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STUDY OF HUMAN KINEMATICS
IN A
ROLLED-OVER AUTOMOBILE

for the
LIBERTY MUTUAL INSURANCE CORPORATION

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SUMMARY

The Cornell Aeronautical Laboratory has conducted a research program in the field of automobile roll-over crash safety under the sponsorship of the Liberty Mutual Insurance Company of Boston, Massachusetts. This program was directed toward controlling and reducing body injuries to the occupants during a roll-over type of accident. The automobile roll-over crash safety project was to determine, by experimental tests and the use of time-motion study, the kinematics of the human body in relationship to the interior of the car body when a roll-over condition was imposed upon the vehicle.

The testing equipment consisted of a typical four-door passenger car body mounted on a roll-over simulator. Articulated dummies were employed to represent human passengers. A high-speed motion picture camera and an accurate timing device were utilized to collect data on the kinematics of the dummies.

The roll-over simulator was designed for two separate operating conditions. First, the car body would be revolved about an axis through the ground contact point of the tires. This phase represented only the first 90 degrees of the rolling automobile. The second condition represented rolling of the car from its 90 degree position until the rolling motion stopped. During this stage of testing, the car body would be rolled about the center of gravity of the complete automobile.

Results indicated that the general motion characteristics of the occupants of the vehicle under the imposed roll-over conditions were of a predictable nature. The initial motion of the occupant was found to be fairly consistent and repeatable. In all cases, the occupants continued to move until they hit or struck a part of the automobile's interior.

A sequence of tests was conducted with both a full-scale dummy and a "six-year old child" dummy representing occupants. The action of the dummies when a restraining device was not in use was violent. Aircraft lap-type seat belts were demonstrated to be of major value in preventing the head from striking the sides of the interior of the automobile.

High-speed photographic techniques proved invaluable in determining the motion history of the dummies since post-crash examination of the final resting position of the dummies proved to be an inadequate method of defining the kinematics of their flight path.

The results of this phase of the test program proved conclusively that the first 90 degree of roll of an automobile subjects the passengers to high rotational accelerations and determines the direction and the point of impact of the passengers. Under practically all test conditions, the passengers' heads struck some part of the interior of the car body before the car had rotated 90 degrees.

INTRODUCTION

The Cornell Aeronautical Laboratory, Inc., has been engaged in research and development in the field of transportation safety for approximately twelve years. A continuous effort toward solving the engineering and mechanical problems of providing a safer human compartment for air and ground transportation has been expended. The goal has been to protect the occupants of a transportation vehicle from injurious blows within the vehicle during all types of crash conditions. The investigations were directed to acquire knowledge related to the fundamental human kinematics and kinetic aspects of the problem and have resulted in developing protection devices such as body restrainers, energy absorbing structures, and improved compartment design and the relocation or elimination of injurious objects.

The problem of the roll-over type of accident is one of considerable complexity as it covers a wide range of rolling conditions. It was decided that the roll-over problem should be approached in an introductory manner with full realization that the initial budget would allow only a preliminary test program.

The Cornell Aeronautical Laboratory collaborates with the Automotive Crash Injury Research Committee of Cornell University which studies the overall problem of protecting the occupants of vehicles. This research center has gathered injury data which freely demonstrates that approximately 19% of all injury-producing accidents involve a roll-over type of accident, although the resultant injuries are not always necessarily the result of the rolling action of the car. Crushing of the top structure is also a serious problem

Introduction (Cont'd.)

as this effectively destroys the package compartment, leaving no room for the occupant.

The Liberty Mutual Insurance Company has had a full appreciation of the cost of highway accidents, both in property damage and human injuries and death. The high cost of accidents has brought a realization of the need for action to reduce the loss of property and lives. The Automotive Safety Research Program sponsored by the Liberty Mutual Insurance Company was initiated in 1952 to collect information for use in the study of methods of reducing property damage and human injuries resulting from automobile accidents. The main subject of this report is one phase of the automobile accidents - The Roll-Over Type Accident.

PROBLEM STATEMENT

The statistical data gathered have demonstrated that approximately one-fifth of all injury producing accidents are involved in a roll-over type of accident. These data clearly demonstrate that the roll-over type of accident is well worth studying as a phase of the over-all crash safety program.

The automobile death rate on the American highways persistently remains at approximately 35,000 persons per year. The persons injured exceed one-million per year. This represents a direct loss of over a billion dollars per year. Despite the determined efforts of many agencies to cut down on the number of automobile accidents, the record of losses still continues.

The disastrous effects of accidents can be substantially reduced by improving the design of the vehicle itself. The bulk of the automobile accidents occur with impact speeds of 40 mph or less. Crash safety studies have indicated that the human body can be protected from death or serious injuries for crash velocities of that magnitude. It is therefore quite conceivable that, if adequate effort were applied to the problem of alleviating the effects of automobile crashes, the injury and death rate might be substantially decreased.

Since the majority of passenger fatalities are the result of head blows, primary emphasis was placed on the protection of the head. This program sought first to establish the relative hazard to the head of various components and sections of the interior of the automobile which the head may strike during a roll-over condition and, second, to recommend configurations

Problem Statement (Cont'd.)

of automobile interiors for optimum safety design.

The relative hazard to the head of any interior component of the automobile is believed to be the function of three variables:

a. The relative probability of head impact to that component

b. The relative energy of impact influenced by attitude and posture of the body at the instant of impact (See Figure 29)

c. The relative injury potential of the component as influenced by its shape, mass, and mounting resilience.

