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OPERATOR RESTRAINT TESTING PROGRAM - PHASE II

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16. Abstract

Overturning accidents of forklift trucks were simulated using a variety of turning maneuvers and drop tests. An instrumented anthropomorphic dummy, both restrained and unrestrained, was used to simulate the operator. Test results are given and observations about the validity and repeatability of the test procedures are made.

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Prepared for

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1.0 INTRODUCTION

The Industrial Truck Association (ITA) has been conducting an experimental study entitled "Operator Restraint Test Program," to simulate, in a controlled environment, the overturning of forklift trucks and to record and measure the response of the truck operator during the overturn.

1.1 Background

The first phase of the program was carried out during 1980, when some 36 overturn tests were performed. The results of this phase are given in the final report to ITA.[1]

One of the objectives of Phase I was to simulate reported field accidents in which the truck operator is struck by the overhead guard during a lateral truck overturn. However, none of the attempts in Phase I succeeded in producing this interaction between the operator and the overhead guard.

Another objective of Phase I of the testing program was to evaluate the effects of restraint systems on the kinematics of the occupant during truck overturns. This was to be done by a comparative study of the occupant's kinematic response in tests similar in all respects except for the presence (or absence) of and the type of restraining device.

Such a study would first require that a series of "identical" tests be conducted without any restraint to produce a repeatable occupant

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[1]King, A. I. Operator Restraint Test Program, Final Report. Southfield, Mi.: A.I. King, Inc., January 1981.

response. Another series of tests, identical to the first series except for the introduction of the restraint device, would then be conducted to produce a repeatable, and hopefully improved, occupant response. Using this approach, the effects of armrests and seatbelts were investigated in Phase I. However, because of the complexity of variables affecting the occupant response and the limited number of repeatable tests that were obtained, it was not possible to draw statistically valid conclusions about the effectiveness of any tested restraint device.

The results of Phase I and the experience gained from it led ITA to initiate a second phase of the "Operator Restraint Testing Program," in which the test methods and conditions and the test matrix were carefully designed. Because the first testing phase was performed by ITA at the Corporate Laboratories of Clark Equipment Company, ITA sought an independent testing laboratory to conduct the next series of tests. The Highway Safety Research Institute (HSRI) of the University of Michigan was contracted to perform Phase II of the testing program.

This report describes the tests performed in Phase II during the 3-month period ending with January 1982. The results of the tests are also included, along with evaluations of the test methods and a discussion of results.

1.2 Objectives

Phase II of the testing program was conceived by ITA to accomplish certain objectives by simulating two types of overturn accidents: those that occur while the truck is traveling and attempting a left turn, and that which occur while the operator is engaged in maneuvering activities on a loading dock. The objectives were:

(a) Obtain repeatable occupant responses from overturn tests where test conditions are duplicated from Phase I.

(b) Conduct overturn tests under modified but realistic operating conditions that were more likely to produce the field-observed interaction between the operator and the overhead guard.

(c) Document the effects of restraint systems on the operator response during truck overturns.

After the first nine lateral dynamic overturn tests, during which the effects of seatbelts and armrests were being systematically studied, it became clear that the test conditions in the dynamic test series were not producing the desired interaction between the overhead guard and the "operator". The remaining tests were subsequently conducted without operator restraint, with the objective of determining the precise vehicle and occupant dynamics that would result in the operator being caught between the overturning guard and the ground.

1.3 Approach

In order to achieve the above objectives of Phase II, the test plan called for two categories of tests identified as (1) Lateral Dynamic Overturning Tests, and (2) Static Dock-Related Tests.

The effects of restraint systems were to be studied by conducting "repeat" tests with (1) unrestrained operator, (2) operator in a seat with armrests, and (3) operator wearing seatbelts.

Various modes of overturning were to be performed, simulating various types of reported or projected accidents. Thus, the dynamic tests were to be conducted while the truck was moving at its maximum speed, and (1) executing a sharp J-turn to the left causing the truck to overturn on its right side, (2) executing a sharp S-turn also resulting in an overturn on the truck's right side, and (3) executing a sharp J-turn but with the truck traveling in reverse for a right-side overturn.

The static (dock-related) tests were to include (1) longitudinal overturning (tipping forward) with the truck carrying its maximum rated capacity load, and with the load at its maximum fork height, (2) rear drop-off where the forklift, with its front wheels parked on a trailer, is dragged by the moving trailer away from the dock, and (3) lateral overturning, where the operator, steering away from the edge of the dock, causes the steer wheel to fall off the edge and overturn the truck on its side.

The truck operator in all of these tests was simulated by an anthropomorphic dummy instrumented with accelerometers at the head center of mass, the mid-chest, and the pelvis, as well as with load cells to measure knee loads.

The test plan called for comprehensive documentation of the truck motion and dummy kinematics through the use of transducers and high-speed movies. Finally, the test data were to be processed and analyzed, and the test results presented and discussed.

2.0 LATERAL DYNAMIC TEST SERIES

In this series of tests, the lift truck was made to overturn, by remote control, onto its right side while traveling at maximum speed. A total of 21 successful lateral dynamic overturns were completed, in various modes and under conditions described later in this section.

2.1 Test Site Preparation

The dynamic test series was conducted in a parking lot adjacent to the HSRI building in Ann Arbor, Michigan. One area in the vacated lot was used as the site where the truck would overturn. A 20x20-foot gridwork was painted on the pavement in 1x1-foot squares. The runway was 100 feet long to allow the truck to reach its maximum speed of about 12 mph as it traveled toward the gridded test site. See Figure 2-1.

Two high-speed, 16-mm movie cameras (Photosonics 1B) were placed at right angles and aimed toward the center of the grid along the grid diagonals. Because of the layout of the runway and the parking lot, the two cameras were aimed in the general southern direction, that is, looking into the sun. Thus, it was necessary to provide high-intensity lights over the test pad, totaling over 20,000 watts, to eliminate the shadows from the filmed event. Vertical markers were placed alongside the edges of the square test pad to provide accurate scaling of the projected image for quantitative film analysis. In addition, test identification slates were included in the field of view. In most of the early tests, however, these ID's could not be clearly seen. In later tests, larger test numbers were attached to the side of the truck, and a close-up of the test ID and conditions was spliced to the original

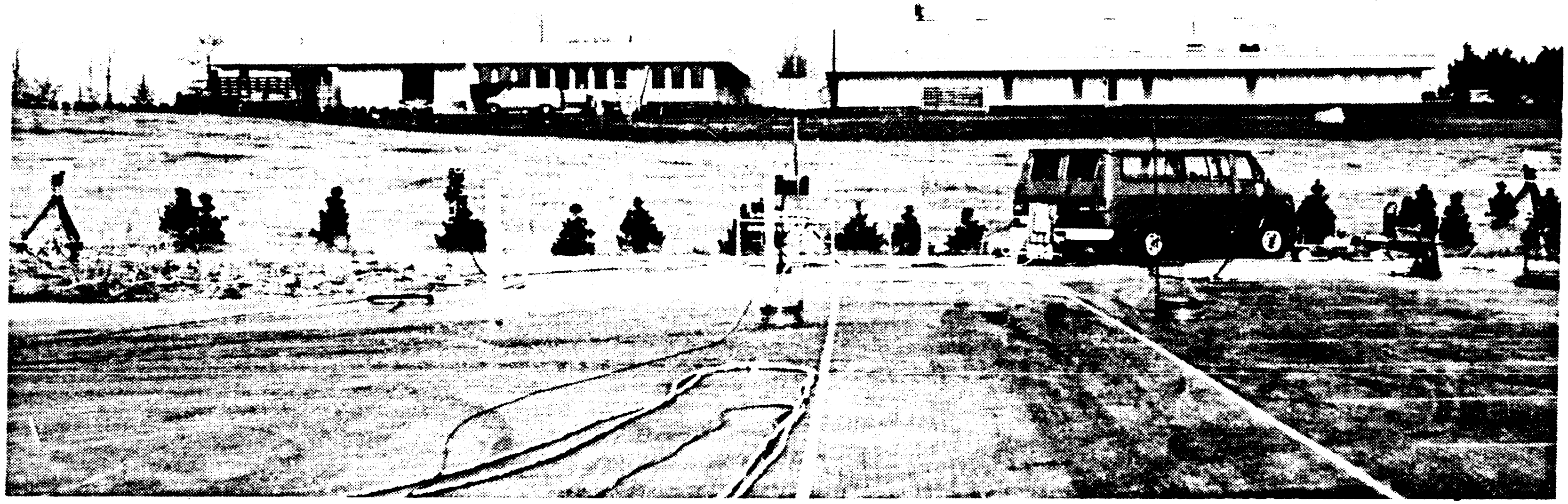

Figure 2-1: Overall View of Dynamic Test Site

film of each test before copying. Finally, an additional hand-held zoom movie camera was used in later tests to obtain a 64 frames/second movie of the truck approach and a close-up of the dummy motion at impact. The test site, runway, and camera locations are shown in Figure 2-2.

2.2 Test Equipment

Two major pieces of equipment were used in this testing program: (1) the forklift truck itself, modified for remote control, and (2) a 95th percentile male anthrpomorphic dummy simulating the truck operator.

2.2.1 The Test Vehicle and Controller. The forklift truck used in this series was a Clark model number C500 Y30 that was equipped with a steering control system allowing for remote control of the steering function. All dynamic tests were conducted with the vehicle in the unloaded condition with the forks set twelve inches above the ground.

The standard hydraulic steering valve (actuated by turning the steering wheel) was replaced by an electro-hydraulic servo-control valve. The steer cylinder was equipped with a linear variable differential transformer (LVDT) to provide the necessary feedback signal for the control system. An umbilical cord, trailed from the vehicle, provided the means to transmit the necessary electrical signals to and from the vehicle.

Steering position commands were generated for this system by two sources. As the vehicle approached the immediate rollover sight, the experimenter controlled steering directly by turning a control dial on a hand-held control box. To initiate the actual event, the vehicle passed through a "gate" consisting of two standards, between which was strung a trip-wire. When the vehicle hit the wire, a switch was thrown that introduced a new level of steering position command. The servo-system

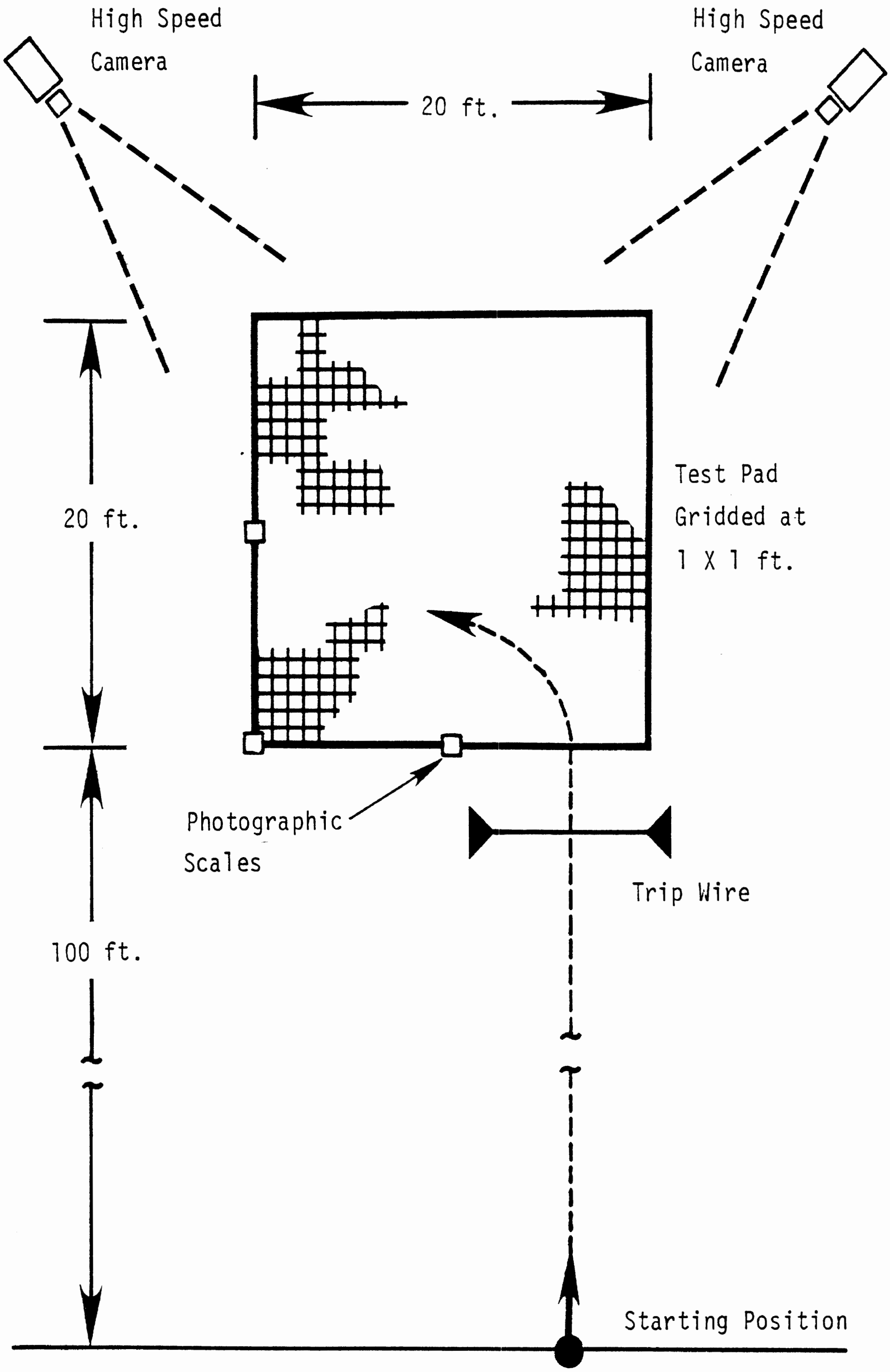

Figure 2-2: Diagram of Dynamic Test Site and Camera Locations

would then cause steer wheels to turn at the maximum rate toward the new command position. Two successive gates could be employed in one run to provide two different steering position commands. Figure 2-3 shows a simplified diagram of the control system. (The system was initially provided by the sponsor in a somewhat different form. Figure 2-3 illustrates the system as modified by HSRI in order to provide a broader range of input possibilities than initially available.)

