Automobile-Barrier Impacts

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This paper describes the first of a series of proposed tests through which (1) the protective or restraining features of an automobile chest-type, lap-type and shoulder-type safety belt will be evaluated and (2) an engineering analysis of the collapse characteristics of an automobile structure on impact will be made. The study of the collision properties of the car should lead to a better understanding of the nature of deceleration by collision and the causes of departure of collision-deceleration patterns from the theoretically ideal pattern of uniform deceleration. There should follow the determination of those structural modifications which, in the case of headon type collision, will provide automobiles with improved progressive collapse characteristics.

The automobile used in this test was a 1937 Plymouth which had been instrumented with mechanical and electrical accelerometers and electrical strain gages. An instrumented anthropometric dummy was secured by a chest-type safety belt to an instrumented seat. The instrumented car was accelerated by pushing, guided by remote control, and allowed to coast into a fixed barrier. The barrier was constructed of large diameter utility poles backed up by dirt so as to provide an essentially nonyielding wall.

A high-speed motion-picture camera and several accessory movie cameras were directed at the point of impact. The instrumented or crash car was suitably calibrated with visual markers to facilitate accurate evaluation of the deceleration pattern of the car during impact through subsequent film analysis.

●AS a general economy measure, the research engineer attempts to reduce the system under analysis to a laboratory model where observations may be made under conditions which are more-easily controlled. After considering a variety of laboratory models, it was decided that none of them could be developed to accurately duplicate all of the possible reactions of the automobile under impact without exceeding the time and cost of full-scale investigation. Full-scale automobile impact studies eliminate the unknown factors which appear when attempting to interpret the laboratory findings in terms of their application to the full-scale device.

With these problems in mind, crashing test cars into a fixed barrier appeared to be the system which provided the best experimental control without deviation from the concept that the tests should duplicate the physical conditions common to the severe impact. A barrier 8 feet high and 14 feet wide was constructed of large-diameter utility poles backed by suitable cross members and braces and several tons of dirt.

A truck was used to push the instrumented car up to the desired speed, to provide a mobile position for the remote-control operator, and for carrying the Hathaway 12-channel recording oscillograph. The truck pulled the trailer used to carry the portable power unit. An electrical cable which could be paid out rapidly from the pushing vehicle linked the instruments in the two vehicles. The car was guided by remote control to crash into the barrier. Electronic, mechanical, and photographic instrumentation were used to record decelerations, strains, and the other dynamic phenomena under observation during the impact.

An instrumented human subject and an instrumented anthropometric dummy, secured by a chest-type safety belt, simulated the drivers of this 1937 Plymouth test car for the low- and high-speed tests, respectively.

The first impact test was made at approximately 10 mph. with a human subject as well as the dummy in the car. Both the subject and dummy were restrained by safety belts which passed horizontally

Figure 1. The test car and dummy.

across their chests and under their arms to rigid anchorages behind them. The belts were made of 3-inch nylon webbing attached to 40-G hardware. In the interests of safety it was considered inadvisable to use a human subject at higher speeds. The test to destruction was executed at a speed of 25 mph. The dummy sustained some damage to the neck and arms at the peak deceleration of approximately 24 G, but the failures were essentially those associated with construction details not corrected during the dummy's modification for these tests. The restraining device gave a satisfactory performance.

The barrier-impact technique provides a practical means for studying the reactions of automobiles and motorists under destructive impact conditions. For the particular car used in the test, the bumper and its fastenings were crushed in a distance of 12 inches without absorbing any significant amount of energy. The frame of the car absorbed on impact less than a fourth of the car's kinetic energy. The deceleration pattern indicated a higher G loading than there would have been if the automobile design had provided energy absorption upon impact by the progressive collapse of the forward structure. The intact portions of the car frame appear to reach peak rates of deceleration somewhat higher than the adjacent upper parts of the automobile body. One of the more-significant contributions of this crash-injury program to date has been the development of a testing technique suitable for conducting controlled automobile crashes which yield adequate and reasonably accurate scientific data without hazard to research personnel.

THE TEST CAR

A 1937 four-door Plymouth sedan was modified for the crash in the following manner:

1. The front and rear doors on the driver side were removed to provide an unobstructed view of the dummy (Fig. 1). This provision allowed the dummy's movements during impact to be photographed by the high-speed camera. The removal of the doors did not affect the car's structural properties significantly. Experience has shown that doors frequently fly open under similar conditions of impact, and the cabin structure of the automobile was not subjected to decelerative forces sufficient to produce a permanent set in the cabin structure, even without the doors.
2. Windshield and window glass were removed.
3. The front and rear seats of the car were removed.
4. A specially designed seat and seat support were installed in place of the standard car seats. The purpose of this structure was to provide a rigid mount for the seat which would allow the strain elements attached to the seat to be free from detecting the unrelated, complex, high-frequency vibrations which generally mask the principal forces of deceleration in this type of crash.

The two seat and foot rest supports were secured to two parallel 4-by-6-inch steel I beams mounted longitudinally on the floor of the car (Fig. 1). This permitted the loading of the seat and footrest during impact to be detected by electric strain gages.

5. A vertical I-beam member secured

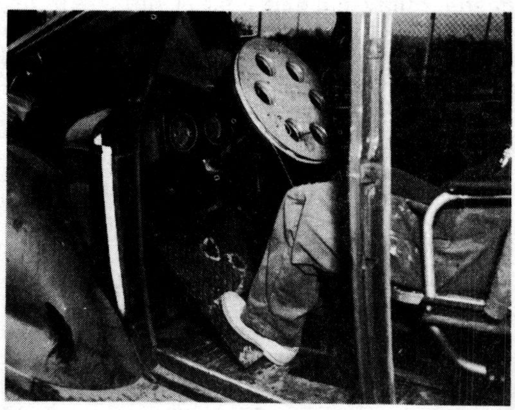

Figure 2. Remote control steering apparatus.

to the horizontal member provided a T post to which the terminal mounts and strain gage elements of the safety belt were secured.

6. Remote steering was provided by a large pulley bolted to the steering wheel and, as shown in Figure 2, actuated by a cable joining it to the pulley of a selsyn, mounted on the horizontal I beam between the legs of the dummy. This selsyn was connected electrically with a similar unit on the instrument truck used for remote control.

7. The test-car parking brake was rigged so that it could be actuated mechanically from the instrumented truck.

8. All items in the car cabin which were inadequately secured were removed or bolted down to prevent their shifting forward during impact.

THE INSTRUMENTED TRUCK AND TRAILER

A $1\frac{1}{2}$-ton Chevrolet carryall was used to push the test car into the barrier and to carry the electrical recording equipment (Fig. 3). A horizontal deck, 4 feet deep and 6 feet wide was built over the engine hood of the truck to provide an area on which to lay the excess length of instrumentation wires used to connect the test car with the instrument truck. The wires were bound together to form a cable, and this cable was laid on the deck in a manner which prevented it from snagging as it was drawn rapidly from the decelerating truck by the test car coasting on into the barrier.

