIR COSTS FOR FRONT-TO-SIDE CAR-TO-CAR IMPACTS

Program Run[a]	Vehicle Component for Test Vehicle		Stationary Target Vehicle	Actual Impact Speed mph	Damage Description - Repair Approach (Itemized)	Estimation of Repairs (Cost Without Tax)			
						Estimator			Average ±(1) Standard Deviation
	A	B				I	II	III	
2	Stock side	Stock front	B	4.7	Right front passenger door damage - reskin[b]	$225.78	$231.05	$145.60[d]	
					Right rear passenger door damage - putty[c]	64.78	64.95	68.60	
						$290.56	$296.00	$214.20	$266.92 ± 46
7	Stock front	Stock side	B	5.0	Right front fender damage minor - putty	50.24	24.40	24.23	
					Right front passenger door damage - reskin	225.78	220.15	294.69	
					Right rear passenger door damage - putty	66.98	73.20	72.67	
						$343.00	$317.75	$391.59	$350.78 ± 38
5	Stock side	Modified front	A	5.3	Left front (driver's) door damage - reskin	225.78	$244.00	217.26[e]	
								39.25[g]	
						$225.78	$244.00	$256.51	$242.10 ± 15
5	Stock side (normalized to 5 mph)	Modified front	A	5.0		$173.34	$222.25	$118.37	$171.32 ± 52 or $197.80 ± 35[f]

(a) See Table 21 for total test matrix.
(b) Reskin means panel replacement.
(c) Putty means to recontour and cosmetically repair.
(d) No reskin - rebend and putty.
(e) Replacement panel price misquoted.
(f) Average for estimates I and II alone.
(g) Cost difference of panel,
$113 (estimated by I and II)
$73.75 (estimated by III).

Sample Calculation (Estimation of 5 mph damage for Program Run 5)

$$[C] - \left[\frac{(A) - (B)}{4.7 \text{ mph} - 5.0 \text{ mph}}\right] (5.3 \text{ mph} - 5.0 \text{ mph}) = D$$

$A \triangleq$ Cost to repair Program Run 2.
$B \triangleq$ Cost to repair Program Run 7.
$C \triangleq$ Cost to repair Program Run 5.
$D \triangleq$ Normalized to 5 mph cost for Program Run 5.

of the three estimators for Run Nos. 5 and 7*). In an attempt to make the average repair cost estimate for Run No. 5 more directly comparable to that of Run No. 7, a cost scaling computation has been performed to adjust the Run No. 5 results to an impact speed of 5.0 mph. This scaling assumes a linear relationship between cost-to-repair and impact speed. As discussed previously, it is probable that a nonlinear relationship exists between damage and impact speed and, therefore, that a linear type of scaling will produce a conservative result. An assumed linear relationship between cost-to-repair and impact speed actually involves two intermediate linear assumptions: (1) between damage (i.e., physical distortion) and impact speed; and (2) between cost-to-repair and damage.

In Run No. 6 (the 10 mph front-to-front collision involving modified and stock bumpers) the modified bumper system itself sustained minor damage. Battelle has chosen to exclude a cost-to-repair value for this damage (i.e., minor deformation of the bumper backbar shown in Figure A-6 in the Appendix)for the following reasons.

(1) The damage to the bumper backbar suggests a marginally-designed beam strength for this specific hardware implementation. It is believed that in a fully developed design (particularly one intended for production), no-damage performance capability would be readily attained without compromise to pedestrian protection performance.

(2) Because the backbar for the modified bumper system is not a production type of automotive item, it was not reasonable to expect the automotive damage estimators to render meaningful judgment on the cost of repair

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* By definition, if Run No. 2 had been conducted at an impact speed of 5.0, the cost to repair would have been identical to that of Run No. 7. This comparison assumes identical target areas involved (note the inadvertent involvement of a fender in Run No. 7).

Thus, it is suggested that the apparent difference in damage to the striking vehicle of the stock over the early generation modified bumper system in the 10 mph front-to-front collision mode is not significant.

4.0 DISCUSSION OF RESULTS

Having examined the results obtained from the various test series on an individual basis, a broader viewpoint can be established through selective comparison of several sets of those tests. For this purpose, the following comparisons are discussed.

- The relative effectiveness of a promising first generation front end modification, to a production Pontiac LeMans as measured by the various experimental techniques used in the present study.
- The relative effectiveness of a front end modification to the Phase IV Calspan RSV as measured by the pneumatic impactor and sled techniques.

