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PHYSICAL FACTORS INVOLVED IN HEAD-ON COLLISIONS OF AUTOMOBILES

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SYNOPSIS

TWO HEAD-ON automobile collisions, staged by stunt drivers as a feature of their shows, were studied by means of high-speed motion pictures to determine deceleration rates and times, and other physical factors. A new technique for frame-by-frame analysis of motion pictures, involving use of an optical comparator, is described.

In one collision between cars weighing 3,800 and 4,100 lb., speeds prior to impact were 37 and 23 mph. respectively. Duration of impact was approximately 0.12 sec., and respective average deceleration rates for the main (undamaged) portions of the car structures were 421 and 392 ft. per sec. per sec. (13.1 and 12.2 *g*) respectively. The total amount of mutual front-end crushing was 5.2 ft., or 2.6 ft. per car.

In the other collision, car weights were 3,700 and 3,350 lb., initial speeds 34 and 39 mph., and the deceleration rates 456 and 527 ft. per sec. per sec. (14.6 and 16.1 *g*) respectively. The total crushing was 6.7 ft. or 3.35 ft. per car.

Although there was some evidence of decelerative peaks, deceleration during the impacts was, on the whole, substantially uniform in both collisions.

The average force acting between the two cars in the first collision was approximately 23 tons, and in the second, 27 tons. Rates of kinetic-energy dissipation in the two collisions were 1,975,000 and 2,900,000 ft.-lb. per sec., or 3,590 and 5,270 hp., respectively.

In the first collision, the calculated coefficient of restitution was 0.102, but in the second, only 0.006, presumably due to a locking-together action during structural deformation.

● IT IS a well-known fact that an automobile travelling at high or even moderate speeds possesses a great deal of kinetic energy. During normal decleration, this energy is dissipated gradually. In a collision, its rapid and ungoverned dissipation usually causes extensive structural deformation of the automobile and, all too often, injury or death to occupants.

Much commendable effort has been devoted to the study of the causes of accidents with the purpose of reducing their number. Much less has been done in the way of engineering study of the physical phenomena manifested during accidents. Those which occur on the highway lend themselves very poorly to engineering study, because it is difficult or impossible to establish accurate values for important physical factors such as initial velocity, velocity at time of impact, rate of deceleration prior to and during impact, and the like.

The discovery that a stunt drivers' troupe[1] staged actual head-on collisions, as a feature of their show, suggested the possibility of making studies which would yield useful information. This report covers observations, measurements and analyses of two such planned head-on collisions. High-speed motion pictures were made and analyzed to establish (1) the speeds of the automobiles just prior to impact; (2) the pattern of velocity change

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[1] The Joie Chitwood Auto Daredevils.

(deceleration) of the undamaged primary structure of the automobiles; and (3) the extent of mutual crushing during impact. Other significant physical data were derived by calculation.

Photographs and measurements taken after the collisions illustrate the nature and extent of structural deformation produced by impacts of automobiles traveling at known speeds.

PROCEDURE

Collision 1

The first study was made at the Culver City (California) Speedway in June 1950. An Eastman high-speed 16-mm. motion-picture camera was set up in the infield, about 100 ft. from the edge of the track. To facilitate analysis of the movements of the cars, measuring boards with 1-ft. intervals, having 3-in. subdivisions, were placed alongside the track over a distance of about 25 ft. A marked disc, rotated by a synchronous electric motor, was placed in the field of view of the camera near the predicted collision point to provide means for measuring time intervals. Reference lines were painted on the sides of the cars, and marks spaced 3 ft. apart were placed on the hood of one car.

In these demonstrations, the cars start from adjacent positions in front of the grandstand, proceed around the track and pass each other on the backstretch. They are then made to collide head-on as nearly as possible at a predetermined point in front of the grandstand. Old-model four-door sedans are used and each vehicle is so prepared that the driver can operate it from a standing position behind the front seat structure, the back side of which is provided with extra padding. The driver leans over the seat to steer the car, and control the speed by means of a hand throttle, until a few moments before the collision. During these few moments he drops quickly into a crosswise position in back of the front seat structure.