The wires from the test-car steering selsyn were routed through the common

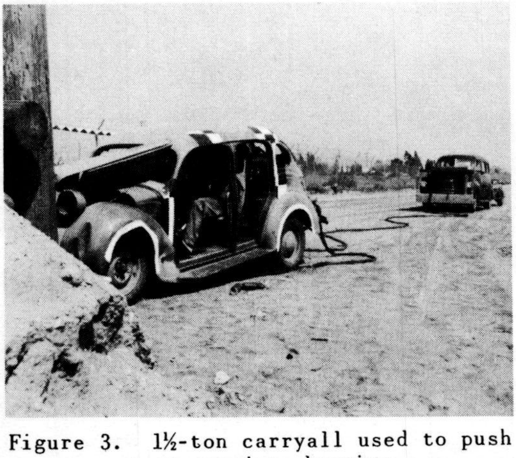

Figure 3. 1½-ton carryall used to push test car into barrier.

Figure 4. Twelve-channel recording oscillograph.

cable to the instrument-truck control selsyn and power source. The control selsyn was operated from a vantage point on the cable deck of the instrument truck.

The instrument truck carried a Hathaway 12-channel recording oscillograph and accessory equipment (Fig. 4) and pulled a 6-foot, two-wheel trailer which carried the portable 115-volt power unit.

THE ANTHROPOMETRIC DUMMY

The phase of this research project concerning the development and evaluation of devices appropriate for restraining the motorist against the effects of crash deceleration suggested the need for a test dummy. This seemed advisable owing to the small amount of information known about the deceleration pattern of the crashing automobile and the effects of such irregularities on the human body secured by restraints of new design. Eventual evaluation of the voluntary limits of such protective devices must, of course, be made by human subjects, possibly preceded by tests made on live animals having anatomy comparable with the human body, e.g., apes.

The anthropometric dummy developed by the Institute of Transportation and Traffic Engineering, University of California, will be referred to for simplicity as the ITTE Dummy. In addition to the requirement that this dummy should have the physical appearance of man, it was considered necessary that it should have a total weight

TABLE 1

CALCULATION OF MEAN PERCENTAGE FOR WEIGHT DISTRIBUTION OF THE HUMAN BCDY AND ITS COMPONENT PARTS

Segment	Cadaver II		Cadaver III		Cadaver IV		Arithmetic Average	Mean % of Total Body	Dummy Weight [c] (Grams)	Dummy Weight [c] (lb.)
Total		%		%		%				
Body Gms	75,100	100	60,750	100	55,700	100	63,850	100	71,214	157
lb.	165.6		133.9		122.8		140.8	100	154	
Head	5,350	7.1	4,040	6.65	3,930	7.06	4,440	7.0	4,985	11.0
Trunk	36,020	48	28,850	66.5	23,780	42.8	29,550	46.2	32,901	72.5
Intact Arm [a]	4,870	6.5	3,515	5.7	3,615	6.5	4,000	6.3 [b]	4,486	9.9
Upper Arm	2,570	3.4	1,935	3.2	1,875	3.4	2,127	3.4	2,421	5.3
Forearm & Hand	2,300	3.1	1,575	2.6	1,740	3.1	1,872	2.9	2,065	4.6
Forearm	1,650	2.2	1,085	1.8	1,270	2.3	1,350	2.1	1,495	3.3
Hand	645	.86	485	.86	470	.85	533	0.8	570	1.3
Intact Leg	12,005	16	10,450	17.2	10,380	18.7	10,945	17.1	12,180	26.8
Upper Leg	7,475	9.9	6,450	10.6	6,450	11.6	6,792	10.7	7,620	16.8
Lower Leg & Foot	4,485	6.0	3,965	6.5	3,930	7.1	4,127	6.4	4,558	10.0
Lower Leg	3,265	4.3	2,875	4.7	2,935	5.3	3,025	4.7	3,347	7.4
Foot	1,130	1.5	1,075	1.8	995	1.8	1,067	1.7	1,211	2.7

[a] Remainder of this column gives the arithmetic average of right and left body components.
[b] Remainder of column applies to percentage weight of one side of body only, e.g. 6.3% x 2 = 12.6%, the percentage weight of both arm
[c] UCLA Dummy.

comparable to man and that the distribution of this weight among the various components of the body follow that of man. It was further considered essential that the weight distribution among the various component parts of the body be adjusted so that the center of gravity of each body segment approximate that of man. The specifications used in determining these factors were based on the cadaver studies by Braune and Fischer (1). A final specification was that this dummy possess a degree of joint fixation in the principal joints of the body which approximates that of an average strength individual alerted to an impending crash.

Such additional refinements as the provision of tissue compressibility and

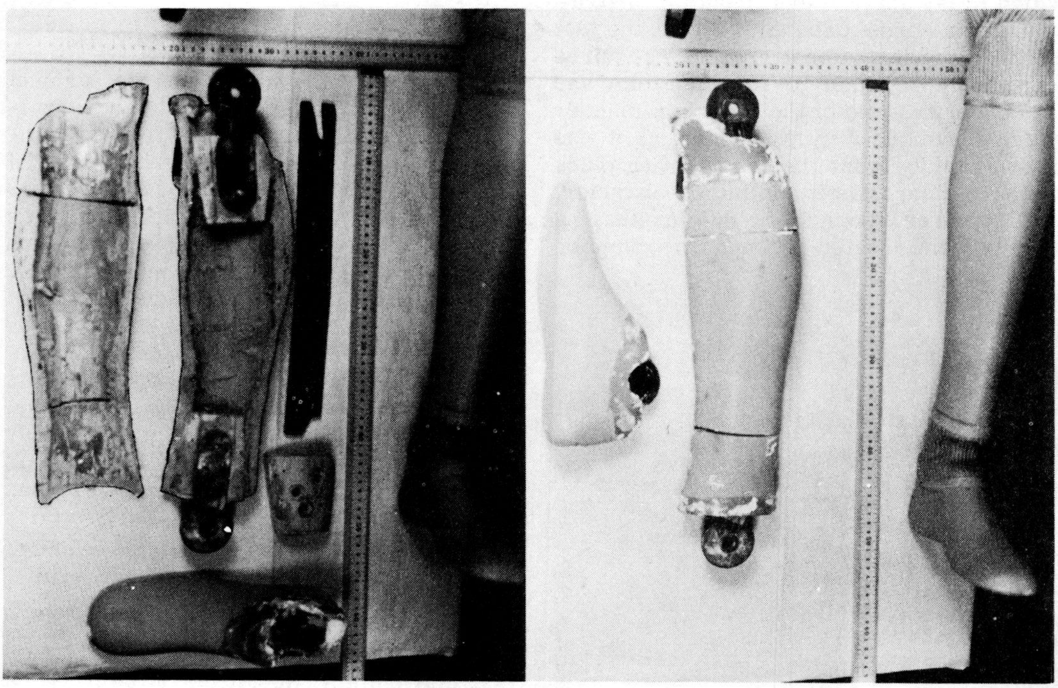

Figure 5. Modifications made in dummy leg to resemble human leg.

tissue resiliency, as well as muscle return, could not be incorporated in this experimental model, since this would involve the expenditure of time and funds far in excess of practical limits.

TABLE 2

MEAN PERCENTAGE FOR CENTER OF GRAVITY LOCATION
(After W. Braune and O. Fischer)

Segment	Proximal	Distal
Total Body	[a]	[a]
Head	[b]	[b]
Trunk (and neck)	[c]	[c]
Intact Arm	0.94 [d]	0.06
Upper Arm	.47	.53
Forearm and Hand	.47	.53
Forearm	.42	.58
Hand (slightly flexed)	[e]	[e]
Intact Leg	.89 [f]	.11
Upper Leg	.44	.56
Lower Leg and Foot	.52	.48
Lower Leg	.42	.58
Foot	.43	.57

[a] 1 cm under Promontory, 4 cm in front of 2nd Sacral vertebra.
[b] In the fossa tarini 0.7 behind the Sella turcica, exactly in Sagittal plane.
[c] At first Lumbar vertebra (near the medial plane).
[d] In upper arm just above elbow axis, 1.5 cm in front of bone.
[e] 5.5 cm p, 1 cm in front of the center of III Meta carpal near skin of the palm.
[f] To knee joint, although entire leg is being considered.