The vehicle was also equipped with a solenoid that, when activated, tripped the throttle from the "IDLE" to the "ON" position. Thereafter, the vehicle speed was controlled by the engine governor, and the vehicle proceeded at maximum speed.

Finally, the system included a shut-down switch, that turned off the engines and activated the brakes.

2.2.2 The Test Subject. This was a 95th percentile male anthropomorphic dummy, which is typically used in automotive safety testing. This dummy is the best currently available substitute for man, and is used whenever the testing environment is too dangerous for human volunteers. To help the dummy maintain a certain posture, muscle tone was simulated by "setting" the joints to 1 g. This is done by tightening the joints at the elbows, shoulders, hips, and knees just enough so they will hold the weights of the extremities. Active muscle tone is absent in this and all dummies, because they cannot "tense up" in reaction to, or in anticipation of, the impact.

2.3 Instrumentation

In addition to the two high-speed cameras filming the sequence of events, various time-histories of the truck motion and the dummy kinematics were monitored.

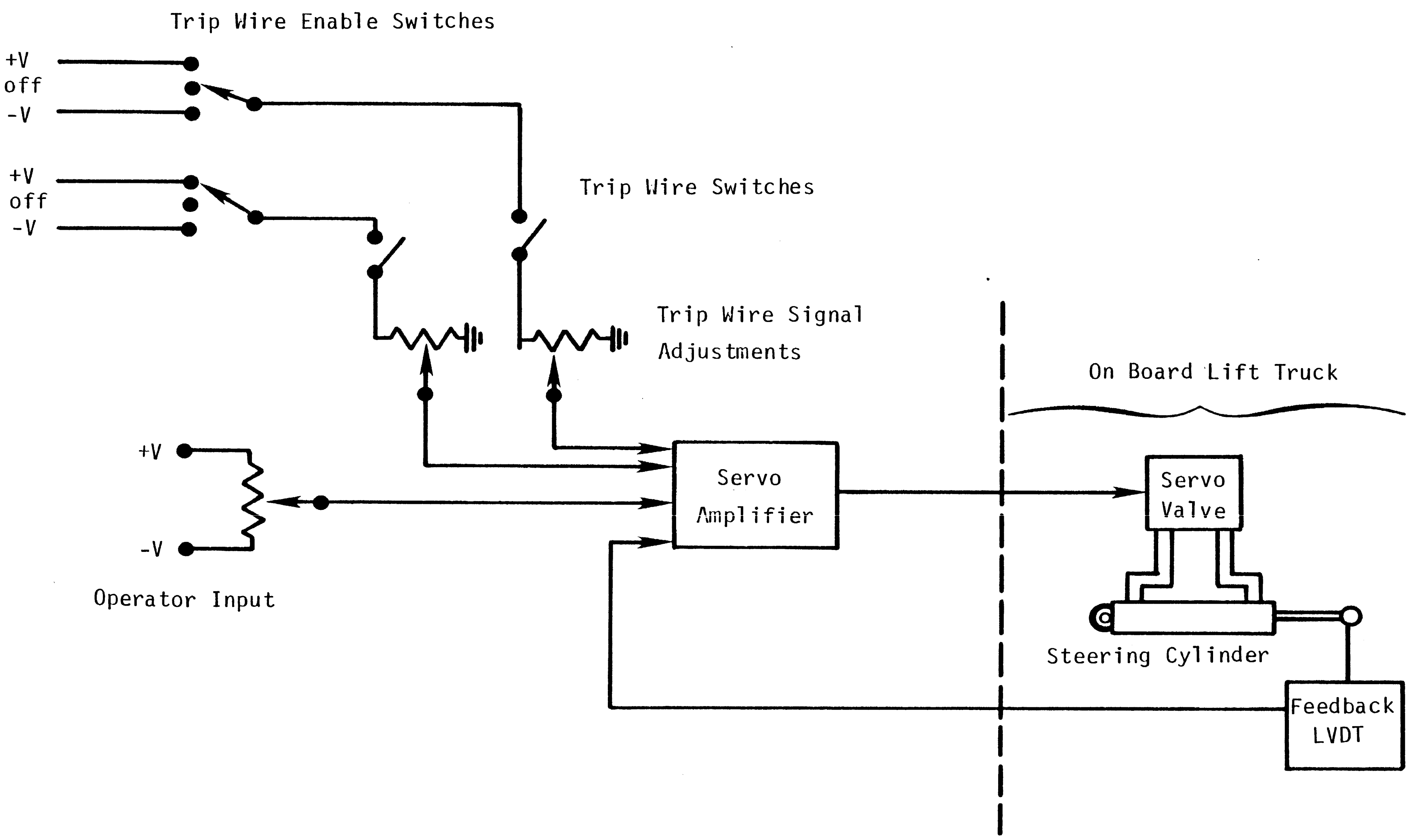

Figure 2-3: Steering Controller Schematic Diagram

The truck was instrumented with a triaxial accelerometer package to monitor its deceleration at impact in the A-P (anterior-posterior), L-R (left-right), and S-I (superior-inferior) directions. The truck velocity was obtained from one of the truck wheels via a velocity transducer. This transducer generates magnetic pulses, that are in turn converted to a voltage proportional to the truck velocity. Finally, a mercury switch was attached to the truck counterweight at a 45-degree angle so that it closed when the truck was about to overturn. The switch closure was recorded along all other signals, and it was also used to fire a flashbulb mounted on the truck to synchronize the events from the movies with the analog signals recorded on tape.

Standard dummy instrumentation included triaxial accelerometer packages to measure the A-P, L-R, and S-I accelerations at the head center of gravity, the mid-chest, and the pelvis. For most of the dynamic tests, knee load cells were not used. The forces exerted by the dummy's hands on the steering wheel were measured with a steering column load cell, which included three orthogonal force transducers in the A-P and L-R directions (perpendicular to the column long axis), and in the S-I direction (along the column axis), as well as two torque transducers about the A-P and L-R axes. Finally, in tests in which the dummy was wearing a seatbelt, the left and right belt tensions were also recorded.

All cabling to the transducers emerged as one bundle and was channelled to the HSRI indoor instrumentation room via two 350-foot umbilical cables. The signals were conditioned but not filtered. The conditioned signals were routed to two FM analog tape recorders where they were recorded on magnetic tape for storage and for later analog-to-digital conversion and data processing.

2.4 Data Processing

At the end of one day's testing, all movie films were labeled, packed, and shipped for developing. The processed original film was usually returned after one business day. The original was edited to remove the beginning of the film showing the empty test site, and to include only the film segment which showed the truck or occupant in motion. A close-up of test title, code, and conditions was spliced with every test, and the original was then sent back to the processing lab to make a workprint. Movies from only two tests were totally lost, while several movies of unsuccessful overturn attempts were obtained.

The analog tapes containing the recorded signals were converted to digital signals, and those signals were processed on the University's Amdhal/V7 computer. A special purpose program was written to handle the exceptionally long (approximately 640 ms) digitized signals. The sampling rate was 6400 Hz (samples/second) for each signal, for a total of 4096 points per signal. Since the synchronization signal from the mercury switch did not function at all in some cases, or since it fired too late in others, the beginning of the digitized signal was manually controlled.

The raw (unfiltered) signals were then plotted in their entirety to determine whether a cable was broken or a signal was lost before it was included in the final processing. With these raw plots in hand, the processing was carried out by specifying not only which signals would be processed, but also what 320-ms segment of the total 640 ms should be extracted.

Once the desired segment of data was selected to include all the impact information, the signals were digitally filtered in accordance with SAE J211b instrumentation guidelines. Different classes of filters having different cut-off frequencies were used depending on the signal source. Thus,

* Class 1000 filter (corner @ 1650 Hz) was used for the head accelerations,

* Class 180 filter (corner @ 300 Hz) was used for the chest and pelvic accelerations and for the seatbelt loads,

* Class 600 filter (corner @ 1000 Hz) was used for the femur (knee) loads, and

* Class 60 filter (corner @ 100 Hz) was used on the truck deceleration signals, and for the steering wheel signals.

Resultant accelerations[2] were calculated point-by-point for the head, chest, pelvis, truck, and steering column signals. The Head Injury Criterion (HIC)[3] was calculated from the head resultant acceleration. The time-histories of all signals were scanned to find their minima and maxima and their time of occurrence. Then these time-histories were computer-plotted in a specially-designed format, suitable for slide presentation. Finally, a one-page summary of all values was printed for inclusion in this report.

Detailed results and computer output of dynamic overturn tests are assembled in Appendix A. A summary of the results is given in section 2.6, while the evaluation of and discussion are presented in section 3.

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[2]Square root of sum of squares of A-P, L-R, and S-I components

[3]Described by the following expression, where "a" is the resultant acceleration of the head and "t_1" and "t_2" are any two points in time during the impact:

$$\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a\,dt\right]^{2.5}(t_2-t_1)$$

2.5 Description of Dynamic Tests

The original plan called for 20 lateral dynamic overturn tests to be conducted under carefully specified test conditions. As testing progressed, the original plan was modified to produce the desired truck/dummy interaction.

In the dynamic tests, the dummy was seated in an upright posture as shown in Figure 2-4, and its hands were tied to the steering wheel with a single strand of 40-pound test nylon fishing line. The seating position was maintained during the acceleration phase of the truck with a chest tether (a 40-pound nylon fishing line) that was automatically cut immediately before the overturn with a knife/solenoid device activated by the mercury switch described earlier. Although the device did not function properly in some tests, it was felt that the inertial forces acting on the chest were more than sufficient to break this tether. That is to say that the tether had negligible effects on the motion of the dummy during overturn, while it served its purpose of maintaining the desired initial posture of the dummy.

In the first 9 tests, a sharp J-turn maneuver was executed while the lift truck was traveling at its maximum speed of approximately 12 mph. The radius of turn was approximately 6 feet, and the truck overturned on its right side. The next three tests were S-turn maneuvers in which a sharp right turn was executed first, followed immediately by another sharp J-turn to the left causing the truck to overturn onto its right side.

The difference between the groups of tests was the presence or absence of restraining devices. Thus, some tests were run with the dummy restrained only by the armrests of the seat, some were run with

Figure 2-4: "Upright" Seating Posture of the Dummy

the occupant in a seat without armrests but wearing seatbelts, while other tests were run with the occupant completely unrestrained, i.e. without seatbelts and without armrests. After the first 9 tests (J-turns) were conducted as described above and the resulting vehicle and occupant dynamics examined, it became evident that three additional factors were affecting the truck/dummy interactions.

First, it was determined that the hand ties to the steering wheel were inconsistently breaking at different force levels, producing both ejection and non-ejection of the dummy under supposedly identical test conditions. This was subsequently remedied by eliminating the stress concentrations at the knot in the nylon line by wrapping the line several times over the hand before taking it to the steering wheel rim. The line gage was also changed to 20 pounds, then to 10 pounds, and several combinations of single and double strands were also tried out.