The test program conducted at Cornell enabled us to answer basically these questions:

a. Where are the occupants of an automobile likely to strike when a car is in a rolling attitude?

b. What are the postures, the attitude, and the flight path direction relative to the automobile body at the instant of head impact?

If parameters influencing the motion of both the occupant and the vehicle are recognized, defined, and evaluated; an analytical solution is possible. This method of approach is not only exceedingly complex but involves conditions which vary over very wide ranges. Therefore, it was decided that an experimental evaluation would result in more positive answers. The primary task, then, was to select values for the variables and design and select test equipment to allow simulation of typical roll-over crash conditions.

DESCRIPTION OF TEST APPARATUS

Obviously, live subjects could not be used; nor would it be economically feasible to crash and destroy a car for each test run. The first step was, therefore, to devise test equipment that would permit proper simulation of the desired roll-over conditions.

The following equipment was designed and erected by the Cornell Aeronautical Laboratory, Inc., to permit the simulation of the desired roll-over attitudes.

Dummies

Two dummies were previously designed at the Cornell Aeronautical Laboratory for use in research projects in the field of automobile safety. These were utilized in studying the effect of the roll-over attitude of human occupants inside an automobile. (See Figure 1.)

The dummies were made of a tubular steel skeleton with body contours approximated by properly shaped blocks of balsa wood. They were constructed with proper size and weight distribution and joint articulation to achieve dynamic similarity to their human counterparts. The full-sized dummy is proportioned to the average American who weighs approximately 160 lbs. with an overall height of 5'9". The actual weight of the dummy was approximately 1/4 the full weight of the man. This difference in weight is unimportant in studying the kinematic motions. The small child-size dummy is dimensionally a 2/3rds scale model of the large dummy and approximates a 6-year-old child. It weighs 22½ lbs., or approximately 1/2 the weight of its human counterpart. The weight distribution and the joint articulation are both extremely

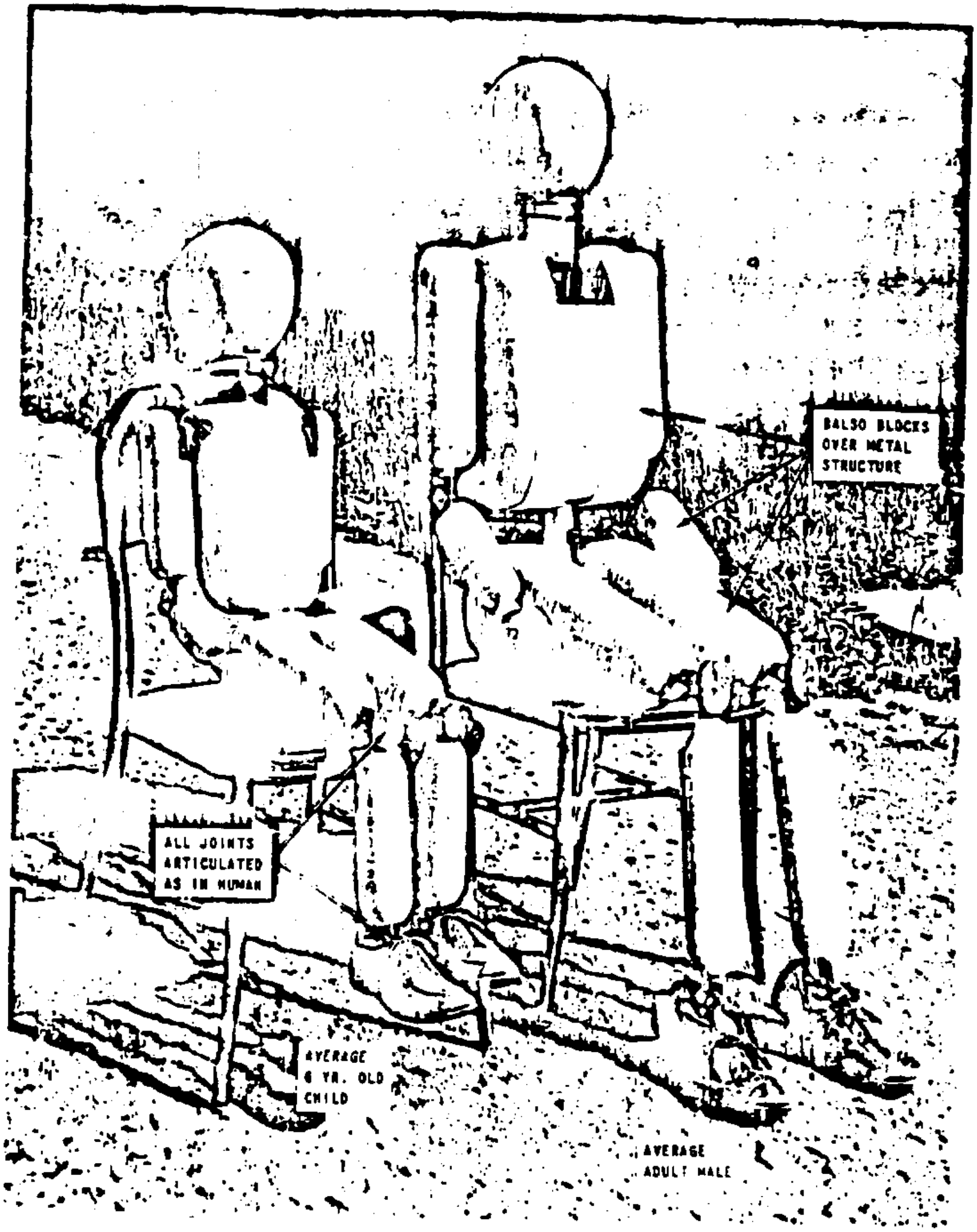

FIGURE I C.A.L. CRASH DUMMIES
(DYNAMICALLY SIMILAR TO HUMAN COUNTERPARTS)