Because of the limited running time of a high-speed camera (8 to 10 sec. at 500 frames per sec.), an operating plan was formulated whereby the camera was trained on the car approaching from the right for about the last 200 ft. of travel and the motor was started a few seconds prior to the instant of collision.

Figure 1. Peak of impact, Collision 1.

Figure 1 is an enlargement from one frame of the film, at the approximate peak of the impact. Following the collision, the cars were removed from the track. After being photographed, each car was carefully measured to determine the nature and extent of structural deformations.

Collision 2.

The second study, which benefited from the experiences afforded by the first, was made at the Carrell Speedway in Gardena, California, in June 1951. The general technique was similar, except that the camera was set up outside the track area, on the roof of a press box at the rear of the grandstand, about 140 ft. from the track.

As in the first study, both cars were provided with reference markings, with 3-ft-spaced markings on the roofs just above the doors. Distance markers were placed on the track, and timing facilities were improved by the fact that during the period between the two studies the camera had been provided with a built-in time marker for automatic recording on the film. The entire sequence of operations was successful.

ANALYSIS OF FILM RECORDS

The film record of each collision was first studied carefully by repeated projection at normal speed, which provided a time magnification up to about 25 times normal. Each film was then subjected to frame-by-frame analysis preparatory to studying the motion of each car as a function of time. After trial by several other methods, with disappointing results, a satisfactory solution was found in use of an optical comparator.

The instrument used was a Bausch and Lomb contour measuring projector. This instrument has a work table over a light source from which a beam is projected upward through a plate-glass window in the table. By means of a lens and mirror system, the beam is focused from behind onto a vertical translucent screen in front of the operator. The image of a film laid on the window of the table may be projected onto the screen at various degrees of magnification. The efficiency of the optical system, together with heat-absorption at the light source, makes possible the projection of a brilliant image for indefinite periods without heating of the film.

With the film fixed in position over the window of the table, the latter may be moved accurately on cross slides to shift the position of the image on the screen. Desired points in the image may thus be indexed to reference lines on the screen. Micrometers facilitate measurement of displacements of the table to an accuracy of 0.0002 in.

The frames of each film, in the portions chosen for analysis, were consecutively numbered for convenience in the tabulation of data. The optical projector was then employed to determine, for successive frames of the film, the distance between a given reference point on the car (chosen so as not to be affected by structural deformation) and a fixed point on the track. These measurements, made in terms of micrometer readings of table displacement, were tabulated against film frame numbers. They were then converted into actual distances by a conversion factor obtained from the work-table displacement corresponding to the 3-ft. distance marked on the car. This distance-base method was found to be more accurate than that involving the use of the measuring scales on the track, since it had no parallax error.

Since film speed was found to be changing due to camera acceleration in both studies, the interframe time intervals were determined and tabulated. The distance moved by each car, between successive frames, when divided by the corresponding time interval, provided the velocity of the car for that interval. The successive values for these velocities were plotted against time, and regression lines indicating the trend of velocity change with time were fitted by the method of least squares.

Graphs were also constructed, indicating the longitudinal positions, prior to and during the impacts, of chosen reference points on undamaged portions of each car's structure. These were plotted in such a way as to indicate the progressive and cumulative mutual crushing of the cars' structures, as a function of time.

Calculations were also made of the momentums and kinetic energies of the cars immediately before and after the impacts. Average values were derived for a number of other physical quantities, such as deceleraton rate, rate of energy dissipation, aggregate force acting between the two structures in each impact, and coefficient of restitution.[2]

RESULTS AND DISCUSSION

Information resulting from the study of the two collisions is presented in Table 1 and Figures 2, 3, 5, and 6.

Table 1 summarizes the basic and derived data for both collisions.

Figure 2 is a graph showing the velocities of both cars in the first collision, plotted against time. The initial velocity of the car approaching from the left was 54.5 ft. per sec.

[2] Computed by $\frac{v_2 - v_1}{u_1 - u_2}$ where u_1 and u_2 are the respective velocities before impact, and v_1 and v_2 the velocities after impact.