Second, it was found that the dummy always ejected from the rear in those tests in which ejection occurred. The seating posture was subsequently modified from "upright" to slightly "leaning" forward, as most operators do when driving a forklift truck, as shown in Figure 2-5.

Finally, after trying out various hand tying schemes and seating the dummy in a forward-leaning posture, it was determined that there was little difference in the dummy motion between the J-turn and the S-turn tests, and that the final J-turn causing the overturn was too severe to produce the desired ejection mode of the dummy.

Thus, attention was turned to modifying the vehicle dynamics by changing the radius of turn to 18 feet instead of the sharp 6-foot radius. After several tests were conducted, it was found that such a slow turn was causing premature side-ejection of the dummy, because the

Figure 2-5: Slightly "Leaning" Forward Seating Posture

sustained overturning motion was too long, allowing the dummy to eject from the cage and hit the pavement before the truck was finally overturned. A detailed discussion of the vehicle and occupant dynamics is given in section 3.

Subsequently, the turn radius was reduced to about 15 feet. The last six tests were conducted at this turn radius, producing several different types of dummy interaction with the overhead guard. Two of these involved the guard impacting the dummy after it had ejected. Table 2-1 summarizes the test conditions of all lateral dynamic overturn tests conducted in Phase II.

2.6 Results of Dynamic Tests

The results of 21 dynamic lateral overturn tests are summarized in Table 2-2. Detailed output of data processing is given in Appendix A. Highlights of these results are presented in the next subsections.

2.6.1 Results of Q1, Q2, and Q3.

These were severe J-turns with seatbelts but no armrests. The belt anchors were at the left and right mounting bolts of the overhead guard rear legs. Review of the high-speed movies indicated that the dummy stayed inside the cage (overhead guard) but slid sideways on the seat as the truck struck the ground. The lap belt kept the head of the dummy from hitting the top of the cage in the tests. The dummy hit the ground at the shoulder first, after the truck had already struck the ground. In test Q1 the head did not strike the ground. The dummy final positions in these tests were typically as shown in Figures 2-6 and 2-7. The peak resultant accelerations averaged 30 g for the chest and 27 g for the pelvis. The head peak resultant ranged from 73 g to 417 g, and the HIC from 132 to 1636.

TABLE 2-1: TEST CONDITIONS OF DYNAMIC OVERTURNS

Test Code	Test Conditions
	9 Tests of 6-ft. J-Turn, Upright Dummy Single Wrist Ties of 40# Line:
Q1, Q2, Q3....	With Seatbelts (no armrests)
R1, R2, R3....	With Armrests (no seatbelts)
S1, S2, S3....	Unrestrained (no seatbelts or armrests)
	3 Tests of 6-ft., S-Turn:
U1............	With armrests (no seatbelts), 1x40# wrist line, Dummy upright
V3, V4........	Unrestrained, Double wrist ties of 20# line, Forward-leaning dummy
	3 Tests of 18-ft. J-Turn, Forward-Leaning Dummy:
U2............	With armrests (no seatbelts), Single wrist ties of 40# line
U4............	With armrests (no seatbelts), Double wrist ties of 20# line
V1............	Unrestrained, Double wrist ties of 20# line
	6 Tests of 15-ft. J-Turn, Forward-Leaning Dummy, Double Wrist Ties of 20# line:
S5, S6, S7....	With Armrests (no seatbelts)
S8, S9, S10...	Unrestrained (no seatbelts or armrests)

2.6.2 Results of R1, R2, and R3. These were also severe J-turns without seatbelts but with a seat equipped with armrests. In these tests the dummy ejected from the rear, swinging the armrests upward (with the thighs) as it exited from the cage. In test R1, the head missed the top of the cage, but, as the dummy hit the ground, it bounced about 1 foot before it assumed the final position shown in Figure 2-8. In test R2, the dummy hit the ground at the same time as the truck, then bounced away from the rear opening of the cage, and assumed a final

TABLE 2-2: SUMMARY OF DYNAMIC OVERTURN TEST RESULTS

Test	Restraints		HIC	Peak Resultant G's			Observations
	Seat Belt	Arm Rest		Head	Chest	Pelvis	
Q1	w	w/o	132	73	28	28	Retained by Belts
Q2	w	w/o	606	245	29	30	Retained by Belts
Q3	w	w/o	1636	417	33	21	Retained by Belts
R1	w/o	w	1166	363	50	181	Partially Ejected/Rear
R2	w/o	w	1766	439	62	96	Partially Ejected/Rear
R3	w/o	w	709	298	35	165	Partially Ejected/Rear
S1	w/o	w/o	790	371	83	202	Ejected from Rear
S2	w/o	w/o	1646	415	39	99	Ejected from Rear
S3	w/o	w/o	71	96	54	189	Ejected from Rear
U1	w/o	w	4299	925	52	99	Ejected from Rear
V3	w/o	w/o	376	116	32	49	Retained by Cage Top
V4	w/o	w/o	272	112	46	71	Retained by Cage Top
U2	w/o	w	414	275	33	54	Remained with Truck
U4	w/o	w	686	198	56	41	Remained with Truck
V1	w/o	w/o	277	146	39	106	Remained with Truck
S5	w/o	w	5858	691	44	18	Diving Ejection
S6	w/o	w	12	84	8	32	Diving Ejection
S7	w/o	w	2934	624	56	95	Diving Ejection
S8	w/o	w/o	2281	475	57	129	Caught in Abdomen
S9	w/o	w/o	8595	831	54	51	Retained by Cage Top
S10	w/o	w/o	4745	606	48	96	Caught on Head

position similar to Figure 2-8. Finally, in test R3, the dummy also ejected from the rear, and bounced off its own shoulder 4 to 5 feet above the ground with no apparent head/ground contact. Its final position is shown in Figure 2-9. The HIC values ranged between 709 and 1766. Peak accelerations averaged 245, 33, and 27 g for the head, chest, and pelvis, respectively.