An unusually well-designed articulated manikin was purchased and modified along the lines already indicated. This was necessary, since there was no commercially produced anthropometric test dummy on the market at that time. The principal modifications were those concerning the strength and weight distribution of the dummy. An example of such a revision is shown by Figure 5. The lower leg was reinforced by the addition of ¼-by-2-inch iron stock of a length sufficient to allow it to serve the purpose of the tibia in the human counterpart. The other segments of the dummy were strengthened as required. Access doors were provided for the mounting of accelerometers in the head and chest cavities. The plaster-cardboard covering of the head and trunk were resurfaced with a tough fiberglass boat cloth. This was securely bonded to the plaster surfaces with an application of cold-cure boat resin.

Data for the ITTE Dummy

Table 1 provides the data upon which the weight distribution of the dummy was based. Table 2 supplies the mean percentage for center of gravity location, and Table 3 gives the data on articulation of the dummy.

INSTRUMENTATION

Photographic, electronic, and mechanical systems of instrumentation were used to record decelerations, strains, and the other dynamic phenomena under observation during this impact test. An attempt was made to overlap these recording systems wherever possible, so duplication of data could be obtained for verification purposes and for guarding against complete loss of some phase of essential data due to equipment failure during the impact.

The principal source of photographic data was obtained with the use of an Eastman high-speed camera, Type III, which was operated at approximately 1,000 frames per second. A 60-cps. timing light built into the camera recorded a timing signal on the edge of the high-speed film so that allowance could be made for the acceleration of this film. In addition, two checkerboard patterns were painted on the car at an accurately measured distance of 3 feet apart for the purpose of providing a precise length measurement in the field of the camera at the distance of the test car. As may be seen in Figure 6, this calibrated reference was placed above the car doors and

TABLE 3

ARTICULATION OF ITTE DUMMY

This dummy is provided with joints enabling motion comparable with the principal joints of the human body. It will be noted that some of the degrees of freedom of human joints have been omitted since they play no significant part in body dynamics during crash deceleration.

Body Segment	Motion	Angle (Deg.)
Head-(relative to trunk)	Forward flexion	44
	Backward flexion	26
	Sideward flexion (either side)	25
	Rotation (either side)	90
Arm (relative to shoulder)	Forward flexion	180
	Backward flexion	180
	Abduction	140
Forearm (at elbow)	Forward flexion	119
Hand (relative to forearm)	Forward flexion	90
	Backward flexion	90
Hand (relative to elbow)	Rotation (either side)	90
Torso Deflection (Shoulders relative to pelvic girdle)	Forward flexion	25
	Backward flexion	15
	Rotation to either side	60
Thigh (relative to pelvis)	Forward flexion	110
	Backward flexion	25
Lower leg (relative to thigh)	Backward flexion	108
	Rotation (either side)[a]	90
Foot (relative to ankle)	Forward flexion	30
	Backward flexion	30

[a] Not an anatomically correct articulation since this motion accomplished the rotation of the dummy's foot relative to the hip by motion at the knee rather than at the hip as with the human.

Figure 6. Checker board pattern on car for calibration with photographic film.

was used for length calibration of the film at the instant just before the car impact occurred. Other reference markers were painted on the side of the car and calibrated marker boards were mounted on a fence behind the car and in view of the cameras. This film was subjected to a frame-by-frame analysis using a Bausch and Lomb optical comparator[1] to provide accurate information on the deceleration of the car and dummy. A Kodak 16-mm. Ciné Special II operated at 64 frames per second and a 4-by-5-inch Speed Graphic camera provided additional photographic records.

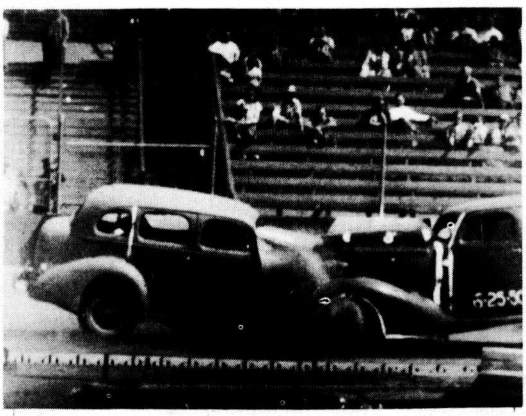

Figure 7. Car-to-car head-on collision.

The electronic portion of the instrumentation consisted of a Hathaway 12-channel recording oscillograph which received signals from Hathaway accelerometers mounted in the chest cavity and head of the dummy as well as on the forward surface of the chest belt. The oscillograph also received signals from strain gages mounted to record the impact forces the dummy exerted on the foot rest, on the seat, and on the chest-level safety belt. The cables from these detectors were bound to the cable connecting the selsyn motor to the remote steering selsyn. The other end of this 100-foot cable was connected to the recording and control equipment in the instrument truck. The excess cable was stored on the truck in the manner already described.

[1] This system produced only an error of 2.2 percent, described by the paper "Controlled Test to Evaluate the Accuracy of Accelerations Derived from the Analyses of High Speed Camera Film Using a Bausch and Lomb Optical Comparator," D. Severy and P. Barbour. Unpublished.

TEST SITE AND BARRIER

Because of the hazardous and unusual nature of this investigation, it was necessary to secure the use of a test site which was located in an unpopulated, fenced-in section having a roadway at least 800 feet long. Arrangements were made with the Los Angeles Department of Water and Power to use a portion of its facilities at the Valley Steam Plant. This department also prepared the necessary dirt roadway and constructed a barrier at one end of the road. As may be seen in Figure 6, the barrier, which was 8 feet high and 14 feet wide, was constructed of large-diameter electric-utility poles. These were sunk to a depth of 8 feet in the ground and backed by suitable cross members and braces to provide a rigid structure. The mass of the barrier was augmented by placing dirt against the rearward side of the structure.

The barrier was inspected directly following the high-speed impact. There

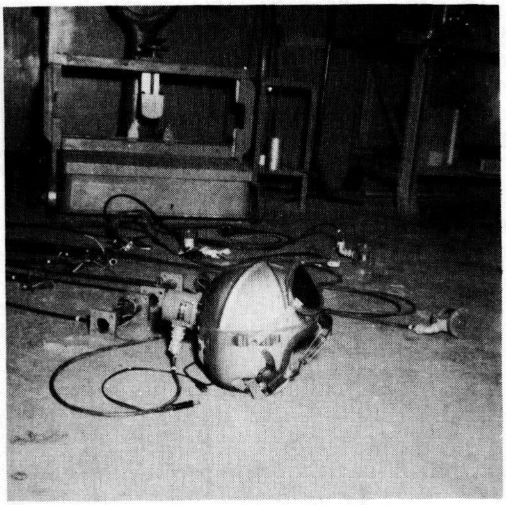

Figure 8. Accelerometer mounted on crash helmet.

was no indication of significant displacement of the barrier. The timber retained a deformation of approximately $\frac{1}{4}$ inch in several small areas. Although there was no doubt that significant energy was absorbed upon impact, it seems reasonable to conclude that the severity of the collision was not reduced significantly by yielding of the barrier.