4.1 EFFECTIVENESS OF A FIRST GENERATION PONTIAC LEMANS FRONT-END MODIFICATION

The most comprehensive collection of experimental data produced by this study for a given pedestrian compatible vehicle front-end modification is for the Pontiac LeMans Mod I configuration (see Figures 15 and 16). The subject data base includes

- Pedestrian safety performance data obtained by
  - Pneumatic impactor measurements
  - Sled impacts
- Low speed damageability performance data observed in
  - Barrier impacts
  - Pendulum-type impacts
  - Car-to-car collisions.

Comparative data on maximum knee/leg impact deceleration (or acceleration) for the production and Mod I LeMans bumpers are shown in Table 23. As measured by the pneumatic impactor technique with a developmental 11.4-lb striker configuration, a 63 percent improvement in performance

TABLE 23. COMPARISON OF DATA OBTAINED WITH PNEUMATIC IMPACTOR AND SLED TECHNIQUES FOR PONTIAC LEMANS

Notes: 1. Nominal impact location 18-in. outboard from vehicle centerline.

2. Data scaled to 25 mph as necessary.

Test Technique	Maximum Knee/Leg Deceleration, a_{max} - g		Change Due to Modification, percent
	Production	Mod I	
Pneumatic Impactor With Knee/Leg Striker			
• 11.4-lb Striker	193	72	63
• 7.25-lb striker	[186](a)	69	[63](a)
Sled-Mounted Test Buck Impacting 50th Percentile Adult Male Dummy	350	120	66

(a) See text.

(i.e., a reduction in maximum deceleration) was achieved with the Mod I configuration. To facilitate comparison with data obtained later with a 7.25-lb striker, the performance for the production bumper under impact with a 7.25-lb striker has been estimated from the measured Mod I performance together with an assumption that the performance improvement is the same 63 percent obtained with the heavier striker. As shown in Table 23, the performance gain measured with the pneumatic impactor (heavy striker) was basically confirmed by the 66 percent improvement observed for the sled impact on the 50th percentile adult male dummy; however, there is considerable difference in the measured accelerations between the two techniques for a given bumper configuration. The higher levels obtained by the sled experiments suggest a mismatch in the mass/stiffness characteristics of the striker and the knee/leg area of the dummy. Since the striker response is reasonably well matched to the cadaveric specimen response (see discussion in Subsection 2.1.3), the reason for this discrepancy is presently attributed to the dummy. Resolution of this question should be facilitated by planned further work involving cadaveric specimen response to sled impacts with both the production and Mod I LeMans.

4.2 EFFECTIVENESS OF A CALSPAN RSV FRONT-END MODIFICATION

As previously described in Subsections 3.3.1 and 3.4.2, the original Phase IV Calspan RSV front end, along with three foam insert modifications, were subjected to 25 mph impacts using both pneumatic impactor and sled experimental techniques. Here, a comparison is made in Table 24 to illustrate the effectiveness of a foam insert that is more compliant than the insert selected by Calspan (recall that for the data tabulated, the increased compliance was achieved by simultaneous reduction of modulus from 33 to 16 psi and density from 5.1 to 4.1 pcf).

TABLE 24. COMPARISON OF DATA OBTAINED WITH PNEUMATIC IMPACTOR AND SLED TECHNIQUES FOR CALSPAN RSV

Notes: 1. Impact on vehicle centerline

2. Data corrected to 25 mph as necessary.

	Maximum Knee/Leg Deceleration, a_{max} - g		
Test Technique	Phase IV	4.1 Pcf/16 Psi Foam Modification	Change Due to Modification, percent
Pneumatic Impactor With 7.25-lb Knee/Leg Striker RSV Front End Mounted on Test Fixture	88	62	30
Sled-Mounted Test Buck Impacting 50th Percentile Adult Male Dummy	71	45	37

The data in Table 24 indicate a 30 percent improvement in performance measured by pneumatic impactor (7.25-lb knee/leg striker) impacting upon a fixture-mounted bumper. Data from the sled impact upon the knee of the 50th percentile male adult dummy exhibit a similar gain (37 percent improvement).

Unlike the data from the LeMans, the Calspan RSV deceleration levels observed with the pneumatic impactor are higher than those obtained with the sled. The reason for this trend reversal from the LeMans is not presently understood. One possible explanation is that the initial spike is very sensitive to the configuration of the leading edge of the fascia. In this particular case, the leading edge of the LeMans fascia (see Figure 14) has a fairly sharp radius (approximately 0.25 in.) and also has a stiff nerf strip, while the Calspan fascia (see Figure 18) has an essentially flat leading edge. Another possible reason may be in the fit of the fascia over the foam. The LeMans fascia has a relatively loose fit over its foam insert which in effect may be a less stiff combination than the Calspan assembly in which the fascia is snugly fitted to its foam insert.