Description of Test Apparatus (Cont'd.)

important in their effects on the kinematics of the body under roll-over conditions. This information is presented in Tables 1 and 2 respectively. The distribution of the weight of each of the body parts is arranged to proportionately duplicate the moment of inertia of the respective part of the human body. The center of gravity location of each major moving part also duplicates the actual human body. Muscular restraint to rotation of the body parts about the joint can be duplicated by varying the joint tightness by an adjustment of the friction washers. The dummies were adjusted to a semi-relaxed condition.

Test Vehicle:

The test vehicle was a standard 1956 Ford four-door sedan. This automobile is shown after modification in Figure 2. The pertinent modifications to the car body are listed below:

1. Only the passenger compartment was used as this fulfilled the requirements for the roll-over program. Use of the car body only, kept the weight to a minimum, thus reducing the power required for driving the simulator. This also kept to a minimum the over-all length of the roll-over platform. The interior of the car body was not changed in any manner. All items such as instrument panel, steering wheel, seats, door handles, etc. were left as conventional items.

2. A standard approved seat belt installation was added to the driver's seat, to allow for a comparison between a non-restrained occupant and an occupant using seat belts.

3. The rear seat was removed from the car body, as only occupants of the

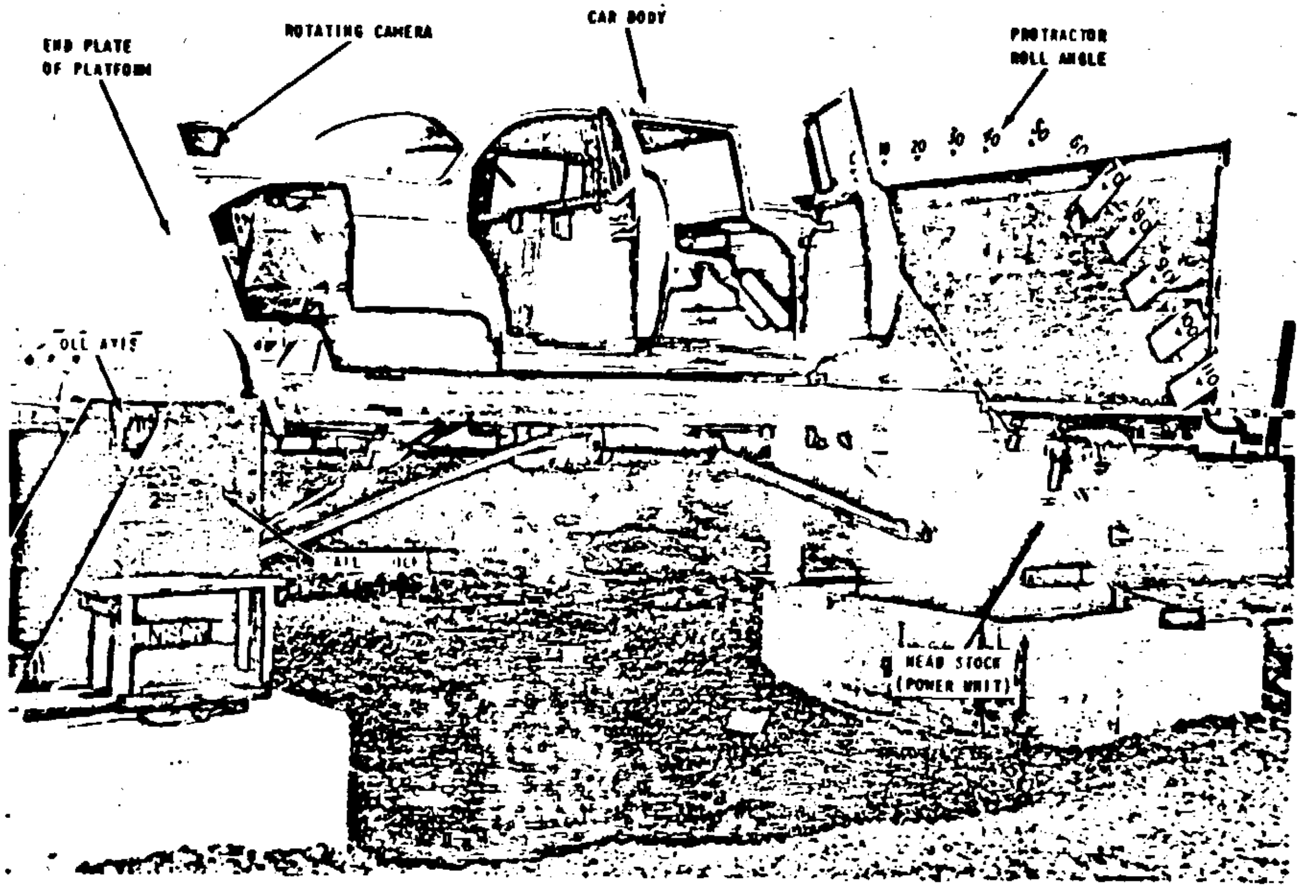

FIGURE 2 ROLL-OVER SIMULATOR
(AT 0° ROLL POSITION)