The barrier impact imposes a more-rigorous test of the protective qualities of a motorist restraint than would generally be encountered in a car-to-car head-on collision. In the latter there would be mutual penetration, as shown by Figure 7, and consequently, a lower deceleration rate than would be the case with the car-barrier impact in which one of the two colliding objects is essentially nonyielding and nonpenetrable.

TEST PROCEDURE

Immediately preceding the experimental impact, the test car was slowly pushed until the front bumper rested against the barrier. The high-speed camera was placed at a point 30 feet from the car, directly opposite its front door. The high-speed camera was adjusted at this position, and other photographic equipment was grouped around it and adjusted for operation. The procedure which proved to be the most practical was to utilize remote-control steering, push the test car up to the desired speed, and allow it to coast into the barrier. Needless to say, numerous dry runs were made before the first impact in order to perfect operational procedures. Following these, the test car was backed away from the barrier about 400 feet in preparation for a low-velocity impact involving the use of a human observer. A Hathaway accelerometer was mounted on the crash helmet (Fig. 8) and a similar unit was secured to the forward surface of the horizontal chest belt used to restrain the human (Fig. 1). The initial impact speed of 10 mph. proved

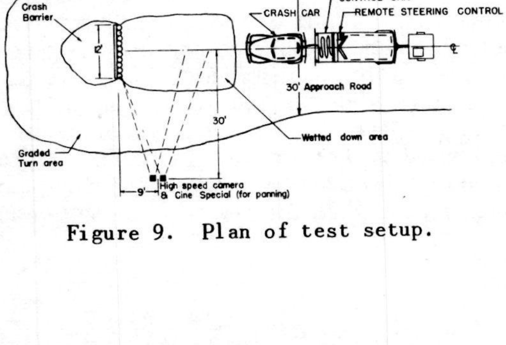

Figure 9. Plan of test setup.

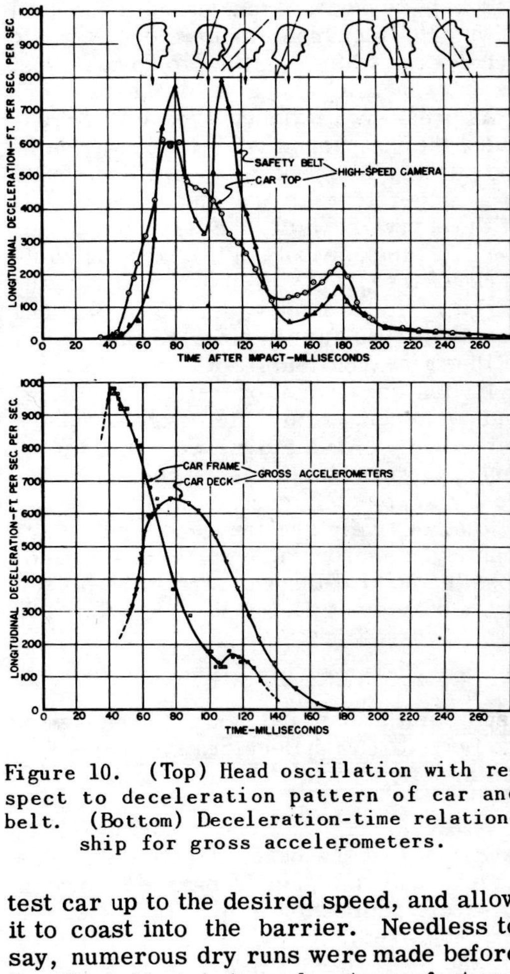

Figure 10. (Top) Head oscillation with respect to deceleration pattern of car and belt. (Bottom) Deceleration-time relationship for gross accelerometers.

to be the limiting velocity of impact for the volunteer subject under the rigorous conditions imposed by this particular barrier crash.

An impact speed of 25 mph. was considered advisable for the high-speed test, using an instrumented dummy, so that the data obtained could be compared directly with a previous study (unpublished) conducted by this institute of a headon collision staged at approximately the same speed. Trial runs showed that if the test car were pushed to a speed of 30 mph. until it was 100 feet from the barrier, it would decelerate, while coasting, to 25 mph. just as it passed to one side of the barrier. This break-away distance of 100 feet enabled the instrument truck which was doing the pushing to break away and decelerate at a moderate rate and stop 40 feet short of the barrier while the test car pulled the instrumentation cable from the cable deck of the truck as it coasted into the barrier at 25 mph. (see Fig. 9). The practical runs familiarized each member of the research team with their responsibilities, and enabled operational problems and equipment failures to be observed and corrected. At the test run speed of 30 mph., the operator experienced some difficulty in remotely controlling the test car by the relatively low-torque selsyn. Fortunately, appropriate corrections were possible so that the car struck the middle of the barrier at 24.9 mph. (Fig. 6).

TEST RESULTS

Head Oscillations and Other Responses of the Body to Crash Deceleration Under Restrained Conditions

Analysis of the motion-picture film revealed that the head of both the human subject and the dummy passed through a 1½-cycle oscillation. In both cases, the head appeared to be forced as far forward as the neck would flex during the first phase of the impact and, subsequently, as far backwards as the neck would flex. An illustration of head oscillation with respect to the deceleration pattern of car and belt is shown in Figure 10. In the human test the subject reported that during the low-velocity impact his head whipped forward so abruptly that he could hear a succession of snapping sounds which he attributed to the sound from the flexing of the cervical vertebrae reaching the audioreceptive organ through the medium of bone conduction. A mild pain in the vicinity of the neck persisted for one day. In the monumental work of Stapp (2) the danger of head-whip was averted by having the subject's head and neck flexed forward as nearly horizontal as possible before impact. It is not believed that such prepositioning would, however, be feasible for motorists because of the special training required. It is also true that this special collision posture would make it impossible for a driver to see ahead and to apply corrective action up to the instant of impact and thereby reduce the severity of the collision. Thus, since motorists cannot be expected to assume this more-favorable-posture during an impending collision, it was decided not to introduce such a protective measure into this investigation, at least until the effects without it were observed. The relatively heavy, protective helmet carrying a 1-lb. accelerometer attachment worn by the volunteer subject unquestionably increased the severity of this head-whip phenomenon.

Restraining Capacity of the Belt

The chest-type belt was anchored to the rear, on each side of both the subject and the dummy. The belt passed under the arms and across the chest horizontally. At the chest level, this device restrained both the subject and the dummy against any observable forward movement under the influence of deceleration.

Photographic analysis showed that on impact the dummy slid forward in his seat approximately 12 inches. This would have put his knees near or against the instrument panel if his seat had been the usual distance from the instrument panel, but his head and shoulders still would have remained clear of the steering wheel under such conditions. Actually, the knees did strike the steering wheel, causing momentary elastic deformation of the wheel. The feet were placed on an inclined surface which simulated the usual floor board arrangement of the automobile. They remained in this position during the impact.

Figure 6 shows the dummy's position shortly after the instant of maximum deceleration. The arms of the dummy were thrown forward and upward from the lap position in a flailing motion despite the preimposed joint fixation. This whip action snapped the left arm free from the shoulder and caused the right hand of the dummy to pull loose at the wrist. The arm failure occurred because there was only ¾ sq. in. of wood available to support this average weighted arm against the combined effects of deceleration, which increased the effective weight of the arm on the order of 20 times, and the bending moment at the shoulder which developed due to the preimposed joint fixation. In the case of the dummy's hand, the spring-loaded ball-pin locking device should have been replaced by a positive locking device to make it correspond more closely to the strength of its human counterpart.