(37 mph.). After the impact, it still had a forward velocity of 4 ft. per sec. The car approaching from the right had an initial forward velocity of 34 ft. per sec. (23 mph.). The impact reversed its motion and gave it a backward velocity of 13 ft. per sec. The total changes in velocity were 50.5 and 47 ft. per sec., respectively.

The time period from first contact to the end of any significant change in velocity was approximately 0.130 second or 130 milliseconds. However, little change in velocity occurred in the first 10 milliseconds, during which time approximately 12 in. of mutual crushing (bumper structures and forward sheet metal) occurred. The significant period of the deceleration, occupying about 120 milliseconds, was obviously caused by deformation of more substantial portions of the structures.

The changing velocity for each car during the impact period is shown in the graph as a broken straight line. This implies uniform deceleration during the impact period, which is quite improbable. However, the regression lines of the original plottings closely approximate the average values expressed on this graph. There was some slight indication of two episodes of increased deceleration, but the limitations imposed by the method of deriving the data did not permit satisfactory resolution of the deceleration pattern. The average deceleration of the left car was 421 ft. per sec. per sec. or 13.1 *g* and that of the right car 392 ft. per sec. per sec. or 12.2 *g*.

TABLE 1
COLLISION ANALYSIS

	Collision 1		Collision 2	
	Left Car	Right Car	Left Car	Right Car
Make and model	1935 Oldsmobile 8	1936 Buick "60"	1936 Buick "40"	1937 Dodge
Body type	4-door sedan	4-door sedan	4-door sedan	4-door sedan
Estimated weight including driver	3,800 lb.	4,100 lb.	3,700 lb.	3,350 lb.
Mass ($W \div g$)	118 slugs	127 slugs	115 slugs	104 slugs
Velocity[a] before impact	54.5 fps. (37.2 mph.)	−34 fps. (23.2 mph.)	50 fps. (34.1 mph.)	−58 fps. (39.5 mph.)
Velocity[a] after impact	4.0 fps. (2.7 mph.)	13 fps. (8.9 mph.)	−1.6 fps. (1 mph.)	−1.0 fps. (0.7 mph.)
Total change in velocity.	50.5 fps.	47 fps.	51.6 fps.	57 fps.
Momentum[a] before impact	6431 lb.-sec.	−4318 lb.-sec.	5750 lb.-sec.	−6032 lb.-sec.
Momentum[a] after impact	472 lb.-sec.	1651 lb.-sec.	−184 lb.-sec.	−104 lb.-sec.
Change in momentum	5,959 lb.-sec.	5,969 lb.-sec.	5,934 lb.-sec.	5,928 lb.-sec.
Deceleration rate	421 ft. per sec.^{2} (13.1 *g*)	392 ft. per sec.^{2} (12.2 *g*)	456 ft. per sec.^{2} (14.6 *g*)	527 ft. per sec.^{2} (16.1 *g*)
Kinetic energy before impact	175,230 ft.-lb.	73,406 ft.-lb.	143,750 ft.-lb.	174,928 ft.-lb.
Kinetic energy after impact	934 ft.-lb.	10,732 ft.-lb.	147 ft.-lb.	52 ft.-lb.
Loss of kinetic energy during impact	174,296 ft.-lb.	62,674 ft.-lb.	143,603 ft.-lb.	174,976 ft.-lb.
Approximate duration of impact	0.12 sec.		0.11 sec.	
Avg. rate of energy dissipation	1,975,000 ft.-lb. per sec. (3,590 hp.)		2,900,000 ft.-lb. per sec. (5,270 hp.)	
Avg. force acting between cars	49,700 lb. (23 tons, approx.)		53,500 lb. (26.8 tons, approx.)	
Coefficient of restitution	0.102		0.006	
Amount of mutual crushing (total)	5.2 ft.		6.7 ft.	
Amount of crushing per car	2.6 ft.		3.35 ft.	

[a] For vectorial quantities (velocity and momentum) positive values indicate motion to right (as viewed), negative values, motion to left.