TABLE 1

WEIGHT DISTRIBUTION CHART
of
C.A.L. CRASH DUMMIES

		ADULT MALE		6 YR. OLD CHILD	
PART	% OF TOTAL	AVE. HUMAN LBS.	1/4 WT DUMMY LBS.	AVE. HUMAN LBS.	1/2 WT DUMMY LBS.
HEAD	6.97	10.7	2.68	3.14	1.57
TRUNK & NECK	46.13	70.7	17.7	20.76	11.38
UPPER ARM	3.29	5.05	1.27	1.47	.73
	3.29	5.05	1.27	1.47	.73
LOWER ARM	2.08	3.2	.80	.935	.47
	2.08	3.2	.80	.935	.47
HAND	.85	1.3	.33	.38	.19
	.85	1.3	.33	.38	.19
UPPER LEG	10.75	16.5	4.12	4.84	2.4
	10.75	16.5	4.12	4.84	2.4
LOWER LEG	4.79	7.35	1.84	2.165	1.1
	4.79	7.35	1.84	2.165	1.1
FOOT	1.69	2.6	.65	.76	.38
	1.69	2.6	.65	.76	.38
TOTAL	100%	153.4	38.4	45	22.5

TABLE 2

JOINT ARTICULATION LIMITS
of
C.A.L. CRASH DUMMIES

ARTICULATION	MOTION	RANGE
HEAD TO TRUNK (NECK)	BACKWARD MOTION	45°
	FORWARD MOTION	45°
	ROTATION	90°R, 90°L
UPPER ARM TO TRUNK (SHOULDER)	FORWARD MOTION	180°
	BACKWARD MOTION	90°
	ROTATION (EACH WAY)	10°
	SIDE MOTION	20°
FOREARM TO UPPER ARM (ELBOW)	FORWARD MOTION	135°
UPPER LEG TO TRUNK (HIP)	FORWARD MOTION	140°
	ROTATION (EACH WAY)	10°
	SIDE MOTION	20°
LOWER LEG TO UPPER LEG (KNEE)	BACKWARD MOTION	135°
FOOT TO LOWER LEG (ANKLE)	UPWARD MOTION	30°
	DOWNWARD MOTION	80°

front seat were evaluated in this testing series.

4. The underneath side of the car body was reinforced to structurally support the roll-over forces.

5. A turn table arrangement was mounted to the underside of the car body so that an adjustment in yaw angle could be provided at the center of gravity of the complete automobile. This adjustment could be made only under static conditions. (See Figure 3.)

6. A wire screen was stretched inside the car between the two centerposts of the automobile body. The wire screening, (Figure 6) was located just aft of the front seat back. The basic function of the wire screening was to serve as a reference grid in defining the action of the dummies. Each large square represents a 4 inch dimension in both the X and Y direction, (See Figure 6.)

7. A sweep second clock, (Figure 6,) was installed in view of the rotating camera to record an accurate time history of the rolling action of the car body.

8. The interior of the car body roof was painted white to increase the lighting effect inside the car body for photographic purposes.

9. Two large photo floods were installed just aft of the rear seat to increase photographic illumination of the interior of the automobile car body. This increased the lighting to record the fast action of the dummies.

<u>Roll-Over Simulator:</u>

The roll-over simulator, (Figure 2,) was designed by Cornell Aeronautical Laboratory, Inc. The simulator consisted of:

1. Two large turn tables mounted vertically, facing each other and spaced approximately 12½ feet apart. The turn tables are sometimes referred to as