5.0 CONCLUSIONS

Numerous specific findings and tabulations of data are presented throughout this report. The purpose of this conclusions section is to set forth several major conclusions which can be drawn at a relatively high generic level. In particular, three topics warrant commentary.

(1) Expansion of a useful data base created by the previous Battelle studies.

(2) Development of a compliance test methodology that appears capable of reliably discriminating, on a pass/fail basis, the pedestrian safety performance of a vehicle front end. This conclusion indicates the attainment of two of the three major objectives of the project (see Subsection 1.2).

(3) Achievement of safety performance levels by potentially practical bumper configurations that are supportive of pedestrian knee/leg injury mitigation and yet show promise of being able to accommodate low speed damageability concerns. This conclusion reflects achievement of the third major objective of the project.

The present study has contributed significant new information to the data base on pedestrian safety performance of vehicle front end design concepts, particularly in regard to bumper impacts with the knee/leg area. These additional data (1) represent several kinds of recent vehicle front end designs, (2) demonstrate the flexibility available to a designer in the use of foamed polymers (in particular, polyurethane), and (3) characterize the velocity and temperature sensitivities that must be considered in utilizing such design concepts.

The present study also has shown that, even without extensive iterative design optimization, safety performance levels relatable to significant reduction in permanent disability (in particular, to the knee/leg area) can be achieved while simultaneously (1) approaching the presently required low-speed damageability capabilities and (2) using contemporary vehicle space allocations and materials. Furthermore, the study has shown that the pneumatic impactor developed during this project is a useful tool in empirically converging upon bumper designs that can exhibit such characteristics.

The basic objective of developing a straightforward, pedestrian safety compliance test methodology has been met. To date, this methodology has been developed to examine knee/leg injury severity caused by bumper contact. Further work planned and/or in progress will extend the scope of the methodology and associated data base to include pelvic/upper leg and head/shoulder injury mitigation.

6.0 RECOMMENDATIONS

On the basis of the results obtained thus far, three basic recommendations for subsequent activity are suggested:

(1) Further verify/refine the mass, geometric shape and material choice specifications for the striker representation of the knee/leg anatomical segment. This can be accomplished through a well defined set of experiments on cadaveric specimens and complementary verification experiments using the pneumatic impactor.

(2) Develop/define a standardized front-end configuration for calibration of the pneumatic impactor.

(3) Round out the development of the compliance test criteria with the addition of pneumatic impactor striker representations of the pelvic/leg and head/shoulder/chest anatomical segments.

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APPENDIX A
PHOTOGRAPHS FROM CAR-TO-CAR COLLISION TESTS

Notes:
(1) Run No. 1.
(2) Vehicle B struck by Vehicle A.
(3) Actual impact speed - 5 mph.
(4) Apparent damage - none to either vehicle.

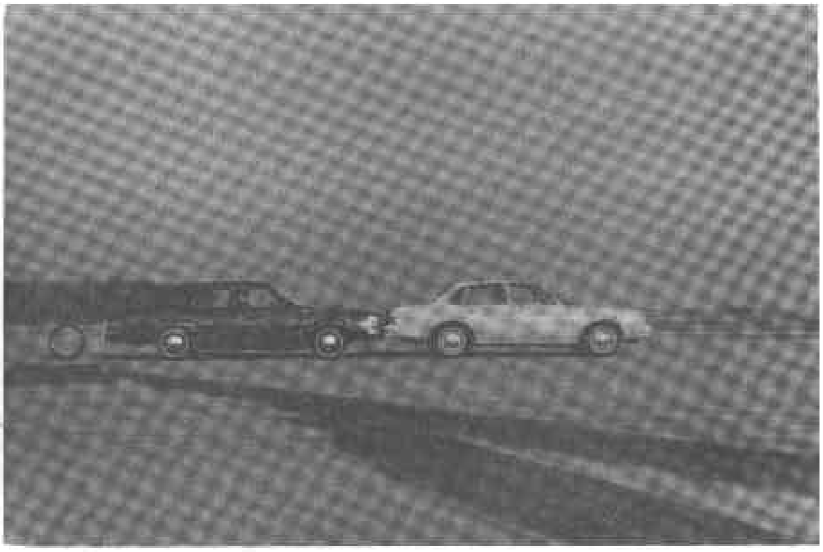
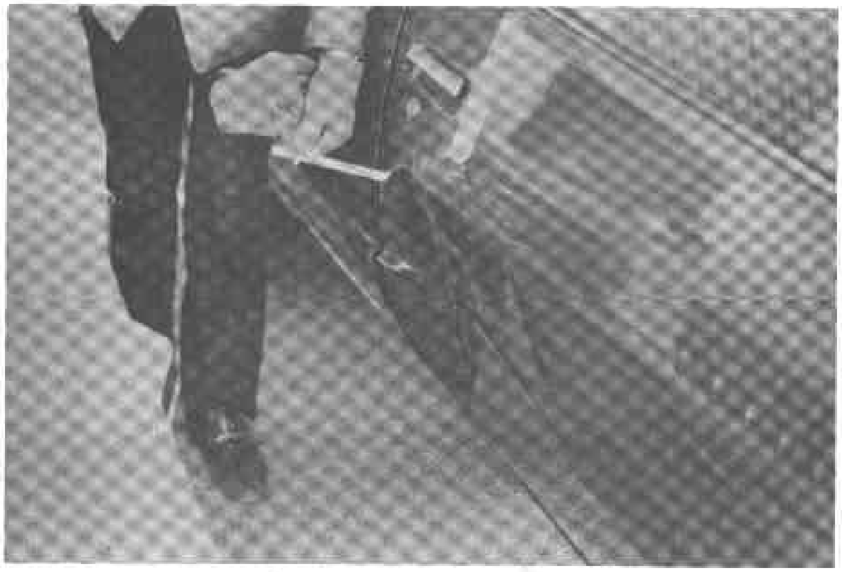