Although there is experimental evidence that human arms do not tear loose from decelerations far in excess of 20 G, the arm of the dummy which remained intact was tested to destruction experimentally. Static loading designed to approximate the dynamic conditions of the barrier impact produced failure for a longitudinal load of 103 lb. and a transverse load of 90 lb. The resultant loading of 137 lb. could be accommodated by an adult male without the occurrence of accidental amputation.

Under the forces of deceleration, the inertia of the dummy's head overcame the resistance of the neck-joint fixation and the head snapped forward against the limit pad with sufficient force to fracture the dummy's neck joint at a location which would correspond to the first thoracic vertebra of the human body. Since this neck joint had not been strengthened for the impact test, it is not reasonable to

TABLE 4

DATA ON THE GROSS MODEL-C MECHANICAL ACCELEROMETERS

(1) Recording: Accomplished by a jeweled stylis on a rotating smoked rotor.
(2) Bidirectional: Records on two axis, 90 degree opposed.
(3) Natural undamped frequency. 70 cps
(4) Damping coefficient. 0. 6 to 0. 7
(5) Release mechanism: Adjustable trigger threshold
(6) Range: ± 50 G
(7) Calibration method: Dynamic and static calibration over the range to be measured.

Unit Number	Direction Recorded	Location	Reference Figure	Maximum Reading, G
3	Frontal Vertical	Frame	2(C), Left side	26. 0
4	" "	Rear Trunk Deck	—	20. 0
6	" "	Frame	2(C), Right side	30. 5

conclude that comparable injury would have been sustained by a human body subjected to the same deceleration pattern.

There were no signs of damage or strain to the dummy which would suggest that a corresponding injury might have taken place if a human subject had been decelerated in place of the dummy. It should

TABLE 5

Impact Data.

Item Number(#)	Description	Derived from	Amount	Units
1	Year and make of car	Data	1937 Plym.	
2	Body type	Data	4 dr. Sedan	
3	Measured weight with dummy	Data	3,077	lb
4	Velocity before impact	Film	36. 5	ft/sec
5	Velocity after impact	Film	-5. 8	ft/sec
6	Peak deceleration rate	Analysis	19. 0	G
7	Duration of impact	Film	0. 250	sec
8	Maximum amount of collapse	Film	2. 3	ft
9	Mass (W/g)	#3/g	95. 6	slugs
10	Momentum before impact	(#4 x #9)	3,490	lb-sec
11	Momentum after impact	(#5 x #9)	-554	lb-sec
12	Total change in velocity	#4 - #5	42. 3	ft/sec
13	Kinetic energy before impact	$\frac{1}{2}$(#9)(#4)^2	63,680	ft-lb
14	Kinetic energy after impact	$\frac{1}{2}$(#9)(#5)^2	-1,608	ft-lb
15	Coefficient of restitution	#5/#4	0. 16	—
16	Change in momentum	#10 - #11	4,043	lb-sec
17	Loss of kinetic energy during impact	#13 - #14	65,290	ft-lb
18	Average force acting on car	#16/#17	16,170	lb
19	Average rate of energy dissipation	#17/#7	261,170	ft-lb/sec
20	Crash horse power	#19(60) / 33,000	475	hp

be emphasized, however, that the ITTE Dummy does not have flesh and chest-compressibility properties which tend to reduce slightly the deceleration rate for a human subject in one respect, but which would, in another respect, permit the generation of destructive shear forces that might produce serious or even fatal injury. This matter will be given special attention in subsequent tests.

Lap Versus Chest Type Safety Belts

A review of Accident Facts (3) will show that the only statistically significant sources of injury to the motorist result from collision or other sources of destructive and rapid deceleration of the automobile. A motorist secured by a safety belt in a vehicle under the usual conditions of vehicular motion, can have only one principal reactionary force prevail during an accident or rapid deceleration which can be anticipated. This is the force of the body against the restraining device as the body attempts to continue along the original path of motion under a condition in which this motion is being decelerated. Regardless of the gyrations and distortions which the automobile, and consequently its occupants, may suffer during accidental deceleration, the law of conservation of energy states that the human body must dissipate its kinetic energy (of forward motion) by a reactive force on the body through a distance which represents the total work equivalent to the body energy of forward motion.

Those collisions which generate forces from the lateral, vertical, or rearward directions or combinations of these forces with the known forward restraining forces produce unpredictable forces because they do not exist until the peculiarities of a particular accident develop. It therefore seems unrealistic at this point to develop specialized protective passenger restraints to counteract any but the most-frequently encountered force, namely that which restrains the motorist from being thrown against the forward surfaces of the car's interior or, in that general direction, through open doors or through the windshield.

For the average front seat, the lap-type safety belt provides this protection only for the less-vulnerable portion of the anatomy, leaving the vital parts, particularly the head, to destructive deceleration.

The chest-type safety belt, while probably not the final solution to this problem, does provide effective restraint against the only predictable forces of deceleration which can develop during the accident, namely, those which tend to decelerate both the car and the motorist.

A common category of accidents are those in which a relatively minor oblique impact from the opposing vehicle or fixed object results in superficial damage to the car. In such accidents, however, the intial impact serves to disorient the driver, causing him to lose control of the car, so that a secondary and frequently severe collision occurs. Circumstances such as these suggest that a properly designed motorist-restraining device should keep the driver and other occupants in their normal seating positions within the car in order to: (1) prevent vital parts of the anatomy from being subjected to injurious impact; (2) prevent the driver and passengers from being thrown from the car; and (3) guard against loss of control of the car following impact.

A simplified shoulder harness is currently being tested which shows promise of providing a more-effective restraint and of overcoming some of the objectionable features of a chest-level belt.

Deceleration Characteristics of Auto-Barrier Collision

The test car was provided with visual reference targets to facilitate a frame-by-frame analysis of the high-speed-camera film which recorded the motion of the car during impact. For the chest-level belt and the intact portion of the car body, Figure 10 portrays the changes in the deceleration with respect to time.

The curves show the abrupt onset of deceleration, which is characteristic of barrier and headon collisions, followed by a less abrupt recovery from the peak deceleration value. The double peak of the safety-belt deceleration curve is attributed to the mass spring characteristic of the system. This explanation is supported by the fact that comparison of the integrals of these two curves shows a mean deviation of only 1 percent. These curves, of course, are based on photographic observations of points on the car and belt at approximately the same distance behind the front bumper. The final peaking of deceleration at about 180 milliseconds is attributed to the forces of restitution.

Three determinants of the limits of survival for the properly restrained subject exposed to rapid deceleration are: (1) rate of onset of deceleration, (2) the maximum deceleration, and (3) duration of the deceleration period. For this test, the rate of onset of deceleration for the dummy was approximately 600 G per sec., and the dummy was exposed to a maximum deceleration of 24 G. The total deceleration period was 250 milliseconds. These values are substantially below the voluntary tolerance limits for humans as determined by Stapp. Reference to Figure 11 will show the car to be accelerating with a reverse velocity, or away from the barrier, at time 180 milliseconds, which is the logical result of the action of restitutional forces.