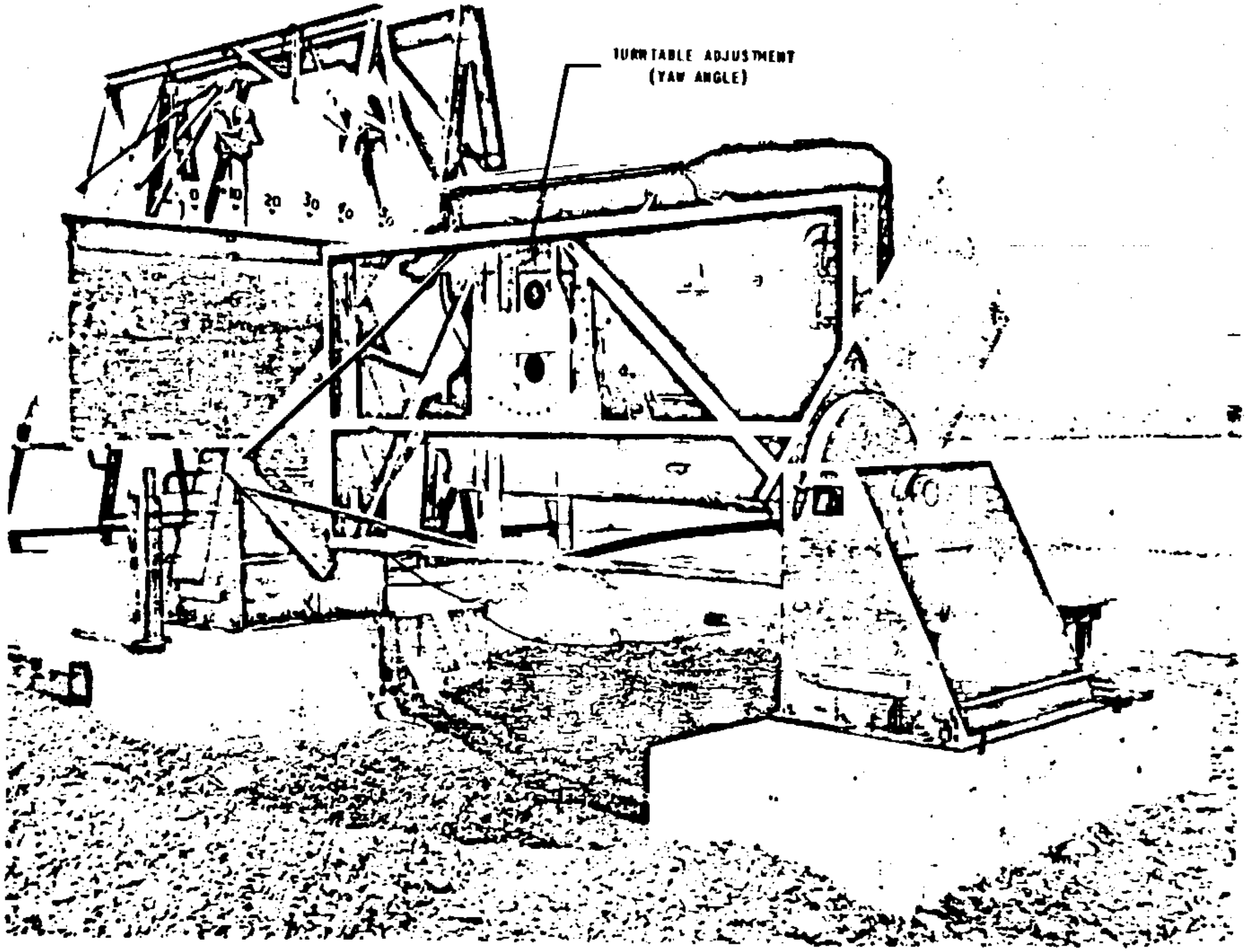

FIGURE 3 ROLL-OVER SIMULATOR
(SHOWING YAW ANGLE ADJUSTMENT OF CAR BODY)

"head stock" and "tail stock", respectively. Each turn table is anchored to a large concrete footing which adequately supports the loading during the rolling action of the car body.

The ground was excavated between the two footings, (Figure 2,) to provide roll clearance and to keep the rolling action of the car body to a minimum height.

2. A structural aluminum frame for mounting the car body was constructed between the two large turn tables, (Figure 4). This aluminum frame was used as the platform for attachment of the car body. The attachment method is described elsewhere in this report.

3. Two large plates were attached to the end of the roll-over platform, providing for the two roll axes, (Figure 4). These large plates have two sets of mounting holes to allow the roll axis to be shifted, thus representing first, the contact point of the tires with the ground and second, the roll axis coinciding with the center of gravity of the complete automobile.

4. The power unit for driving the simulator was incorporated into the head stock of the turn table, (Figure 5). The power unit was designed to deliver a maximum of 10,000 ft. lbs. of torque to the roll-over platform to which the car body was mounted. This torque was sufficient to roll the car body to the 90 degree position in less than one second. A remote control box provided the necessary controls for operating the roll-over simulator.

The power unit consisted of:

a) A seven and a half horsepower electric motor operating on 440 volts A.C. at 1800 R.P.M.

b) The output of the electric motor was coupled through a belt drive

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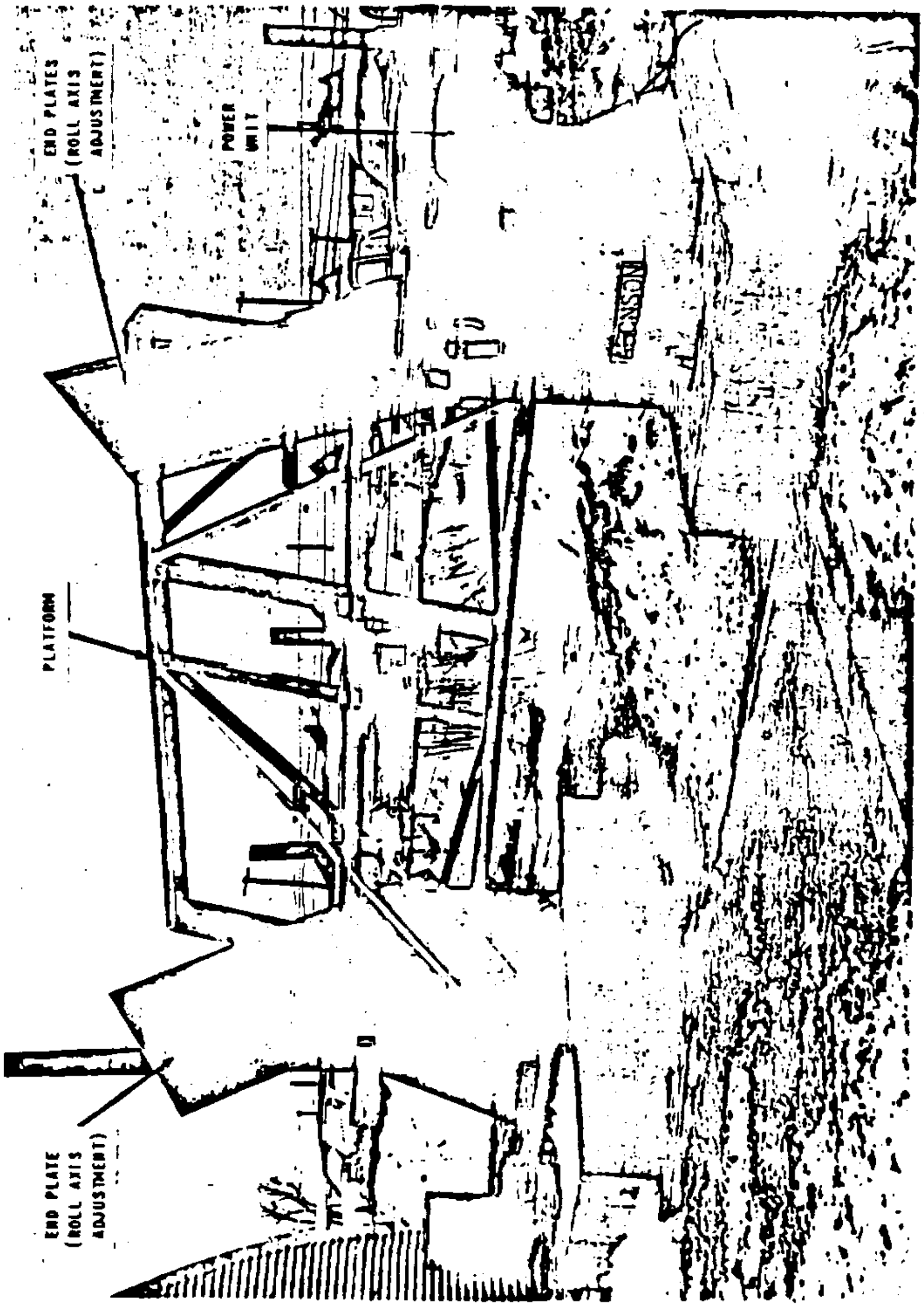