FIGURE A-1. 5-MPH FRONT-TO-REAR COLLISION AT INSTANT OF IMPACT; STOCK FRONT BUMPER

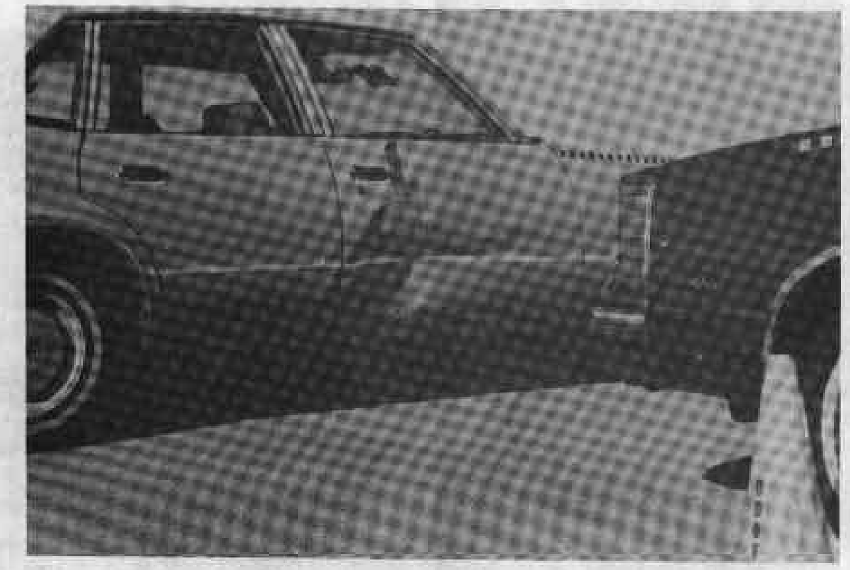
(a) At Instant of Impact



(b) Apparent Damage to Vehicle A

FIGURE A-2. 5-MPH FRONT-TO-SIDE COLLISION: STOCK FRONT BUMPER

Notes:
(1) Run No. 2.
(2) Vehicle A struck by Vehicle B
(3) Actual impact speed - 4.7.
(4) Apparent damage - none to Vehicle B,
see Figure A-2(b) for damage to Vehicle A.



(c) Side View of Damage

Notes:

(1) Run No. 7 (repeat of Run No. 2)
(2) Vehicle B struck by Vehicle A
(3) Actual impact speed - 5.0 mph
(4) Apparent damage - none to Vehicle A

(d) Three-Quarter Rear View of Damage

FIGURE A-2. (Continued)

Notes: (1) Run No. 3.
(2) Vehicle A struck by Vehicle B.
(3) Actual impact speed - 10.1 mph.
(4) Apparent damage - none to either vehicle.