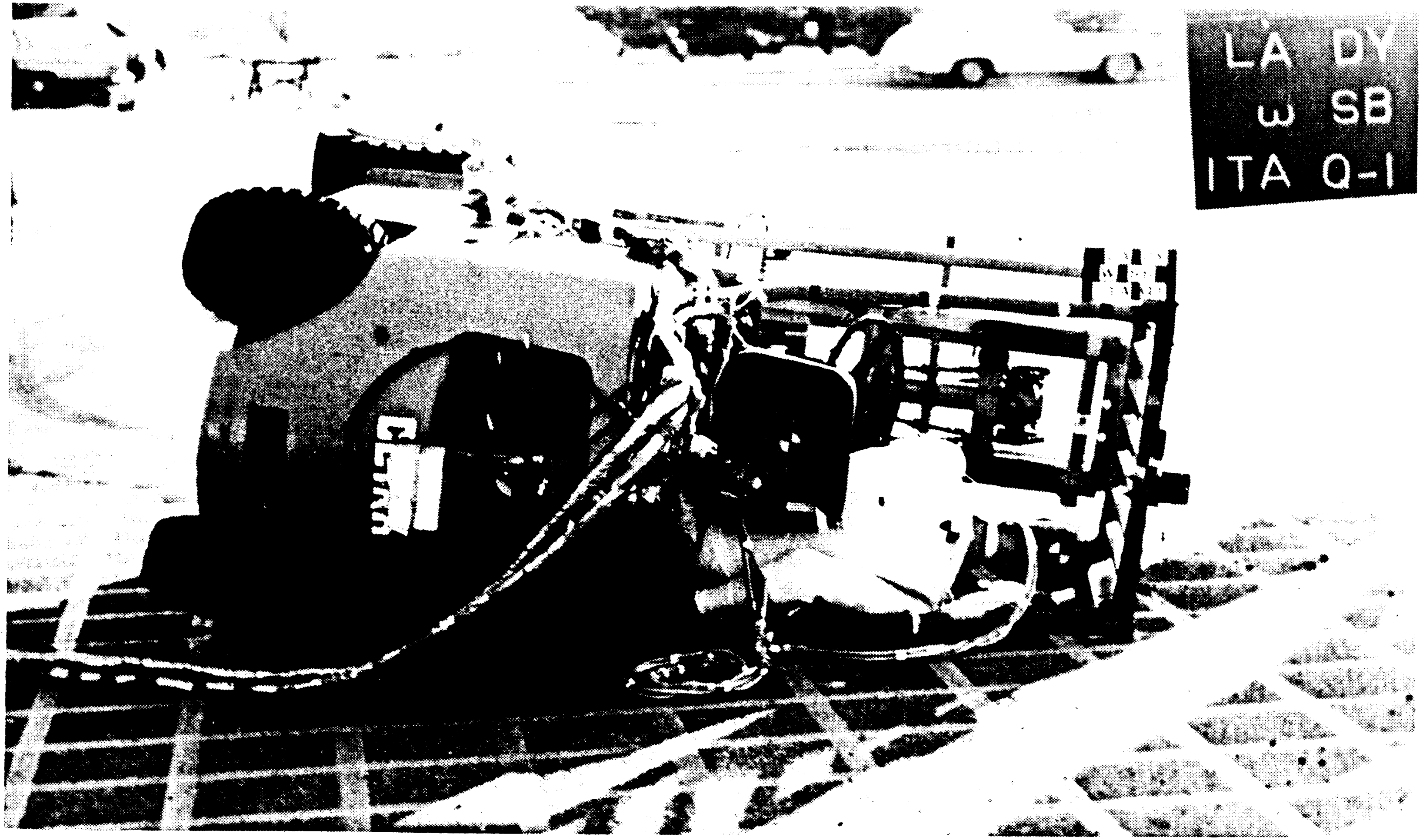

Figure 2-6: Final Dummy Position in Test Q1

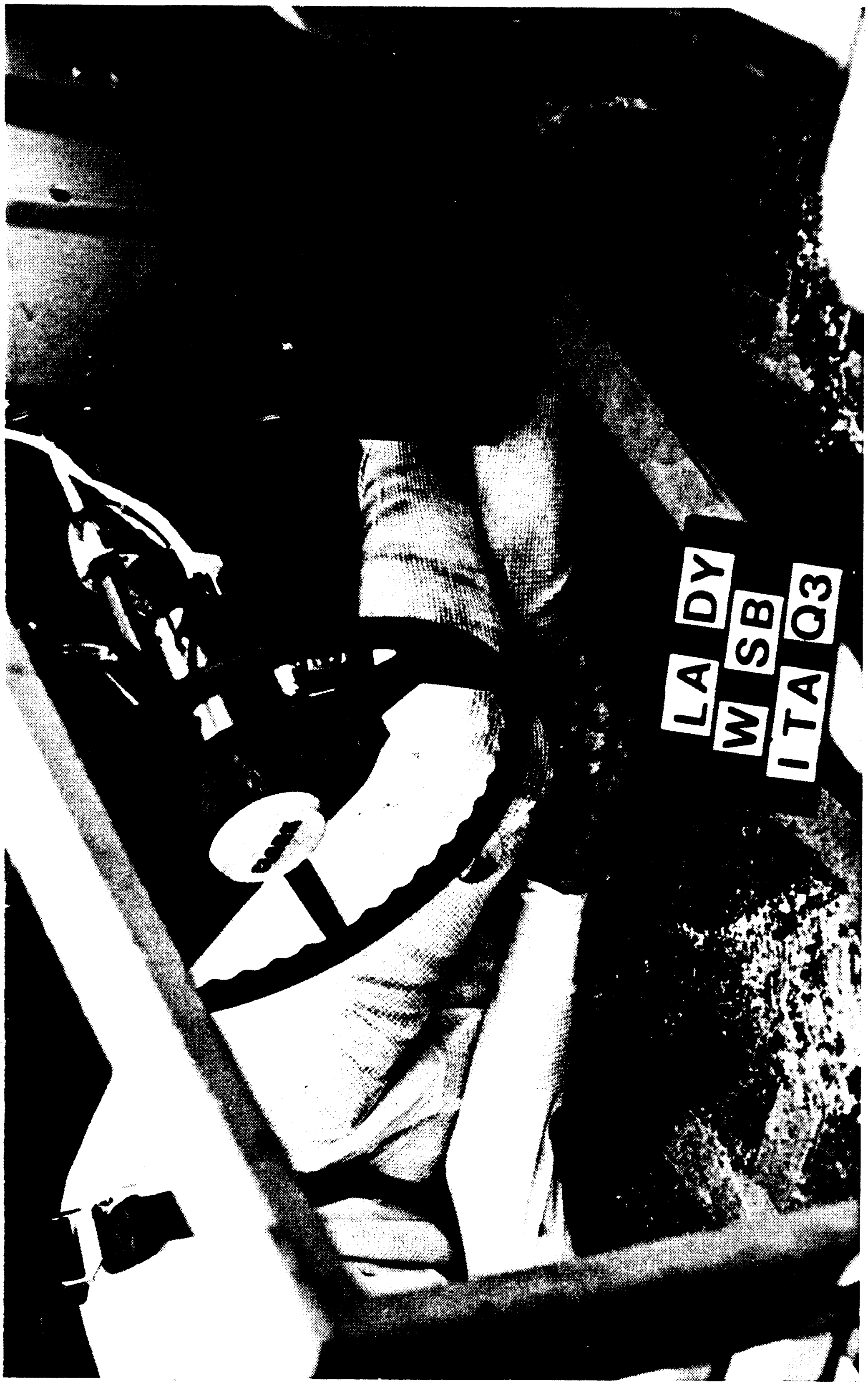

Figure 2-7: Final Dummy Position in Test Q3

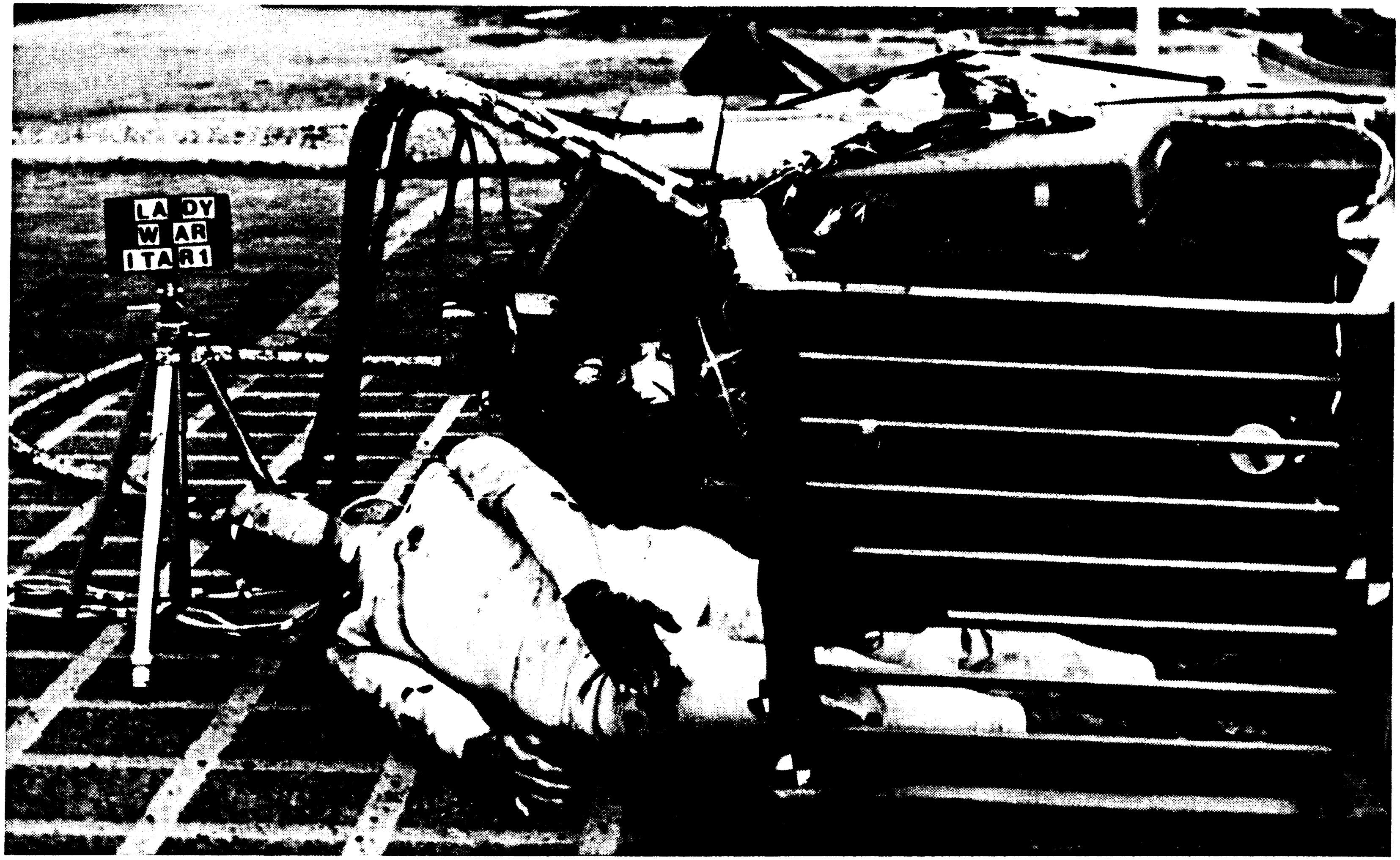

Figure 2-8: Final Dummy Position in Test R1

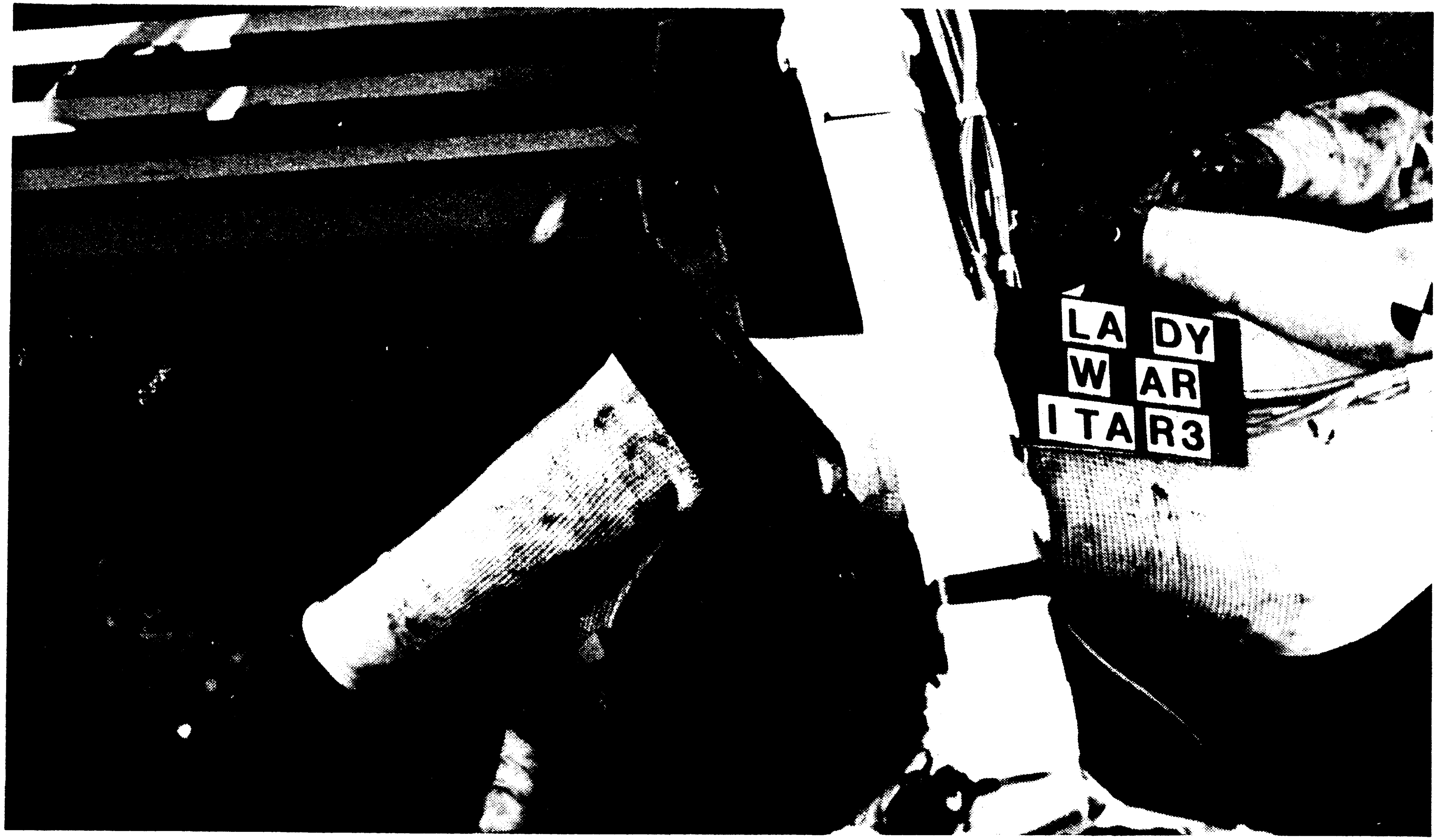

Figure 2-9: Final Dummy Position in Test R3

2.6.3 Results of S1, S2, and S3. Also severe J-turns, these tests were run with the unrestrained dummy (no seatbelts or armrests). In all three tests, the dummy ejected completely from the rear opening of the cage, assuming three different final positions on the ground as shown in Figure 2-10, 2-11, and 2-11. Review of the high-speed movies revealed that in test S1, the pelvis hit the ground first, followed by the shoulder and then the head. In test S2, the right leg was thrown out first, was then caught under the truck side, but eventually was pulled away from under the truck as the dummy slid on the ground away from the truck. The pelvis landed on the overhead guard support (right rear) resulting in lower pelvic accelerations. In test S3, the dummy was partially ejected at the time of truck/ground impact, but the ejection was eventually completed after the truck stopped skidding. The head did not strike the ground due to shoulder contact. The signals for tests S1 and S2 resulted in HIC values of 790 and 1646. Peak resultant accelerations were 371 and 415 g for the head, 83 and 39 g for the chest, and 202 and 99 g for the pelvis. The lack of head contact in test S3 resulted in a HIC of 71 with peak resultant accelerations of 96 g for the head, 54 g for the chest, and 189 g for the pelvis.

2.6.4 Results of U1, V3, and V4. These 3 tests were the only S-turn tests that were conducted. The movies revealed that the dummy's initial position prior to the second J-turn was leaning slightly to the left as a result of the first J-turn. The dummy ejected from the rear only in test U1, missing the right-rear corner of the top of the cage. In tests V3 and V4, the head impacted the top of the cage during the dummy's upward/rearward motion, resulting in its final retention inside the cage. Figures 2-13, 2-14, and 2-15 show the final positions