The momentum (mass times velocity), before and after impact, was computed for each car, and the changes in momentum, which theoretically should be equal, calculated. The values obtained were 5,959 and 5,969 lb.-sec. Since change of momentum is numerically equal to and expressed in the same units as impulse (force times time), division of the value for change of momentum, by the time of duration of the impact (0.120 sec.) gives a value for the aggregate average force acting between the two cars during the impact. This was found to be 49,700 lb. or approximately

25 tons, a value which was also checked from the relationship $F = \frac{W}{g}a$ using the weights of the two cars and their average decelerations.

The kinetic energies for the cars, before impact, were 175,230 and 73,406 ft.-lb., and after impact 934 and 10,406 ft.-lb., respectively. The combined loss of kinetic energy was therefore 236,970 ft.-lb. which was expended primarily in the structural deformation of the cars. Since this energy was expended in a period of 120 milliseconds, the average rate of energy expenditure was 1,975,000 ft.-lb. per sec., which is equivalent to 3,590 horsepower.

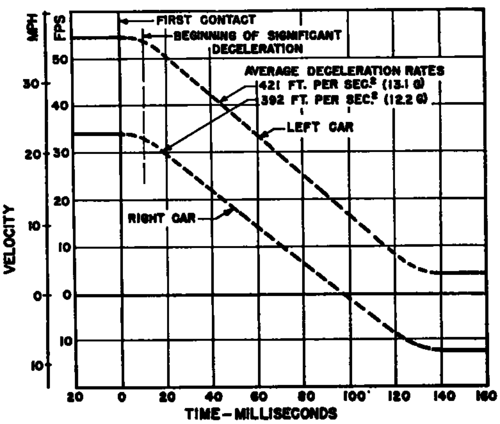

Figure 2. Velocity versus time, Collision 1.

The coefficient of restitution was found to be 0.102.

Figure 3 indicates the relative longitudinal positions and displacements of the two cars just before and during the impact period. This was plotted in such a way as to indicate the amount of mutual crushing of the front ends of the cars. The distance between the two curves, above the point indicating first contact, is a measure of this crushing, which reached a maximum of approximately 5.2 feet.

Figure 4 shows the two cars after the impact. Because the centerlines of the cars were slightly displaced laterally at the time of the impact, the greatest deformation occurred on the right front side of each. The damage to both cars was remarkably similar, consisting of backward displacement of the bumper end and right wheel, and general structural crushing of the order of 18 to 20 in.

The second collision differed from the first principally in the closer matching of initial velocities, as shown in Figure 5. However, another notable difference was the low velocities of both cars after the impact. The force of the impact appeared to produce a considerable degree of locking together of their structures, and they moved only about 6 in. to the left following the collision. There was only a momentary difference in their velocities (1.6 and 1.0 ft. per sec. leftward) after the impact.

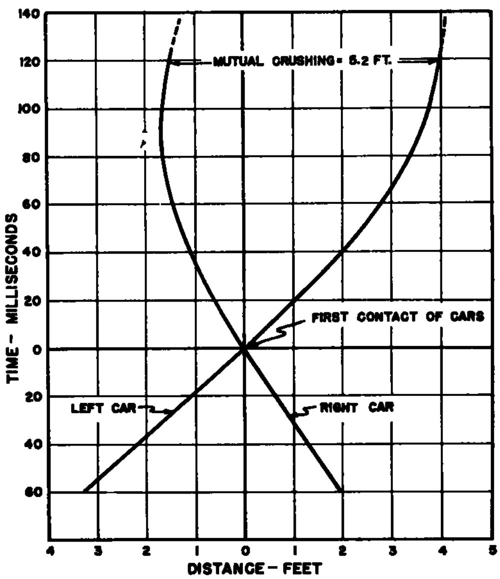

Figure 3. Displacement versus time, Collision 1.

Consequently, the calculated coefficient of restitution, 0.0056, is probably of little significance, except as an indication of the locking together previously mentioned.

The duration of significant deceleration was 0.110 sec. (110 milliseconds), and the respective deceleration rates were 456 ft. per sec. per sec. (14.6 *g*) and 527 ft. per sec. per sec. (16.1 *g*).