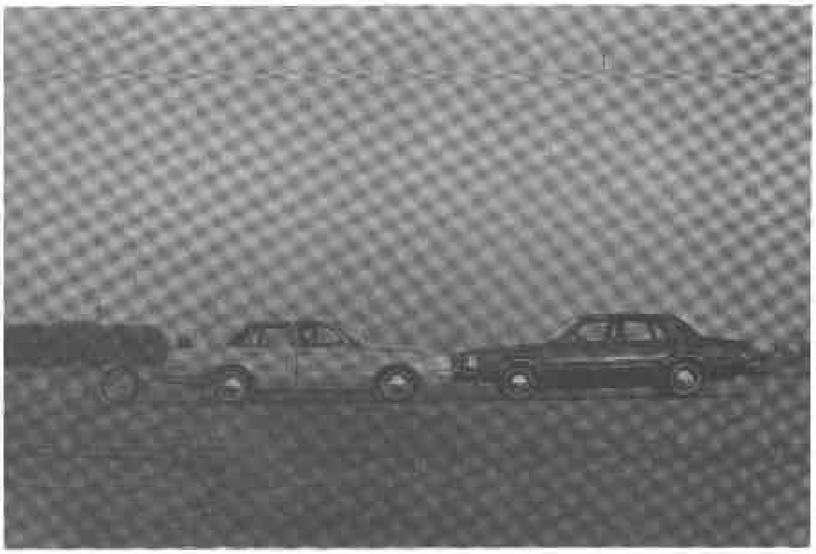


FIGURE A-3. 10-MPH FRONT-TO-FRONT COLLISION AT INSTANT OF IMPACT: STOCK FRONT BUMPERS

Notes:
(1) Run No. 4.
(2) Vehicle A struck by Vehicle B.
(3) Actual impact speed - 5.3 mph.
(4) Apparent damage - none to either vehicle.

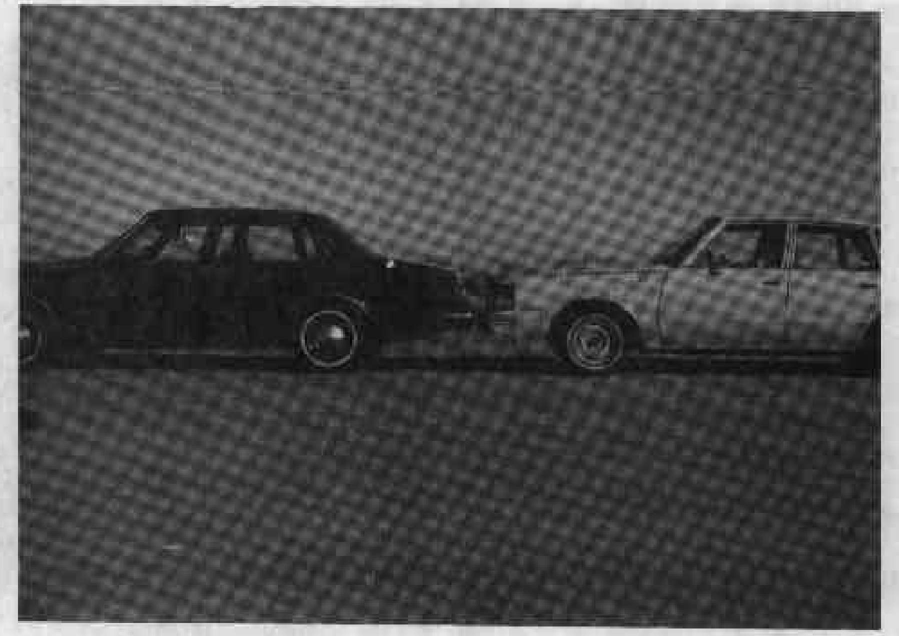
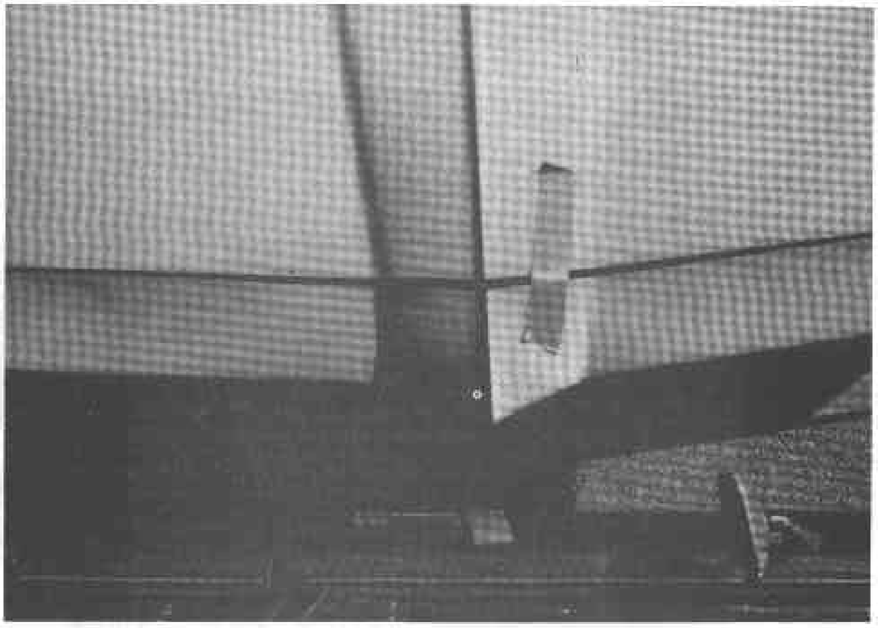