FIGURE 4 ROLL-OVER SIMULATOR WITH MOUNTING PLATFORM

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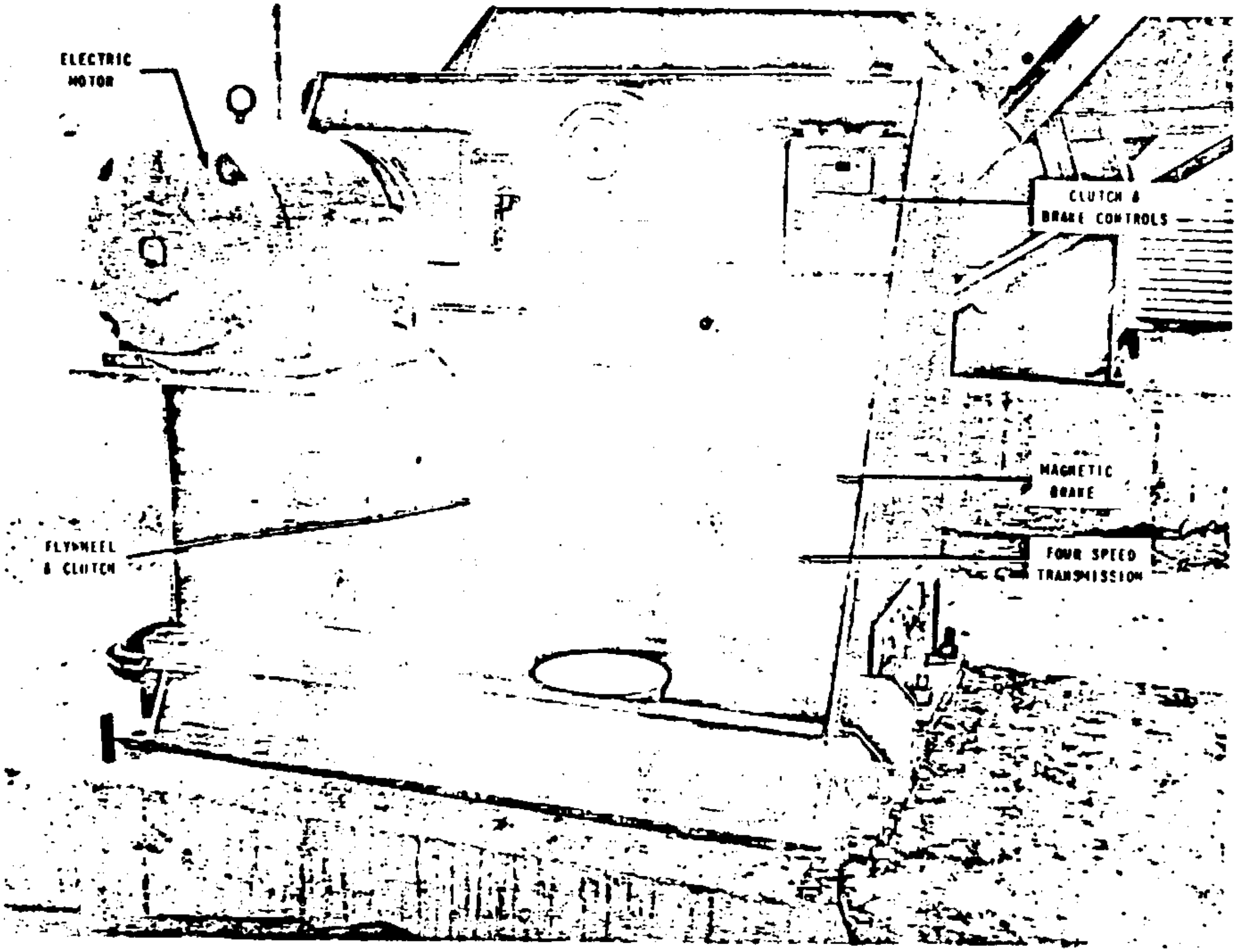