Figure 2-10: Final Dummy Position in Test S1

Figure 2-11: Final Dummy Position in Test S2

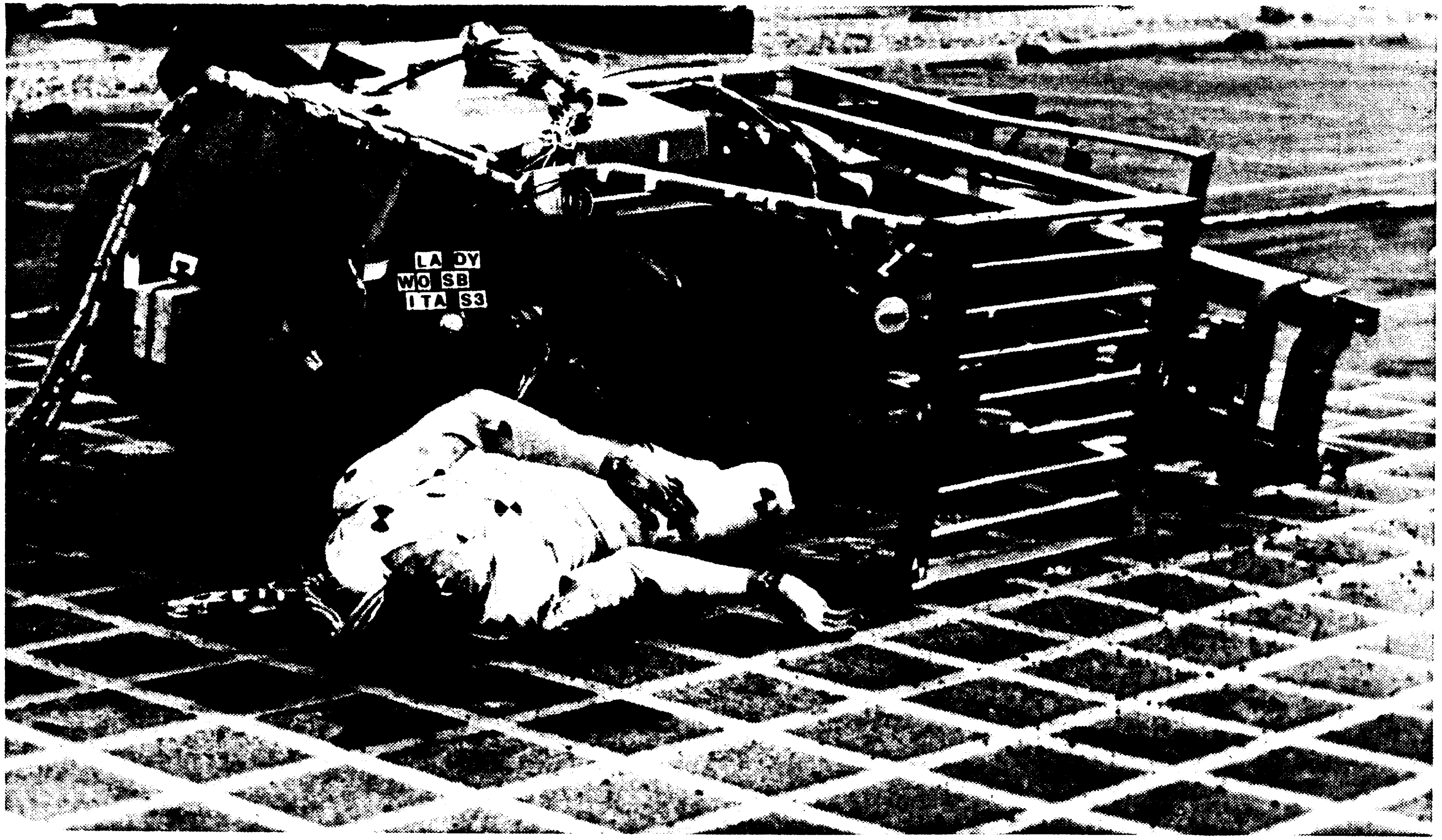

Figure 2-12: Final Dummy Position in Test S3

in these three tests. The HIC for test U1 was 4299 with peak accelerations of 925, 52, and 99 g for the head, chest, and pelvis. Averages for tests V3 and V4 were 319 for the HIC, and 114, 39, and 60 g for the head, chest, and pelvic accelerations, respectively.

2.6.5 Results of U2, U4, and V1. These tests were mild (approximately 18-foot radius) J-turns, all without seatbelts. In these 3 tests, the dummy stayed in the seat and with the truck as it overturned. As a result, the dummy remained inside the cage and side-impacted the ground at the same time as the truck. The HIC ranged between 277 and 686, while the peak resultant accelerations averaged 206, 43, and 67 g for the head, chest, and pelvis, respectively. The final dummy positions in these tests are shown in Figures 2-16, 2-17, and 2-18. Figure 2-19 shows the truck's impending overturn that never occurred in the attempt of test U3.

2.6.6 Results of S5, S6, and S7. The J-turn radius was reduced from 18 feet to approximately 15 feet. These 3 tests were then run with the unrestrained dummy. In all these tests, the dummy was ejected head first from the side opening of the overhead guard. The dummy subsequently dove into the ground while the truck continued its forward motion. By the time the truck was overturned, the dummy had already hit the ground, and, subsequently, was dragged by the umbilical cable as the truck skidded on its side. The final positions are shown in Figures 2-20, 2-21, and 2-22. In test S6, the dummy's leg was caught under the truck's counterweight. Because of the premature ejection, test S6 processing missed the primary impact, and only the secondary impact was processed. The respective results of tests S5 and S7 were HIC values of