FIGURE A-4. 5-MPH FRONT-TO-REAR COLLISION; PRETEST ALIGNMENT: MODIFIED FRONT BUMPER

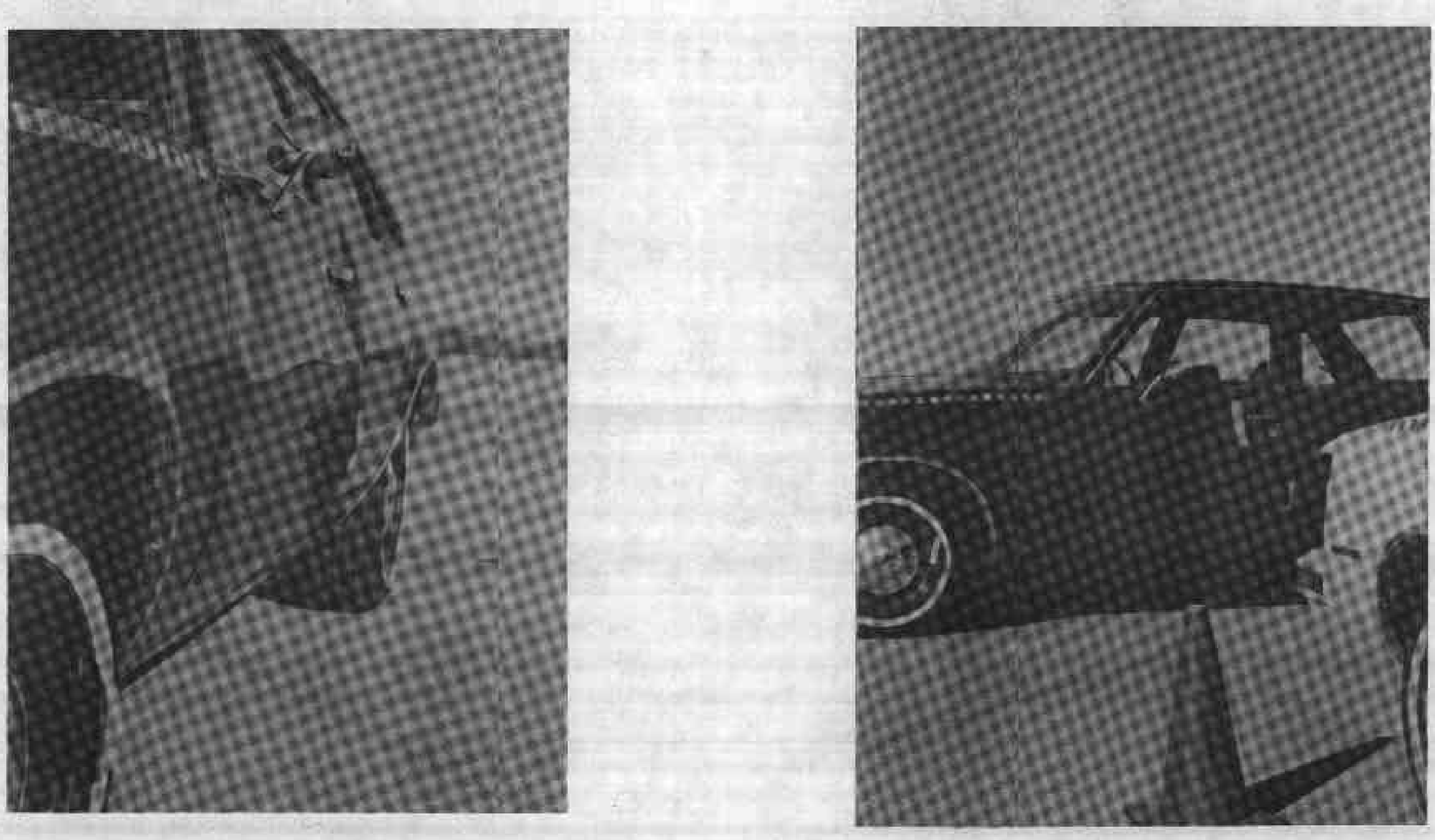


(a) Overhead View of Pretest Alignment

(b) End View of Pretest Alignment

FIGURE A-5. 5-MPH FRONT-TO-SIDE COLLISION; MODIFIED FRONT BUMPER

Notes: (1) Run No. 5.
(2) Vehicle A struck by Vehicle B.
(3) Actual impact speed - 5.3 mph.