It is interesting to note that the head was pitched forward a maximum amount following the second deceleration peak of the belt. It took about 40 milliseconds for the first deceleration peak, applied through the chest, to force the head fully forward. The average velocity of the head at this time was about 15 ft. per

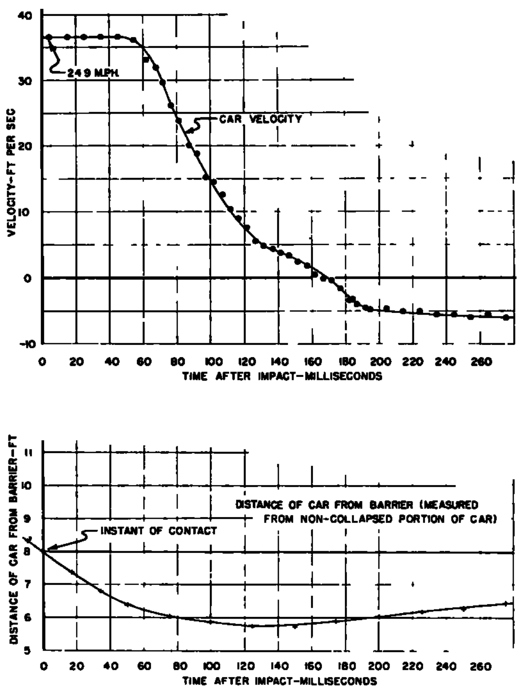

Figure 11. (Top) Rate of acceleration with reverse velocity from barrier. (Bottom) Rate of collapse of forward structure of car with respect to time.

sec. and assuming, conservatively, that at peak G the belt had zero velocity, the center of gravity of the head would have moved about 7 inches during the 40 milliseconds. This corresponds approximately with the flexure limits of the dummy's head. Since both the car top and safety belt had the same initial and final velocities, the areas under the curves of Figure 10 should be the same. As already stated these areas have a mean deviation of only 1 percent.

The velocity curve of Figure 11 has been included to show, relative to the common time axis: (1) the portion of each deceleration curve of Figure 10 which corresponds with the car at zero velocity and (2) the fact that although the velocity of the car has been reversed in direction, the decelerative forces remain positive. Thus, deceleration in the forward direction is the same as acceleration in the reversed direction. This latter point is at once apparent when one refers to Figure 6 and sees that the forces on the intact portion of the car, as well as on the restrained dummy, are the same whether these bodies are being decelerated from a forward velocity or accelerated in a rearward direction.

At this stage of experimental investigation, positive conclusions cannot be reached concerning desired structural modifications. But to the extent that these curves are representative of the modern automobile, they do suggest the need for structural changes which will produce a more-uniform deceleration by reducing the peak deceleration to a level which can be more-safely endured by restrained motorists. These changes would, of course, apply forward of the firewall and would obviously have to be compatible with structural design limitations. It should be pointed out that the trend in modern automotive design toward shortening the space between the front bumper and driver and expanding the trunk space is a sacrifice of space which could be utilized in safer design. Shortening the length of collapsible structure between the driver and front bumper results in the driver being decelerated during a frontal impact at a proportionately increased rate under conditions otherwise comparable. It is suggested that a safer design would be to place some of the storage facilities in a compartment between the firewall and engine.

A maximum deceleration value of 19 G for the intact portions of the car was derived from frame-by-frame analysis of the film taken by the highspeed camera. Figure 3 shows the reference targets painted on the side and top of the car body which were used in this analysis. The top portion of the car was decelerated at a rate exceeding 10 G for a period of 53 milliseconds and 15 G for 19 milliseconds. It is interesting to note that the automobile becomes a flexible structure when subjected to the abnormal stresses of crash deceleration. The deceleration of the intact portion of the car body at or near the top of the car may be expected to be somewhat less than the deceleration measured at the frame at the same distance back from the front of the car. This condition was verified, since a peak deceleration of 19 G was measured at the top of the car by photographic means, while the peak readings of two Gross Model C mechanical accelerometers secured to intact portions of the frame of the car were 26 G and 30 G. A third Gross accelerometer secured to the car

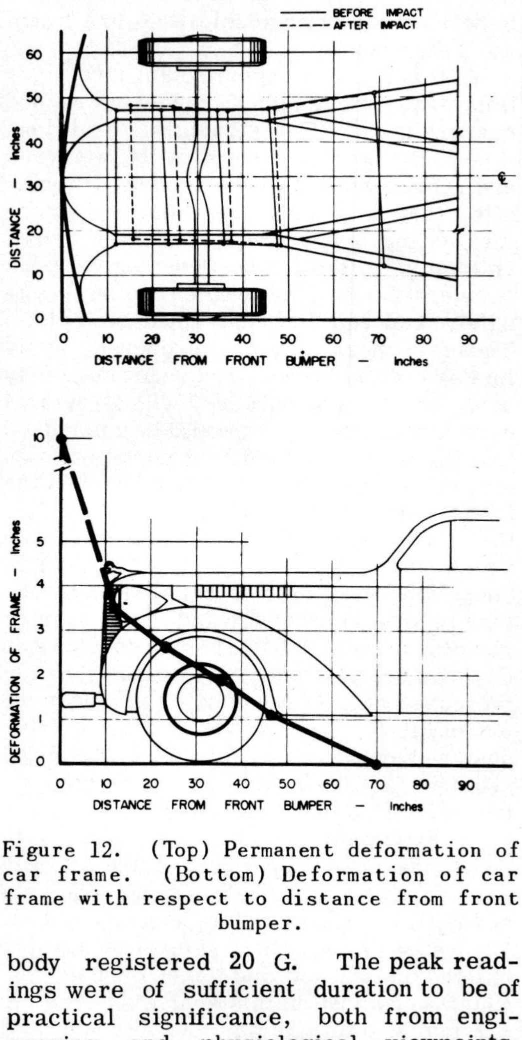

Figure 12. (Top) Permanent deformation of car frame. (Bottom) Deformation of car frame with respect to distance from front bumper.

body registered 20 G. The peak readings were of sufficient duration to be of practical significance, both from engineering and physiological viewpoints.

Figure 10 gives the deceleration-time relationship for the Gross accelerometers. In addition to the photographic and mechanical systems for securing deceleration patterns, a third system involving electronic devices was used, but a readable record was not obtained.

Figure 11 shows the curve of the rate of collapse of the forward structure of the car with respect to time. The high-speed-camera film was used to provide the data. A target painted on the side of the car 8 feet behind the front bumper was used as the reference point, because no permanent collapse of the structure was observed for this section of the car. Neglecting the flexing of the car body relative to the frame, the data of Figure 11 indicates that the frontal structure of the car collapsed 2.3 feet following contact with the barrier.

Frame Deformation Analysis

Figure 12 shows diagrammatically the permanent deformation of the car frame. The graph depicts the deformation of the car frame with respect to distance from the front bumper inasmuch as the abscissa is drawn to the scale of the car.

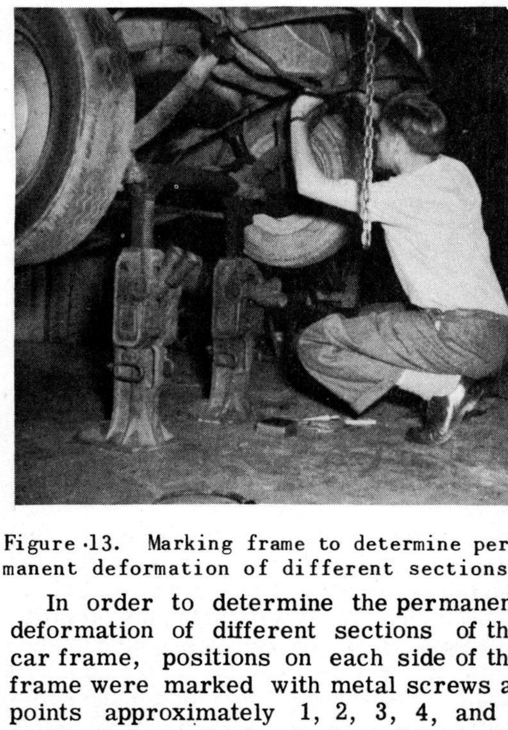

Figure 13. Marking frame to determine permanent deformation of different sections.