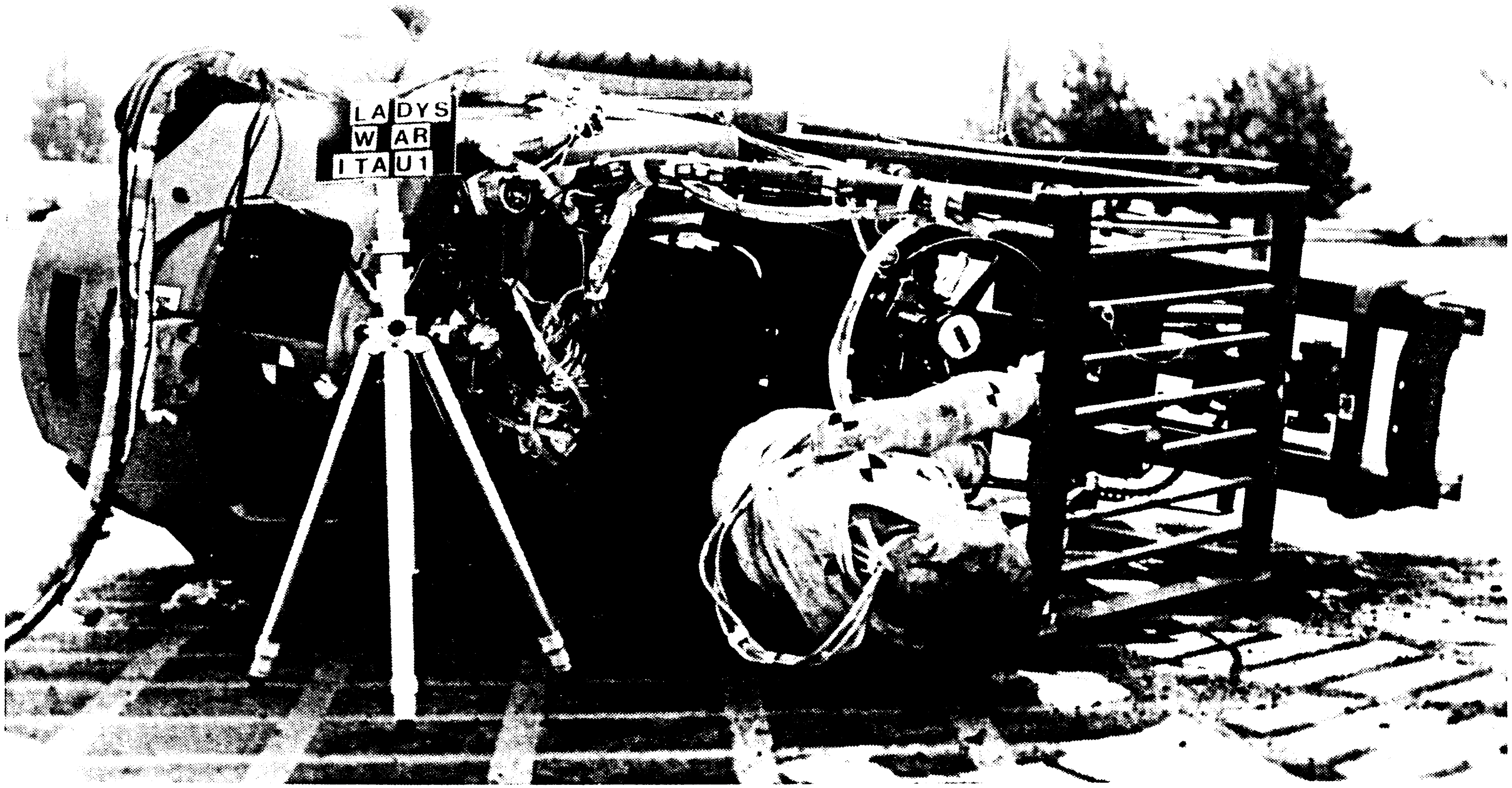

Figure 2-13: Final Dummy Position in Test U1

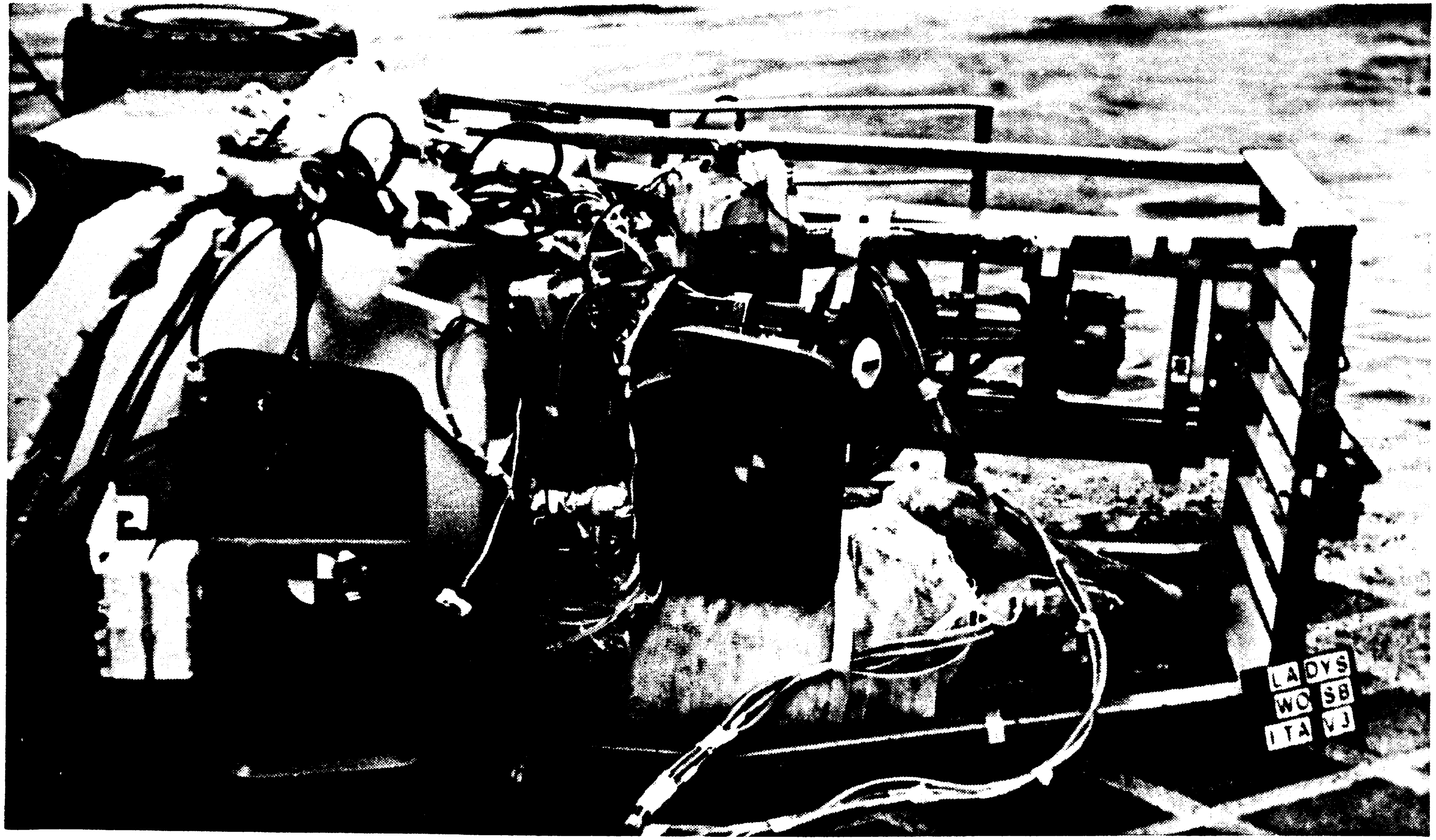

Figure 2-14: Final Dummy Position in Test V3

Figure 2-15: Final Dummy Position in Test V4

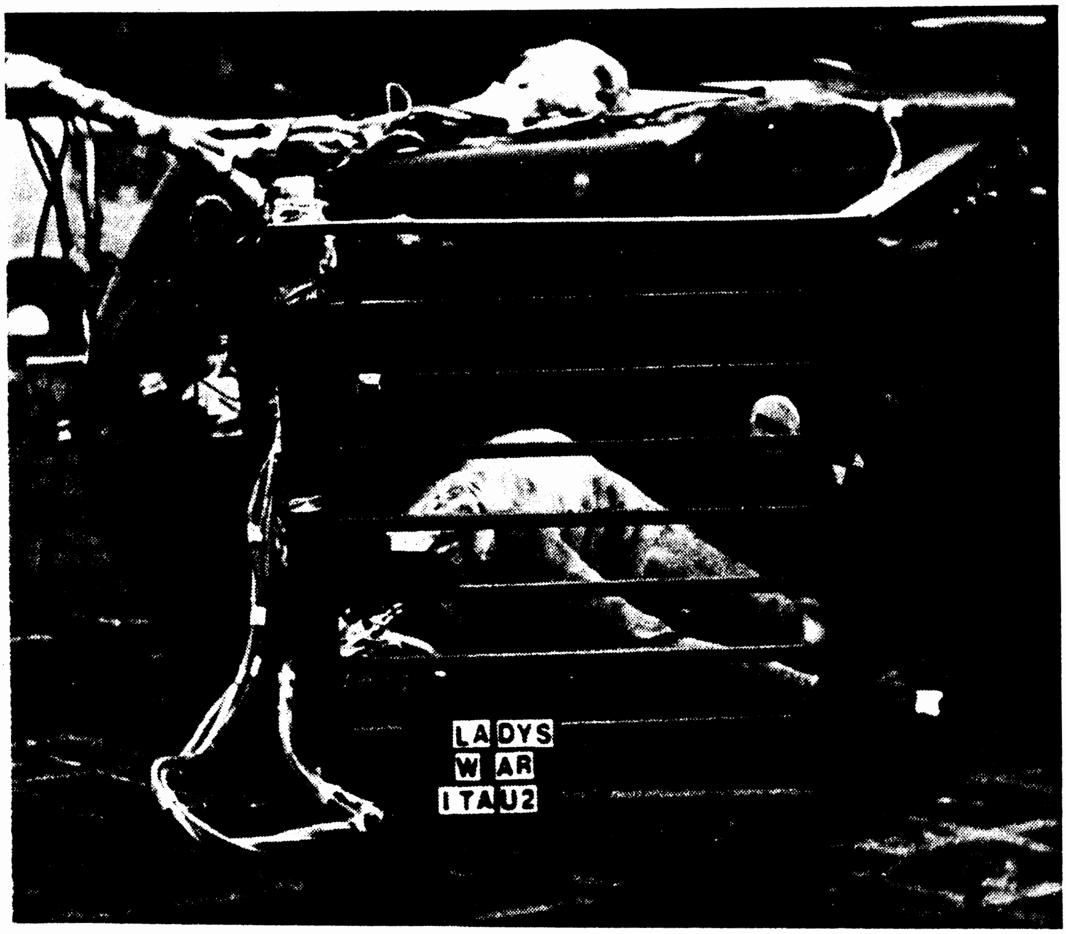

Figure 2-16: Final Dummy Position in Test U2

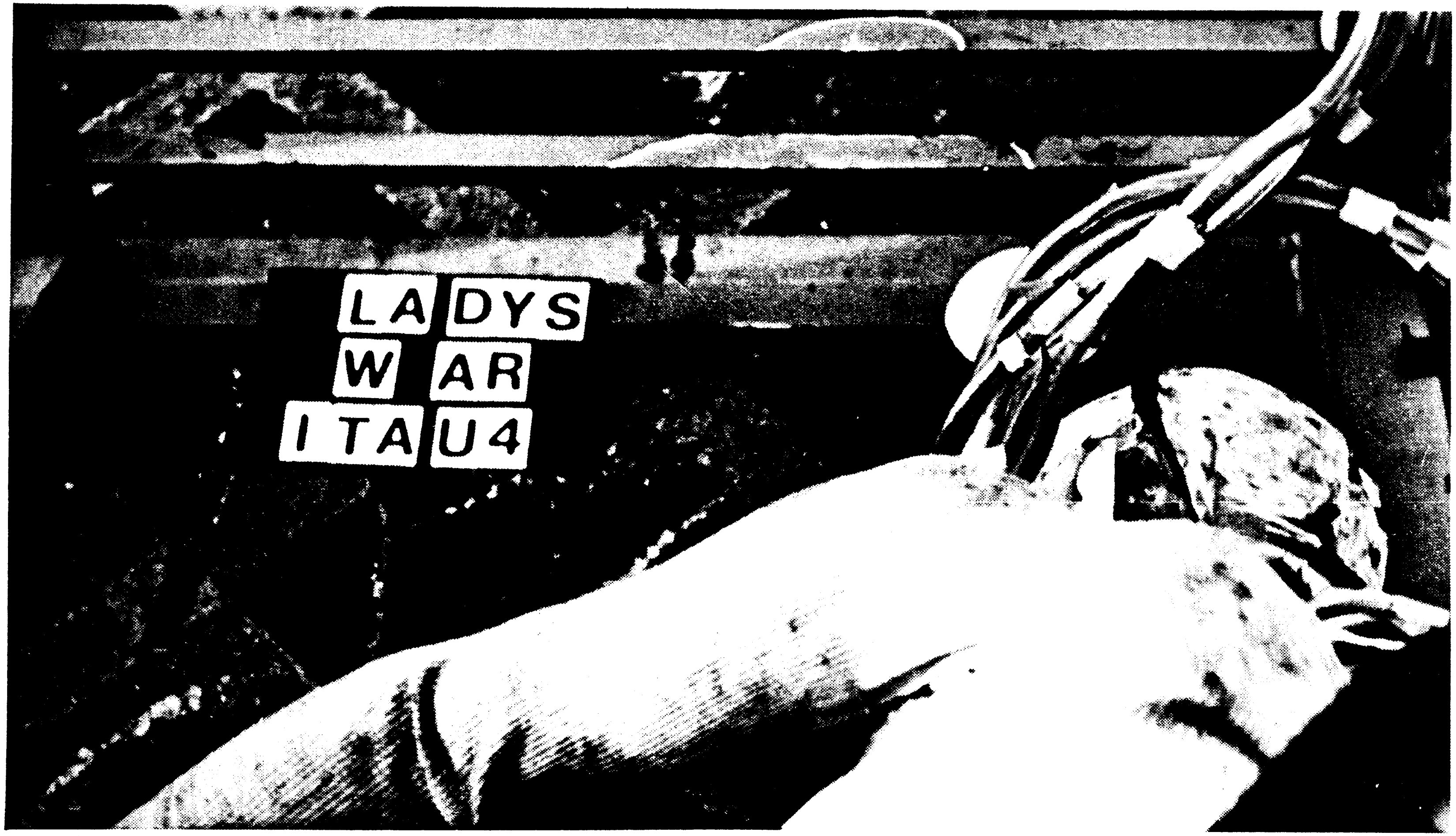

Figure 2-17: Final Dummy Position in Test U4

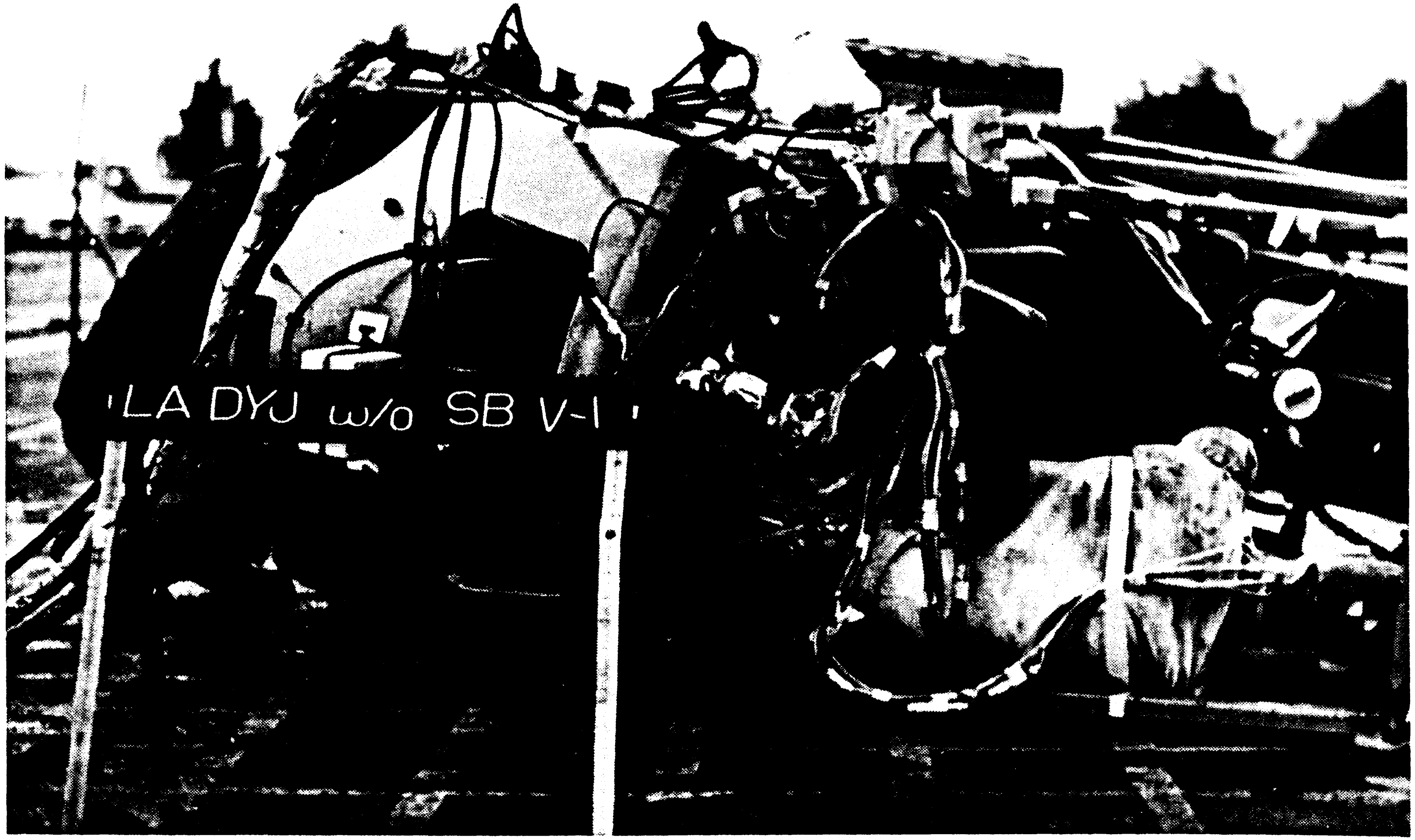

Figure 2-18: Final Dummy Position in Test V1

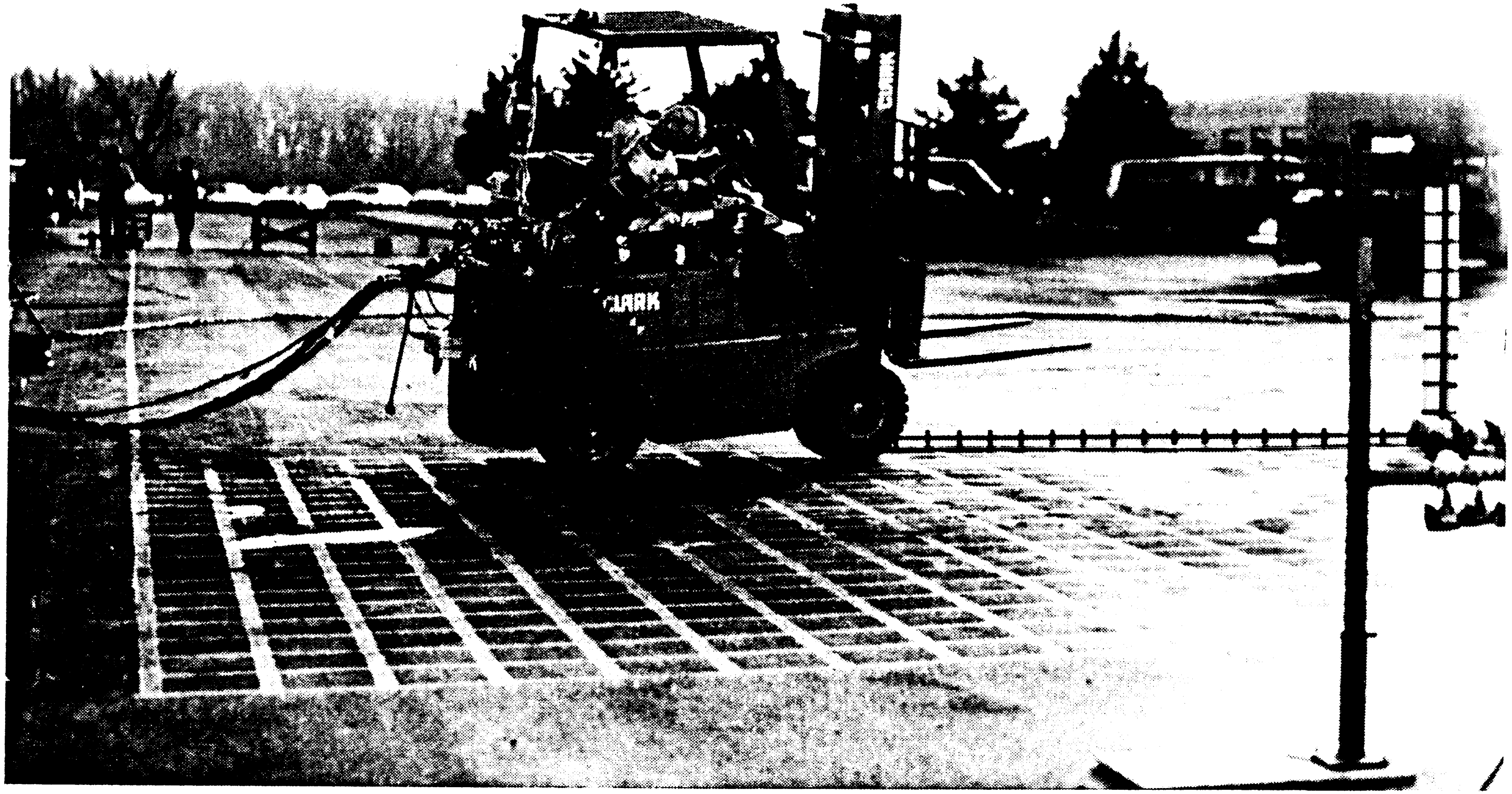

Figure 2-19: Impending Overturn in Unsuccessful Attempt Test U3

5858 and 2934; head accelerations of 691 and 624 g, chest accelerations of 44 and 56 g, and pelvic accelerations of 18 and 95 g.