(4) Apparent damage - none to Vehicle B.

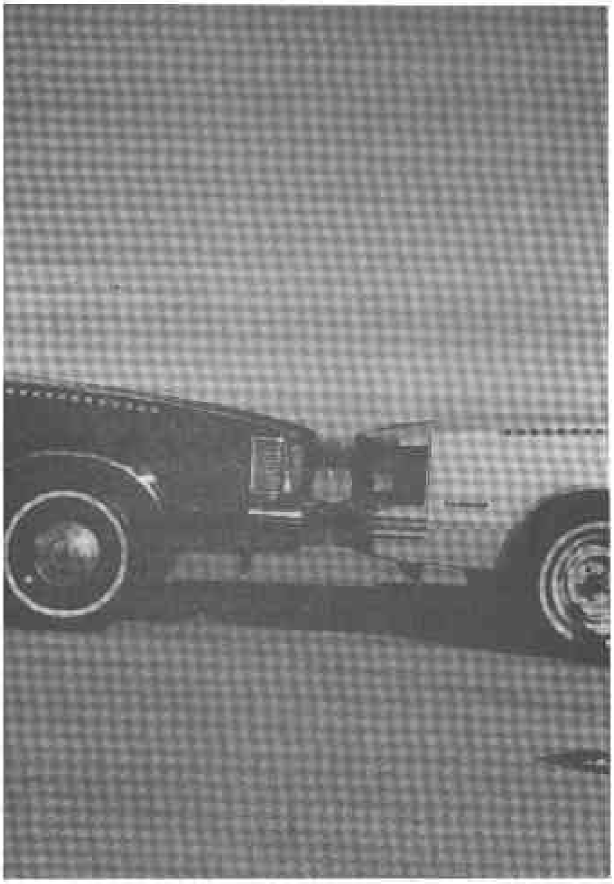


(c) End View of Damage

(d) Side View of Damage

FIGURE A-5. (Continued)

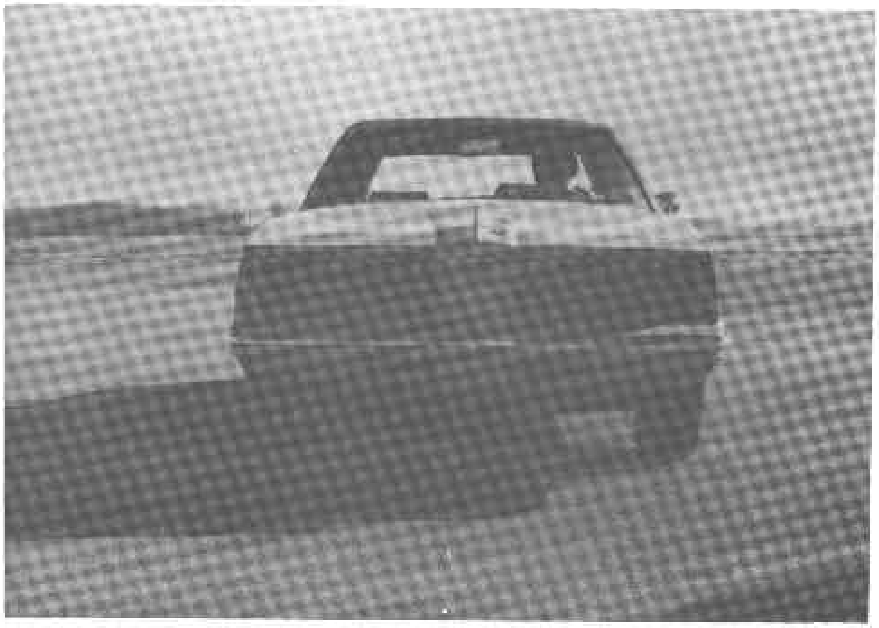
Notes:
(1) Run No. 6.
(2) Vehicle A struck by Vehicle B.
(3) Actual impact speed - 10.1 mph.
(4) Apparent damage - none to Vehicle A.