In order to determine the permanent deformation of different sections of the car frame, positions on each side of the frame were marked with metal screws at points approximately 1, 2, 3, 4, and 6 feet back from the front edge of the bumper (Fig. 13).[2] The dotted lines of Figure 12 show the deformation of the frame for the 10 reference points measured. The frame of the car was deformed by amounts which varied approximately in-

[2] The procedure followed in calibrating the frame consisted of driving the car onto a wide sheet of ¾-inch plywood and projecting onto the latter, by the plumbbob technique, the points defined by the metal screws. Measurements were then made on the plywood surface. It was found that the marker points could be located with a reproducibility which did not vary more than 0.05 inch. Following the barrier crash, the car was again placed on the sheet of plywood, and the same reference points on the frame were projected, measured, and recorded. Since there was no evidence of deformation at the 6-foot point, this station was used as the base in evaluating the deformation of the other points.

versely with distance from the front bumper. The bumper collapsed completely without contributing appreciably to the deceleration of the car.

The frame-deformation pattern illustrates the positions of the frame of the car before and after impact but gives no clue as to the order and rate of assumption of these positions during impact. Thus, for example, if the first two stations to the rear of the front bumper were to yield completely under a relatively low loading, this would use up a major portion of the total collapsible length of the car without contributing significantly to the absorption of the car's kinetic energy. Most of the energy would, therefore have to be absorbed by the remaining small length of structure between Station 2 and the firewall. This could be accomplished only at an excessively high rate of deceleration.

Possibly a more-ideal collapse pattern would be a rectangular one in which the frame exclusive of the minor contribution of the bumper would resist collapse until a given loading was reached and then the entire length of frame forward of the firewall would fail at a rate which maintained this loading until either the precrash energy was entirely dissipated or the frontal portion of the frame was totally collapsed. The frame would be designed to fail under a uniform loading which represented the estimated physiological tolerance limit of an average motorist wearing a specific restraint or which would uniformly absorb all of the kinetic energy estimated to be released from an average crash, whichever was least. In the next test an attempt will be made to further investigate this phenomena.

CALCULATIONS

1. Total Kinetic Energy of Car Immediately Prior to Impact

Velocity, v = 36. 5 ft. per sec.;
Weight W = 3077 lb.

$$KE = \tfrac{1}{2}\,mv^2 = \tfrac{1}{2}\,\frac{W}{g}\,v^2 = (\tfrac{1}{2})\,\frac{3077}{32.2}\,(36.5)^2$$

$$= \underline{63,680 \text{ ft.-lb.}}$$

2. First Approximation of the Amount of Precrash Kinetic Energy Absorbed by Permanent Deformation of the Car Frame

(a) Average total longitudinal deformation of car frame, S = 3.4 inches = 0.283 feet

(b) Average deceleration rate of car frame during impact = 285 ft. per sec. per sec.

(c) KE (absorbed) = Work = (F) (S)

$$= (ma)(S) = \left(\frac{W}{g}a\right)(S)$$

$$= \left(\frac{3077 \times 285}{32.2}\right)(.283)$$

$$= \underline{\underline{7707 \text{ ft.-lb.}}}$$

3. Estimate of Percentage of Pre-Crash Kinetic Energy Absorbed by the Car Frame, Using Average Deceleration Rate of Frame

$$\left[1 - \frac{KE_{\text{Total}} - KE_{\text{Absorbed}}}{KE_{\text{Total}}}\right](100)$$

$$= 100 - \left[\frac{63680 - 7707}{63680}\right](100) = 12\%$$

4. Estimate of Pre-Crash Kinetic Energy Absorbed by Permanent Deformation of Car Frame, Using Maximum Deceleration Rate of Frame

$$KE = \text{work} = \left(\frac{W}{g}a\right)(S) = \left(\frac{3077 \times 980}{32.2}\right)(.283)$$

$$= \underline{\underline{26,440 \text{ ft.-lb.}}}$$

$$100 - \left[\frac{63550 - 26,440}{63550}\right](100) = 42\%$$

DISCUSSION OF CALCULATORS 3 AND 4

The 12-percent value for the percentage precrash kinetic energy absorbed by the car frame as shown in Calculation 3 was obtained using the average rate of deceleration for the impact period. In this calculation the assumption is made that the frame will assume permanent deformation for the loading developed by the average deceleration rate of 285 ft. per sec. per sec. The authors have no experimental evidence upon which to base this assumption, and it is therefore possible that the observed 0. 283 feet permanent deformation resulted from only the peak and near peak deceleration loadings.

Using the peak deceleration rate, an estimated value of 42% of total kinetic energy is calculated to be absorbed by the car frame. This estimate is high for two reasons:

First, the peak of 30G was maintained for only about a millisecond which suggests that deceleration rates substantially below this value also contributed to permanent deformation. This becomes apparent when one considers that if the frame became permanently deformed at a rate equal to the maximum velocity of the car, i. e. , 36. 5 ft. per sec. , it would require 8 milliseconds to produce the 0. 283 feet permanent deformation. Actually, a much greater period is necessary since the frame was deformed elastically as well as plastically and again because after the instant of contact, the velocity, and therefore the rate, of deformation was very much less than 36. 5 ft. per sec. These factors suggest that the frame of this car absorbed significantly less than 42 percent of the gross kinetic energy. This information may be of value in designing the forward third of the car to be a better energy-absorbing structure.

Secondly, not all of the total weight of the car reacted to load the frame of the car, even though this weight was used to provide a conservative estimate. Possibly as little as half of the gross weight of the car serves to actually load up the frame, since the front-wheel assembly, front fenders, grill, radiator, and other frontal elements of the car tend to carry their own apparent weight by direct contact with the barrier. As soon as these elements have been crushed in by a few inches, the engine also may carry its own weight by direct contact with the opposing force. This latter statement appears to be true in this crash test, since the engine was decelerated rapidly enough to cause the firewall to be forced around it. At least during the later stages of deceleration, it appeared that the engine supported its own crash weight. From this discussion, it may be estimated that the frame of the car absorbed no more than a third of the precrash kinetic energy.

5. Estimate of Accuracy of G-t Curves

Procedure: The preimpact velocity obtained from the integral of, or summation of the areas under, each G-t curve has been compared with the observed velocity of 36. 5 ft. per sec. and the percentage deviation is given in Column 6 of Table 6.

Discussion of Table 6

The errors listed in Column 6 are not excessive in that only a portion of these values may be related to the G-t data. The remaining error may be attributed to the graphical integration process used to approximate the G-t curve error.

Column 7 shows close agreement (1% error) between the areas under the G-t curves plotted from independent data. The greater magnitude of error in area agreement (6%), for the gross accelerometer curves, is attributed, at least in part, to the fact that the onset portion of these curves (Fig. 10) had to be extrapolated in order to provide the area information necessary. The onset portions of the gross accelerometer curves are missing because these mechanical devices are preset to trigger off at higher deceleration values than those inadvertently encountered during handling and mounting operations.