2.6.7 Results of S8, S9, and S10. These were 15-foot J-turns with the dummy unrestrained. In test S8, the dummy was ejected from the side of the cage in a diving motion and impacted the ground head first. It then bounced off the ground with enough distance and just in time to be struck in the abdomen by the rear-right leg of the overhead guard. The final position is shown in Figures 2-23 and 2-24.

In test S9, the dummy's upward motion caused the dummy to strike its head on the overhead guard top, pushing it back into the seat and retaining it inside the cage during truck overturn. Its final position is shown in Figure 2-25.

In test S10, the dummy's motion before impact was similar to S8 and S9, except that its head missed the right edge of the cage top as it ejected from the side. But the timing of the truck overturn and dummy ejection were such that the head hit the ground at the same time and location as the overhead guard, causing the dummy's head to be trapped momentarily between the ground and the falling guard. The final position and location of impact to the head are shown in Figures 2-26 and 2-27.

Results for S8, S9, and S10 ranged from 2281 to 8595 for the HIC, and from 475 to 831 g for head, 48 to 57 g for chest, and 51 to 129 g for pelvic accelerations.

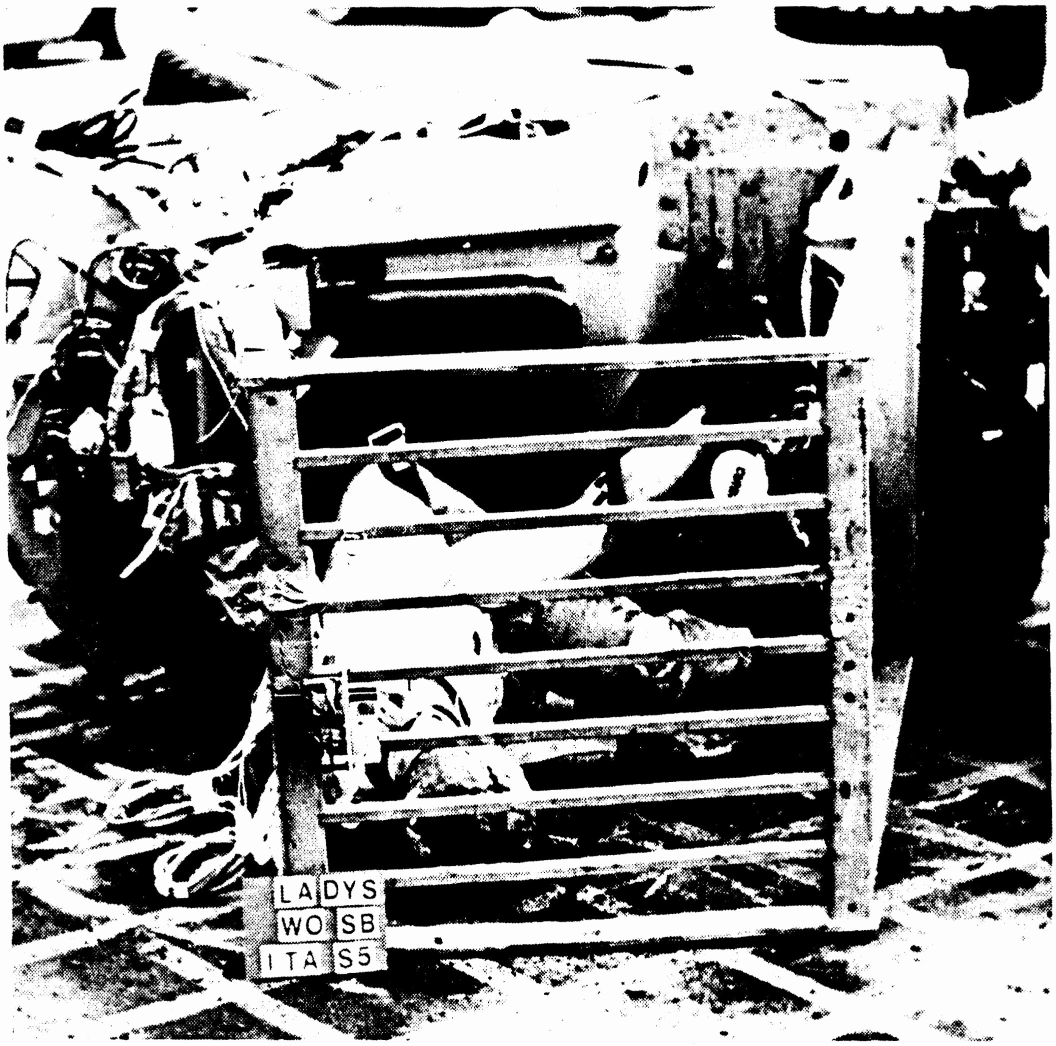

Figure 2-20: Final Dummy Position in Test S5

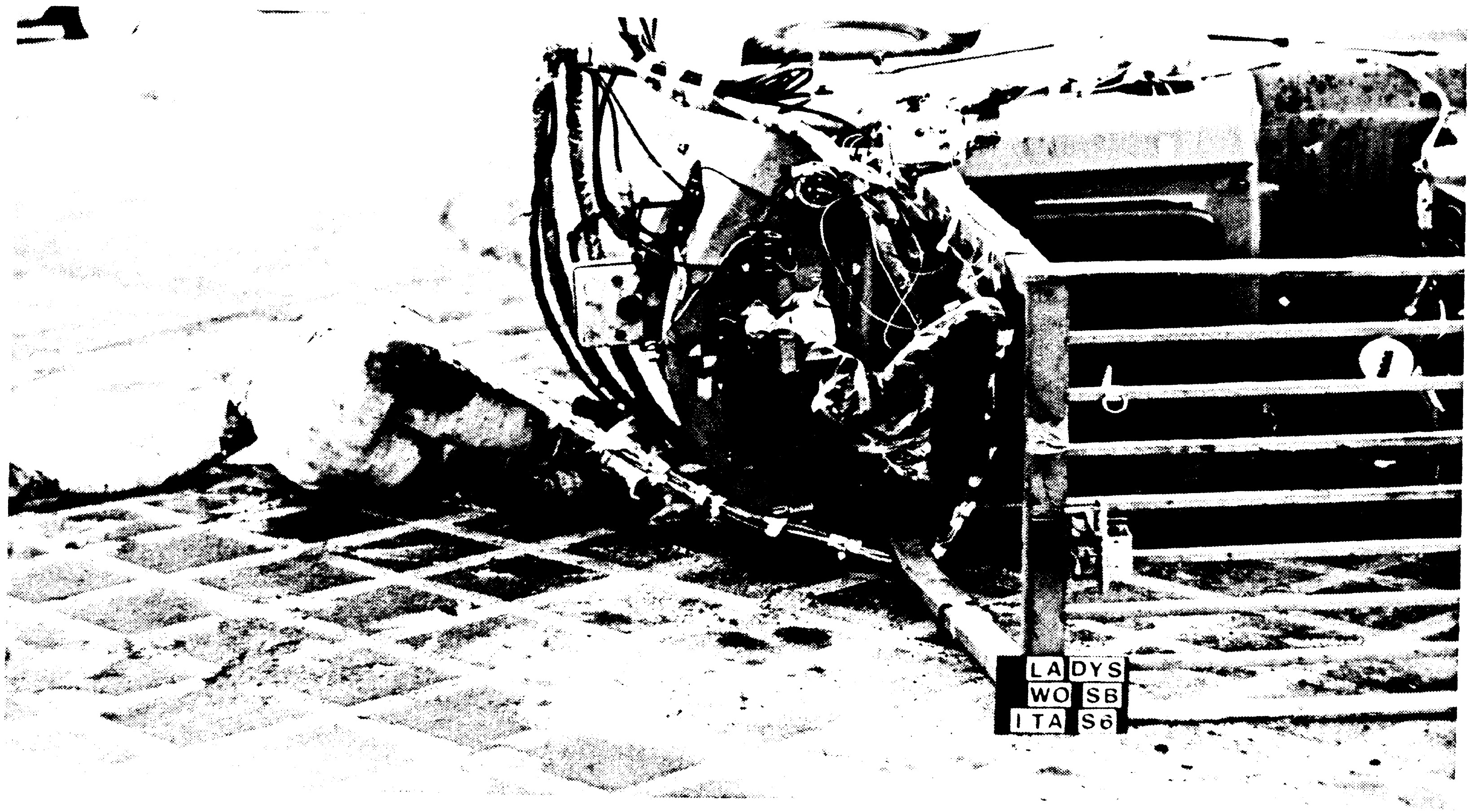

Figure 2-21: Final Dummy Position in Test S6

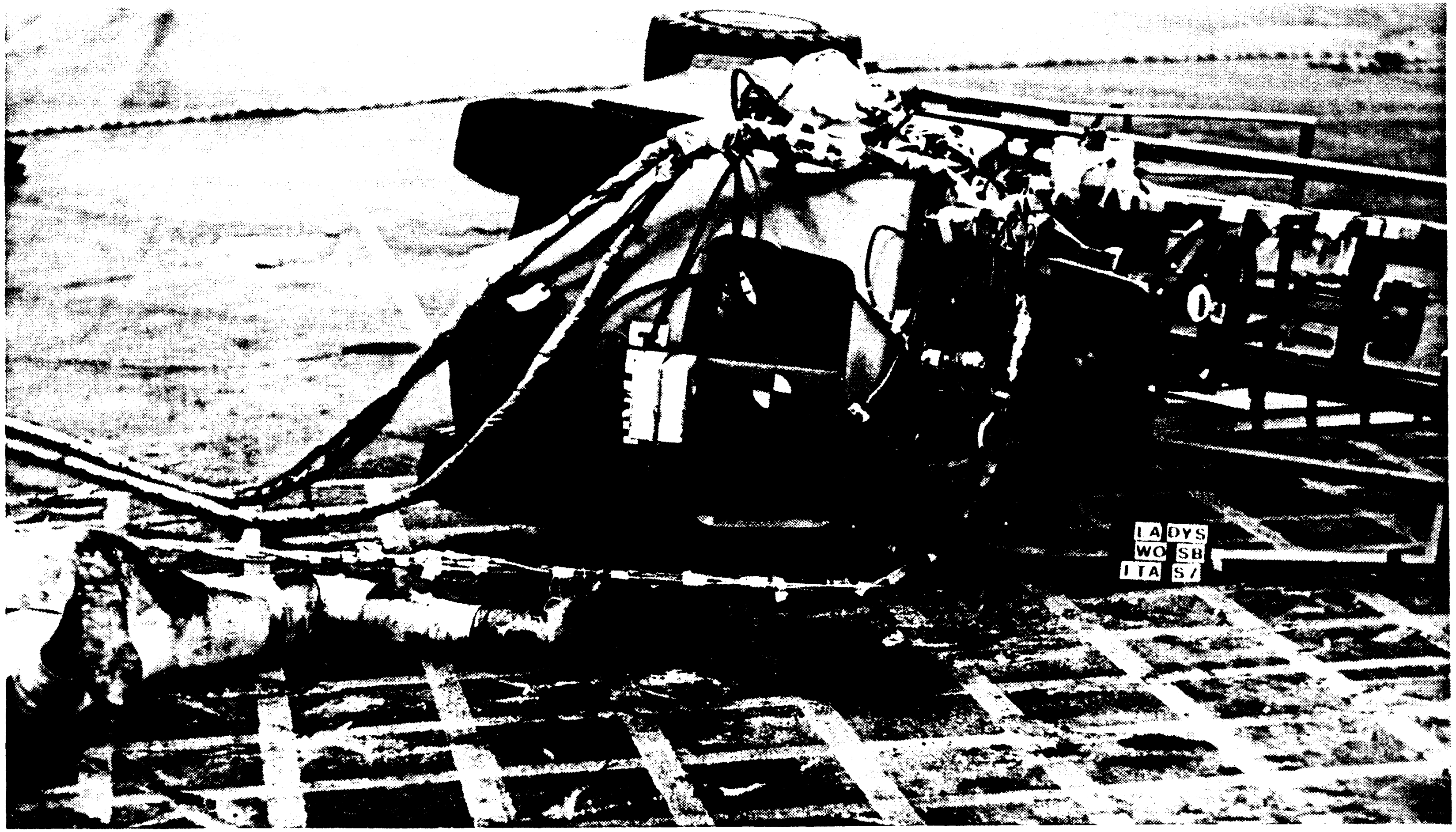

Figure 2-22: Final Dummy Position in Test S7

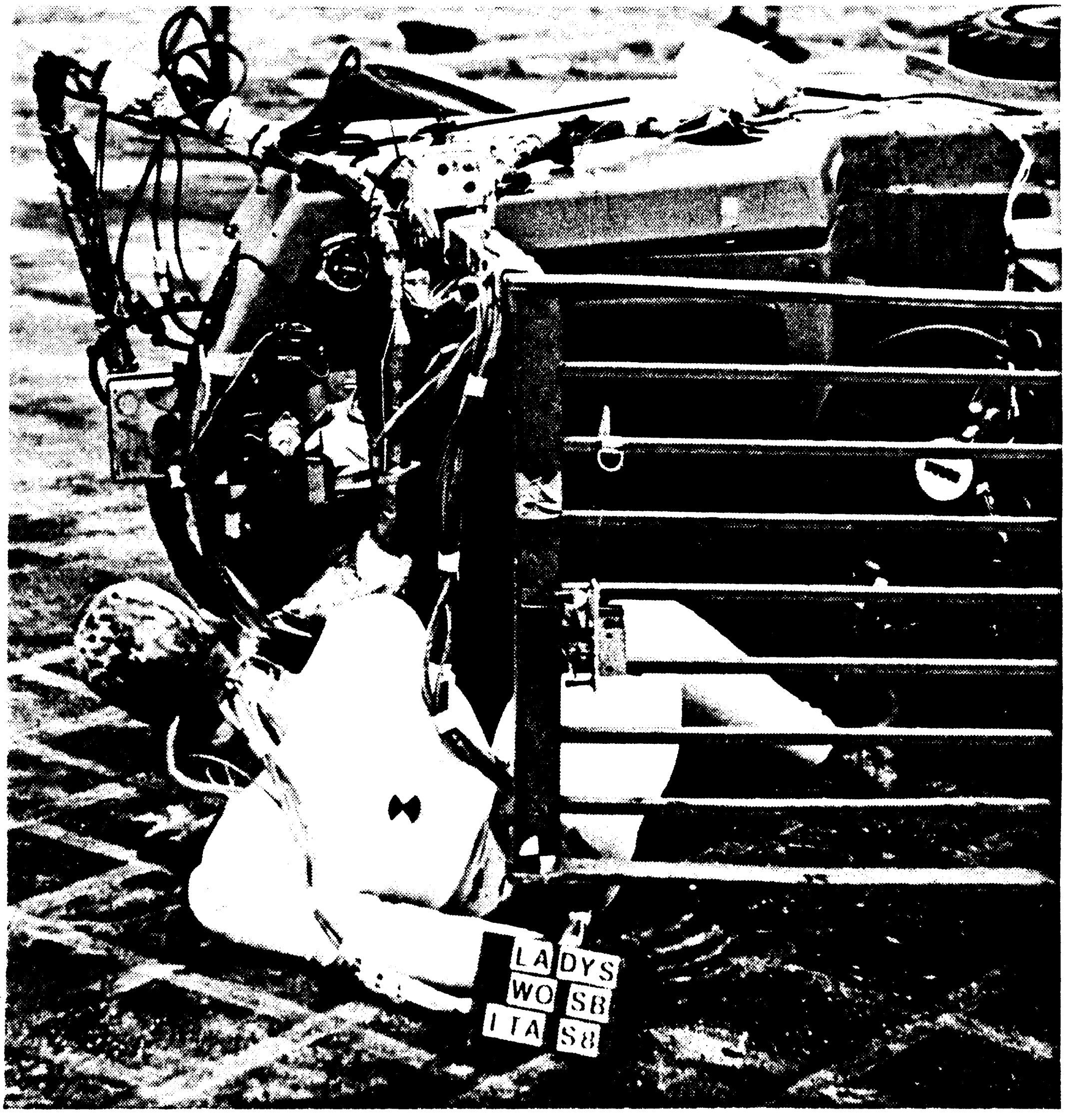

Figure 2-23: Final Dummy Position in Test S8

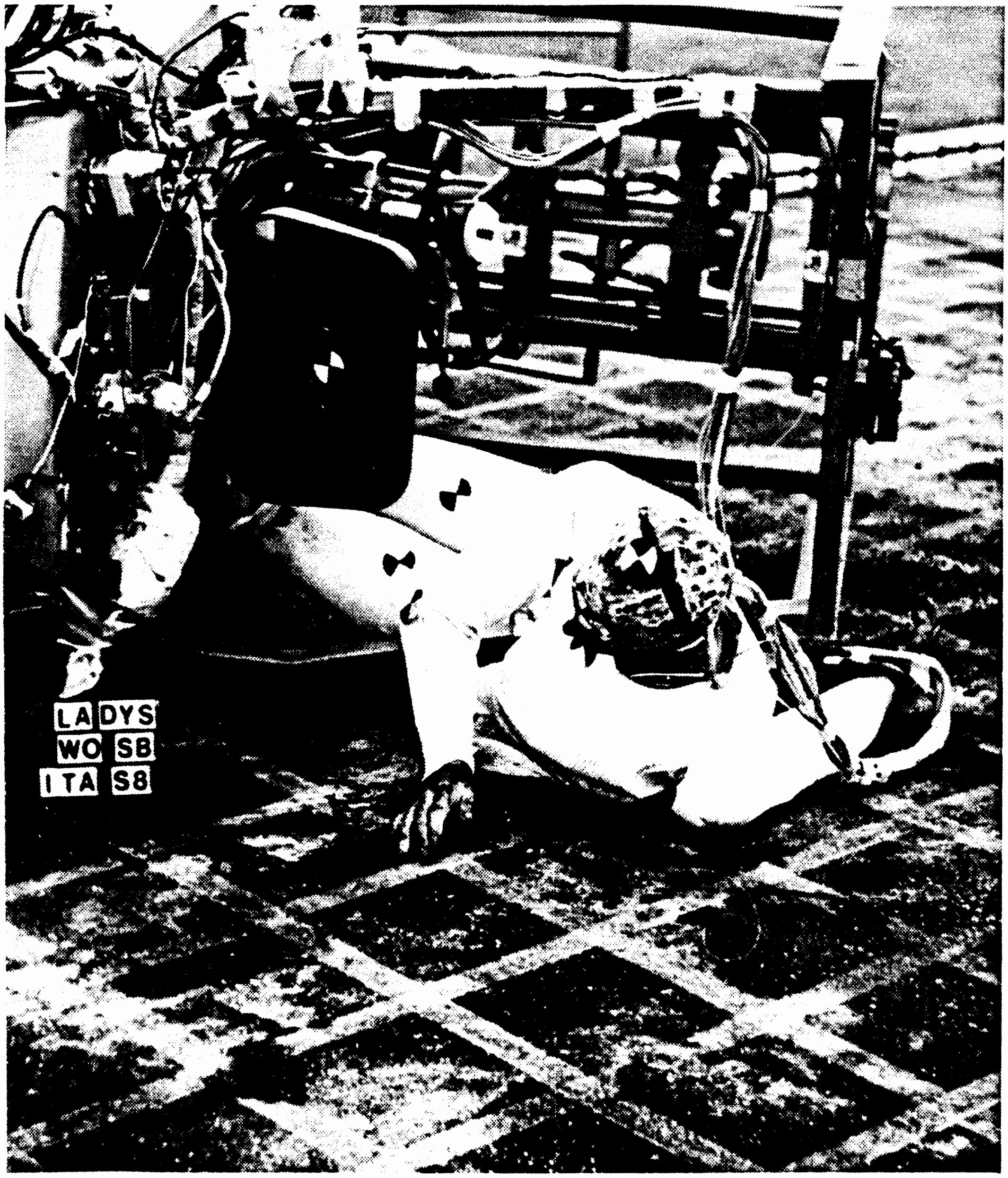

Figure 2-24: Close-Up of Final Dummy Position in Test S8

Figure 2-25: Final Dummy Position in Test S9

Figure 2-26: Final Dummy Position in Test S10

Figure 2-27: Close-Up of Final Dummy Position in Test S10

3.0 DISCUSSION OF DYNAMIC TESTS

The lateral dynamic overturn series of tests was intended to simulate a particular real-world rollover accident. The essential aspect of this event is that, during the rollover, the forklift operator is ejected from the vehicle in such a manner that he is struck and pinned down by the overhead guard when the vehicle lands on its side.

In real-world events of this nature, the operator may attempt to jump out of his seat during a sustained turn, or he may actually be thrown out by the inertial forces generated in the turn. In these experiments employing a 95th percentile anthropometric dummy, it was necessary to depend on inertial forces to eject the "operator." Simulation of operator action was limited to tying the hands to the steering wheel as described in section 2.5. Accordingly, the following discussion is valid only under the assumption that the operator is essentially a passive, inertial object. To the extent that the operator alters the ejection mechanism by active participation, the observations to follow may not apply.

3.1 The Dynamic Test Maneuvers

Initially, the test series was designed around two dynamic turning maneuvers with the assumption that at least one of the test types would result in the test dummy being struck by the overhead guard. The two test maneuvers were:

(1) Severe J-Turn. This maneuver begins with the vehicle initially traveling in a straight line at maximum speed (10-12 mph). As the vehicle passes through the start gate and hits the trip wire . The