FIGURE 5 ROLL-OVER SIMULATOR POWER UNIT

to a large flywheel. The gear ratio between the electric motor and the flywheel was one to one. This allowed the flywheel to operate at a maximum of 1800 r.p.m.

c) The output of the flywheel was then coupled through a magnetic clutch which engaged a chain-drive type of transmission. The magnetic clutch had adequate electrical controls to vary the torque applied to the transmission system, thus controlling the torque applied to the roll-over platform. Electrical control of the magnetic clutch proved successful in controlling the rate of roll of the car body.

d) Four sets of gear sprockets provided wide control of the rotating platform in ratio of 10-20-30 and 40 r.p.m. A wide variation of roll torque was permitted by varying the combination of the magnetic clutch and the r.p.m. of the platform.

e) A magnetic brake provided fast stopping of the roll-over simulator. The braking feature was automatic; as soon as the clutch disengaged, the magnetic brake came into play. Controls for the magnetic brake provided a wide selection of braking torque to control the stopping rate of the rolling action of the car body.

Instrumentation

The instrumentation consisted fundamentally of two high-speed cameras. A 16 mm camera operating at 64 frames per second was mounted on the roll-over simulator to allow it to roll with the car body. This camera was mounted on a bracket outside the rear window to allow the field of view to cover the interior passenger compartment, (Figure 6).

Accurate time data was obtained by mounting a timing clock in view of

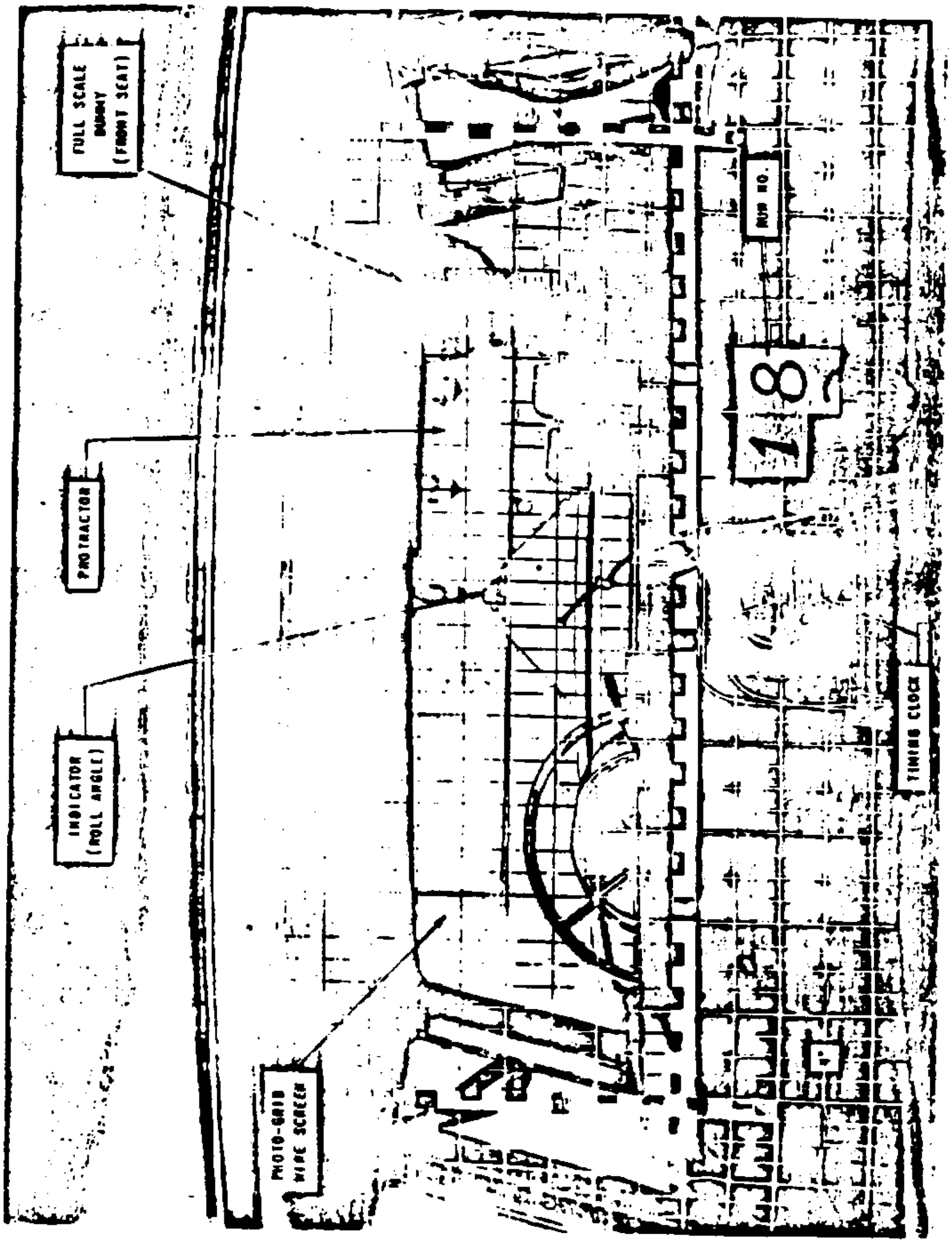


FIGURE 6 ROTATING CAMERA VIEW OF DUMMIES AND BACKGROUND GRID

the camera. Rotation of the camera with the car body facilitated data reduction of the kinematic behavior of the occupants inside the car body.