Calculated values for the change in momentum for the two cars were 5,934 and 5,928 lb.-sec., respectively. The aggregate average force between the cars was 53,500 lb. or 26.8 tons. Kinetic energy loss totalled 318,579 ft.-b., and as shown in Table 1, there was little

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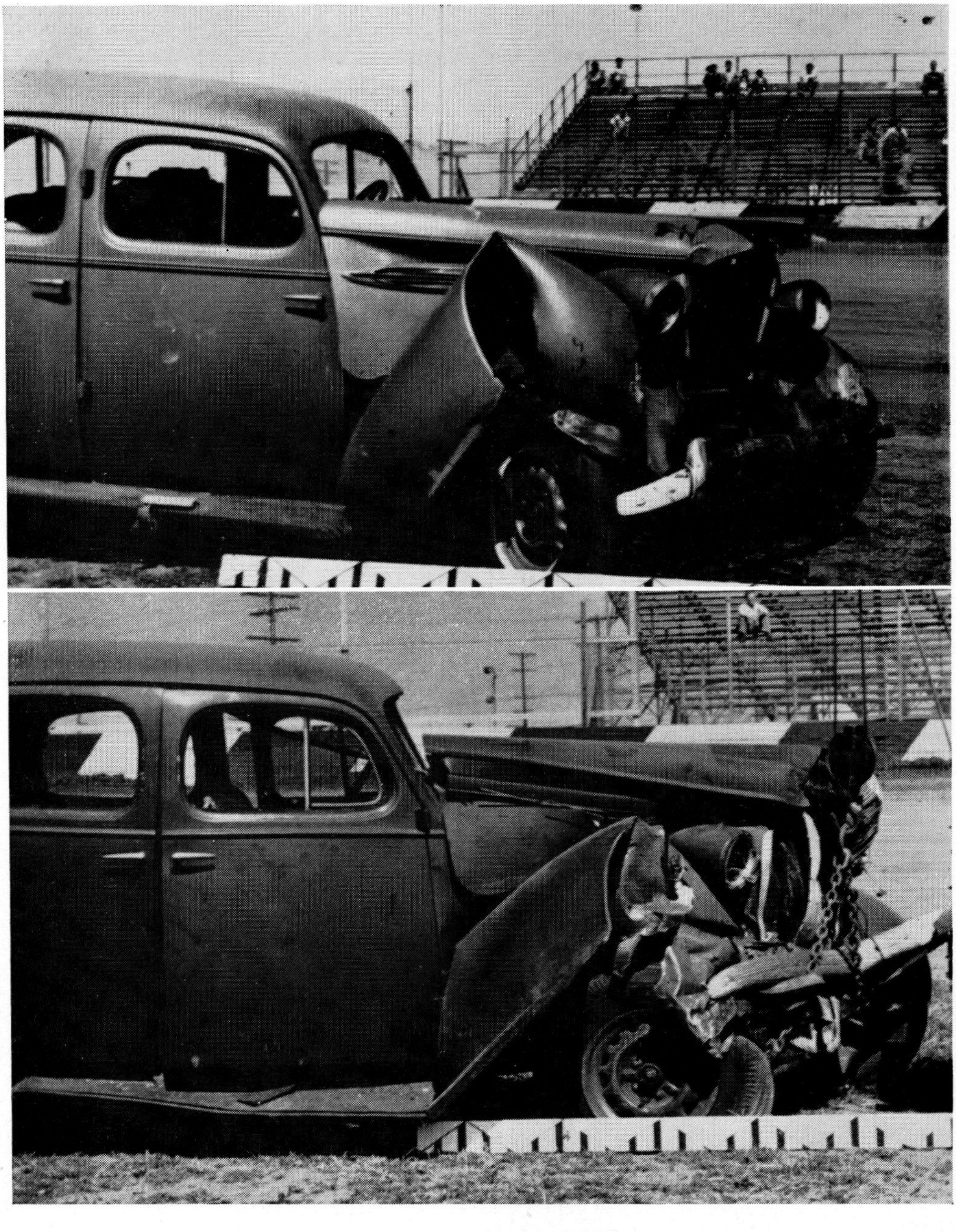

Figure 4. Damage produced, Collision 1.

residual kinetic energy. The rate of energy dissipation was 2,900,000 ft.-lb. per sec. or 5,270 hp.