6. Determination of Percentage Error Between the Change of Momentum and Impulse During Impact for the Purpose of Checking the Accuracy of Evaluating High-Speed Film Data

(a) Change in Momentum $m\Delta v$ = Impulse, FT

$$\frac{W}{g}(v_2 - v_1) = maT = \frac{W}{g}aT,$$

where "a" is the average acceleration for the total time of impact T

(b) Thus, $v_2 - v_1 = aT$

[36. 5 ft. per sec. - (-4. 5 ft. per sec.)]± 167. 5 ft. per sec. per sec. (. 250 sec.)

41. 0 ft. per sec. ± 41. 8 ft. per sec.

(c) Percentage Error equals

$$\left(\frac{41.8 - 41.0}{41.0}\right)(100) = \underline{\underline{2.0\%}}$$

This error is small considering the quantity of data which must be handled and the manipulations necessary to develop the S-t, V-t and G-t curves.

FINDINGS AND CONCLUSIONS

1. This study represents, as far as can be determined by the authors, the

TABLE 6

(1) Curve	(2) Area under curve, units[a]	(3) Total time of event, sec.	(4) Average a, $\frac{ft}{sec^2}$	(5) Velocity, v_0 = (4)(3) $\frac{ft}{sec}$	(6) Percentage error, %	(7) Percentage Mean Deviation of Areas
Safety Belt	13.13	0.250	165	41.2	12.9	1%
Car Top	13.48	0.250	170	42.5	16.4	
Gross Frame	15.85	0.149	-285	42.5	16.4	6%
Gross Car Trunk	14.04	0.152	285	43.3	18.6	

[a] 1 unit of area = 3.24 ft. per sec.

initial test of a motorist-restraining device by experimental collision techniques. The results should, therefore, be regarded as approximate until other tests have been conducted to substantiate these findings.

2. One of the more-significant features of this crash injury project to date has been the development of a testing technique suitable for conducting controlled automobile crashes which yield reasonably accurate scientific data without hazard to research personnel.

3. The barrier-type impact test provides a practical and realistic means for studying the performance of automobiles and the effectiveness of motorist-restraining devices under crash conditions. The barrier appears to impose a more-severe test for motorist-restraining devices than does the headon collision type impact for comparable preimpact conditions.

4. When a motorist driving 25 mph. is effectively restrained by a safety belt, be could experience a maximum rate of deceleration as low as 25 G during impact even with a nonpenetrating fixed object, such as the barrier used in this test. Since deceleration rates in excess of 40 G have been voluntarily tolerated, the problem of avoiding injury from accidents with this degree of severity appears to be one of developing an adequate restraining device which will meet with the approval of the motoring public and which, of itself, will not cause injury.

5. While the restuls of this test are not conclusive in terms of human responses, the postcollision evaluation of the damage to the dummy suggests the improbability of any serious injury had a human subject wearing a similar chest belt been decelerated in place of the dummy. Observation of film from the high-speed camera showed that on impact the dummy shifted forward about 12 inches from the waist down. This movement placed the chest belt high across the sternum, causing it to press upwards under the arms. This shift, which occurs during impact, appears to be advantageous, since it places much of the load on the stronger shoulder skeletal structure, rather than only on the rib cage.

6. For this test, the rate of onset of deceleration for the dummy was 595 G per sec. and the dummy was exposed to a maximum deceleration of 24 G. The overall deceleration period was 250 milliseconds. These values are substantially below the voluntary tolerance limit for the human being, as determined by Stapp.

7. The chest-level safety belt is an effective means for restraining the body against the forces of impact which, in the absence of such a device, would result in the body being hurled against the forward surfaces of the car's interior. However, the possibility of injury resulting from (1) an excessive compressive loading of the chest, (2) an acute flexure of the spine, and (3) an extreme excursion of the head (i.e., "head-whip") cannot be overlooked and is currently being investigated.

8. The vertical acceleration of the car body structure during headon and barrier impacts showed no tendency in this test to disorient the dummy relative to the horizontal chest-level belt. Observations based on this test do not support the belief of some observers that this vertical acceleration would disorient the motorist relative to the chest-level safety belt and cause it to apply a restraining force to some less-favorable part of the anatomy, such as the abdomen. Both a headon and barrier-type collision have revealed maximum vertical accelerations amounting to less than 2 G. Accelerations of this magnitude have no significant influence toward belt-body disorientation when, as for the conditions of this test, the body is loading the belt more than 10 times this amount as a result of forward deceleration.

9. Without overlooking the benefits which may be derived from the use of a lap-type belt for rear-seat occupants in cases where there is sufficient forward clearance, it would appear that if the front-seat injury and death toll is to be reduced appreciably, a device which effectively restrains the head and chest, as demonstrated in this test, must be provided. Even with a lap belt, the outthrust arms cannot be expected to resist the forward forces of the upper torso, which exceeded 2,000 lb. in the 25-mph. impact. For front-seat usage, the lap-type belt provides impact protection only for the less-vulnerable portions of the anatomy, leaving the vital parts (head and upper torso) exposed to gross destructive deceleration.

10. A properly designed motorist-restraining device should: (1) restrain the body in such a manner as to prevent the vital parts of the anatomy from being subjected to injurious impact, (2) maintain driver and occupants in their proper seating position in order to prevent loss of control of the car following impact, (3) prevent driver and passengers from being thrown from the car and being injured or killed (a) by impact with fixed objects, (b) by crushing by their own vehicle, or (c) crushing by other vehicles.

11. The bumper collapsed completely during impact without contributing significantly to the deceleration of the car.

12. Under the stresses of severe impact, the automobile responds as a somewhat-flexible structure. A previous headon impact study (4) as well as the barrier-type impact study indicate that the intact portions of the car frame may reach peak rates of deceleration somewhat higher than the adjacent upper parts of the automobile body. Further study of this phenomenon will provide data suggesting the structural member of the car most suitable for securing the anchorages for restraining devices.

13. The deceleration pattern of the crashing car suggests that the severity of a crash would be reduced significantly if the frame of the car was designed with an energy-absorbing section capable of reducing the peak deceleration by about 30 percent. To what extent, if any, this problem has been met in automobiles of more-recent design than the test car used will be evaluated in subsequent tests.

14. Calculations based on this crash test indicate that the frame of this car absorbed appreciably less than 42 percent of the preimpact kinetic energy. As an estimate, based on the discussion of the text of this paper, not more than a third of the preimpact kinetic energy was absorbed by the frame of the car. The amount of permanent deformation of the frame decreased approximately linearly from the front bumper to firewall, as shown by Figure 13. This information may be useful to those interested in designing the frontal portion of a car to be a more-effective energy-absorbing medium.

15. The deformation pattern of the test car frame appears to be triangular, with maximum deformation occurring at the bumper and decreasing nearly linearly from the front section of the frame towards the firewall. Additional investigation is necessary to determine to what extent this pattern deviates from an ideal collapse pattern, as well as the extent to which late-model cars deviate from the ideal.

16. In the past, the coefficient of restitution for the crashing automobile was estimated as being nearly zero. The coefficient of restitution for the automobile-barrier impact was 0.16. The coefficients of restitution for two headon collision studies were 0.03 and 0.10. These coefficients are valuable in problems concerning the calculation of the estimated preimpact speed of vehicles.

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