The actual angle of the rotating car body with relationship to the ground was recorded by the camera. This was accomplished by constructing a large protractor just outside the front windshield in view of the camera, (Figure 2).

Only a pure roll attitude was investigated for a roll-over type of crash during this test phase of the program. Therefore, the use of only one camera to cover a vertical plane to record the action of the dummies within the car body was required.

The results of this particular camera were most successful in providing data. The test runs have been edited in the form of a short reel of motion pictures.

A second camera, mounted to a tripod located on the ground, covered the complete field of view of the roll-over simulator. Very little data relative to actions of the dummies within the car was provided by this camera. Basically this camera recorded the overall action of the roll-over simulator and car body.

TEST PROCEDURE

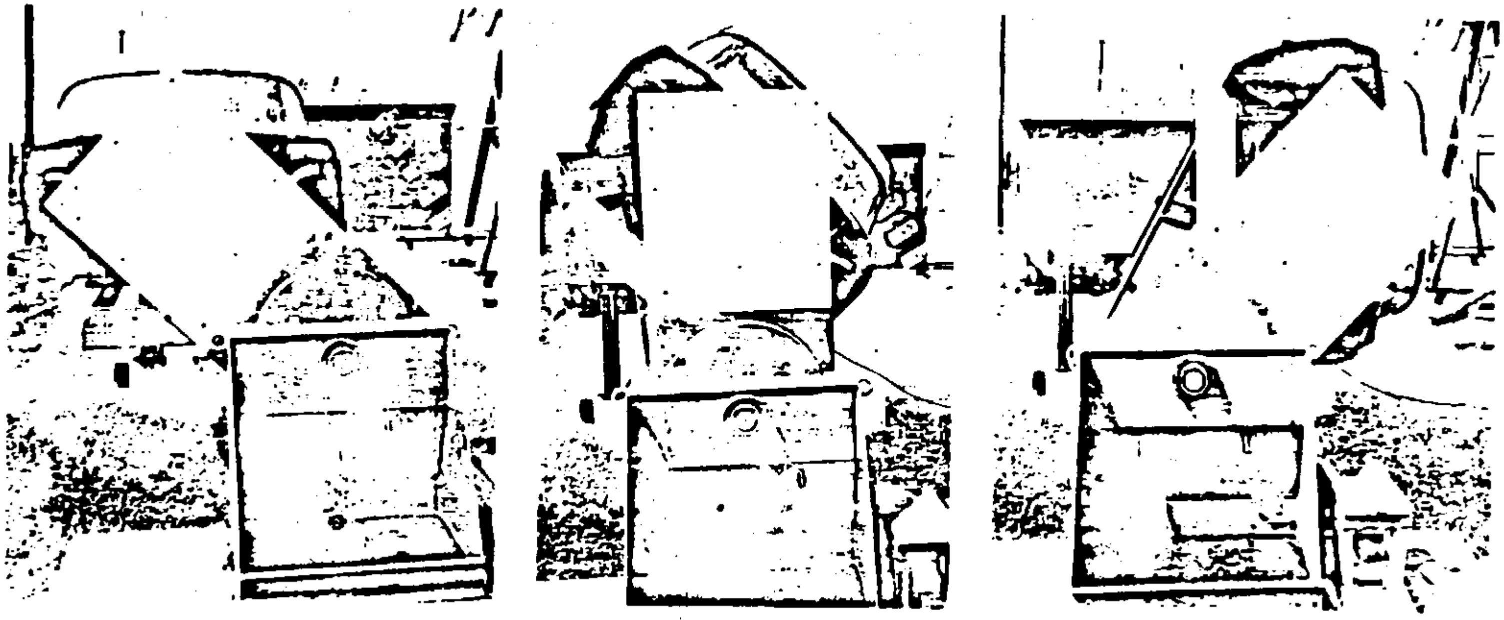
It was recognized at the beginning of the program that the parameters controlling the motion of a rolling car were numerous and in combination were extremely complex. The wide variation of these parameters can result in a virtually infinite variation in the final motion characteristics of the automobile and occupants within.

However, examination of the forces which can effect the kinematics of the occupant of an automobile during a roll-over attitude, coupled with consideration of the occupant's relative position to the interior parts of the vehicle and the nature of the common types of roll-over accidents all served to narrow down the seemingly wide range of conditions worthy of detailed study.

The roll-over test program was conducted under Laboratory controlled conditions. During this test program, we assumed a condition whereby no impact with another object had been realized. Therefore, no energy loss was recorded by hitting a solid object which would have caused extensive structural damage to the car.

It was decided to separate the basic rolling motion into two distinct stages. The first stage included the initial 90 degrees of the rolling action of the automobile. This initial 90 degrees of roll represented the tire contact point with the ground as the roll axis, (Figure 7.)

The second phase of the rolling automobile was to be conducted from the 90 degree roll position until the rolling action of the car had stopped. The second phase of rolling would require a separate set of conditions. The



0° ANGLE 45° ANGLE 90° ANGLE

FIGURE 7 ROLL-OVER SIMULATOR
(FIRST 90° OF A ROLLING
AUTOMOBILE)