(a) Pretest Alignment

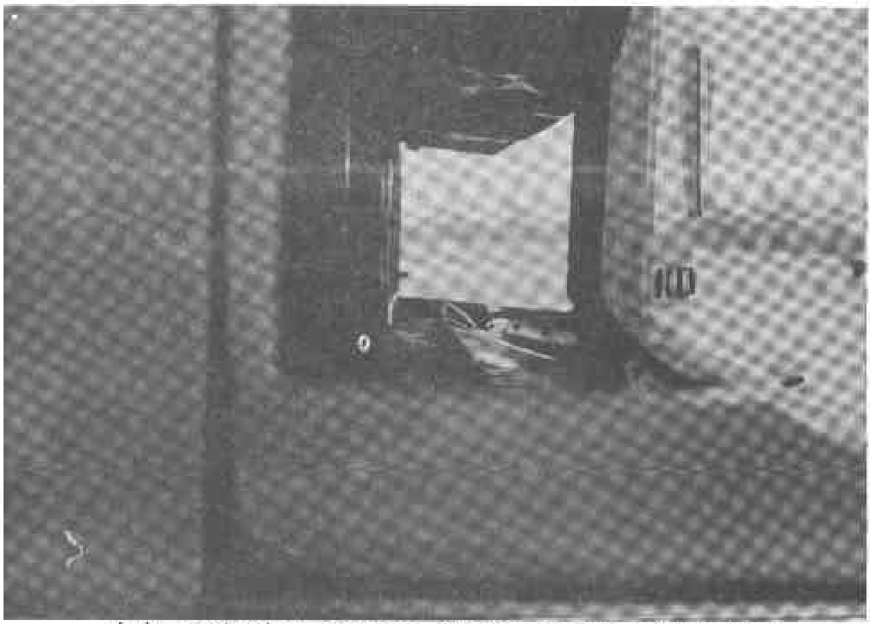
FIGURE A-6. 10-MPH FRONT-TO-FRONT COLLISION; STOCK (LEFT) VS. MODIFIED (RIGHT) BUMPERS

(b) Fascia (and Foam EA) Deformation

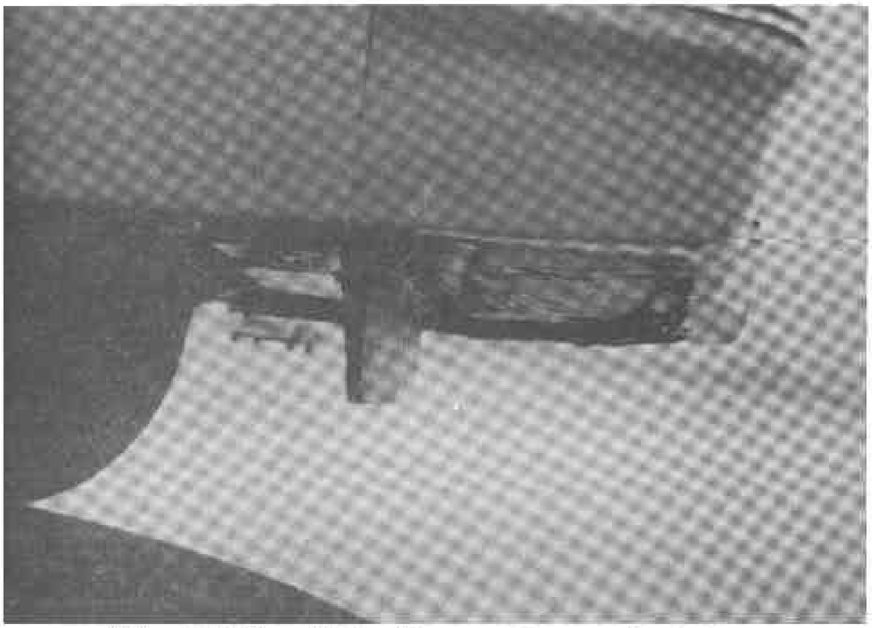


(c) Fascia (and Foam EA) Contours Restored; No Permanent Damage

FIGURE A-6. CONTINUED



(a) End View Between Bumper and Hood Leading Edge Energy Absorbers; Bumper Back Bar Upper Flange Slightly Bowed



(b) End View Below Bumper; Bumper Back Bar Lower Flange Slightly Bowed

FIGURE A-7. CONDITION OF MODIFIED BUMPER SYSTEM FOLLOWING RUN NO. 6