As indicated in Figure 6, the mutual crushing reached a maximum of 6.7 ft.

In this collision, as in the first, the major damage occurred on the right side of each car. Because of the higher average velocities, damage was more extensive, as would be expected from the greater mutual crushing distance

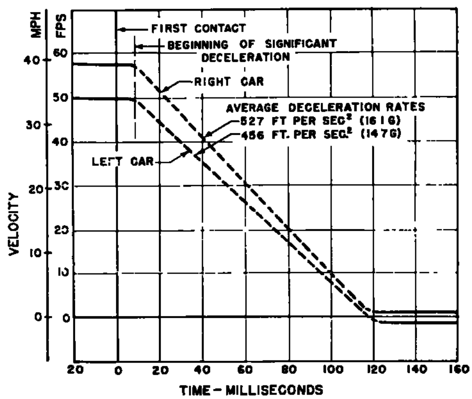

Figure 5. Velocity versus time, Collision 2.

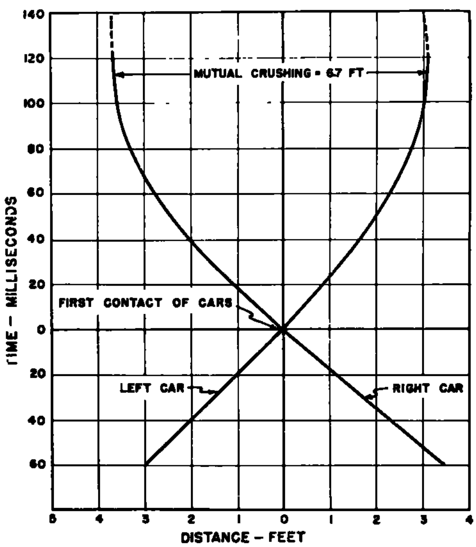

Figure 6. Displacement versus time, Collision 2.

The left car (1936 Buick) had its front suspension forced back so that a line between the front wheels made an angle of about 30 deg. with the transverse axis, and the right wheel was about 18 in. to the rear of the left. The radiator was completely crushed over the front of the motor, and the latter was forced back against the forward body panel, denting the latter back 1 or 2 in. The top of the motor was also tilted about 3 in. leftward. The left side frame member was buckled slightly near the left front motor support, and the right side frame member was crumpled back about 12 in.

The front seat structure, which was of wood, was broken on the right side but not on the left.

The right car (1937 Dodge) had its front end deformed about the same as the Buick, but at a slightly greater angle. The back of the right front wheel was forced back practically to the door. The right side frame member was buckled back by a distance of about 18 in. The motor had been torn loose from its supports and forced back, denting the lower part of the forward compartment panel about 6 in. The top of the motor was tilted left about 6 in.

The center section of the top edge of the front seat, which had been torn loose, had a forward displacement of about 12 in.

COMMENTS

In both collisions, the cars were subject to a certain amount of angular movement during the impacts. Their rear ends tilted upward noticeably, indicating that their centers of gravity were somewhat above the level at which mutual structural resistance was offered. These angular motions undoubtedly accounted for a certain amount of dissipated energy, but the film records did not provide sufficient data for profitable analysis

So far as the forces acting on the drivers are concerned, the fact that these stunts are performed routinely indicates that they are within a tolerable range. In the first collision, the maximum possible forces acting on the men could not have exceeded 12 to 13 times their body weight, as indicated by the decelerations in g units. Actually, because of yielding both of the seat structures and added padding, the forces were probably somewhat less. Similarly, in the second collision, the maximum possible forces would have been 15 to 16 times their body weights, and the actual forces materially less.

Research in aviation medicine has shown that the human body can readily tolerate, without injury, transversely-acting, well-distributed forces up to and probably exceeding