left turn is initiated and continues at a high rate until the maximum possible left-steer angle is obtained.

(2) Severe S-Turn. This maneuver is much like the J-Turn, except that it is initiated with a short-lived right turn. That is, with the vehicle initially traveling in a straight line at maximum speed, the start gate trip wire is used to initiate a high rate of steering to the right. However, within 46 inches of vehicle travel (about 1/4 second at 10 mph), a second trip wire reverses the steering to a maximum left-turn rate that again proceeds to a maximum left-turn steer level.

After conducting several tests based on these two maneuver types, it became clear that neither was likely to ever produce the desired accident events. An explanation for this is given in the following section. A third maneuver was then introduced:

(3) Mild J-Turn. This maneuver is exactly like the Severe J-Turn except that the maximum steering level obtained by the steering control system was limited electronically and this limit was adjustable. Thus, the severity of the turn could be "programmed" by the experimenters, the intention being to obtain a severity of turn just sufficient or slightly greater than that necessary to cause vehicle rollover.

3.2 The Dynamics of Turning

As noted in the previous section, the mechanism by which the dummy would be ejected from the vehicle involved the dynamic forces that it would experience during the turning maneuvers. It is appropriate, therefore, to discuss briefly the dynamic forces involved in turning maneuvers in general.

When a body travels on a curved path, a centrifugal force tends to push that body outward, away from the center of the turn. Conversely, to remain on the curved path, that body must be subject to some externally applied centripetal force, which pushes inward on the body, thereby holding it on the curved path. The centrifugal force is a dynamic force that develops because of the existence of accelerations experienced by the body in question. As such, it always acts through the center of gravity (c.g.) of the body. The centripetal force is applied externally, and therefore may be applied to some other point or points on the body.

A vehicle in a turn experiences both centrifugal and centripetal forces. As always, the centrifugal force pushes outward, away from the center of the turn and acts through the c.g. In the case of a vehicle, the centripetal force is produced by the tires through their frictional coupling with the ground. Figure 3-1 depicts the general situation of a vehicle in a turn.

Figure 3-1 also explains why a vehicle in a turn is subject to rollover. The centrifugal force acts relatively high on the vehicle and pushes outward, while the centripetal force is acting at a very low position and pushing inward. These two forces tend to rotate the vehicle in a roll such that, if they are large enough, they will roll the vehicle over toward the outside of the curve. As either the curve gets tighter or the vehicle speed increases, these forces become larger.

Finally, we need to remember that the vehicle operator is also a body following a curved path. He too experiences centrifugal and centripetal forces. Again, centrifugal force is pushing him toward the outside of the turn and is acting through his c.g. The centripetal

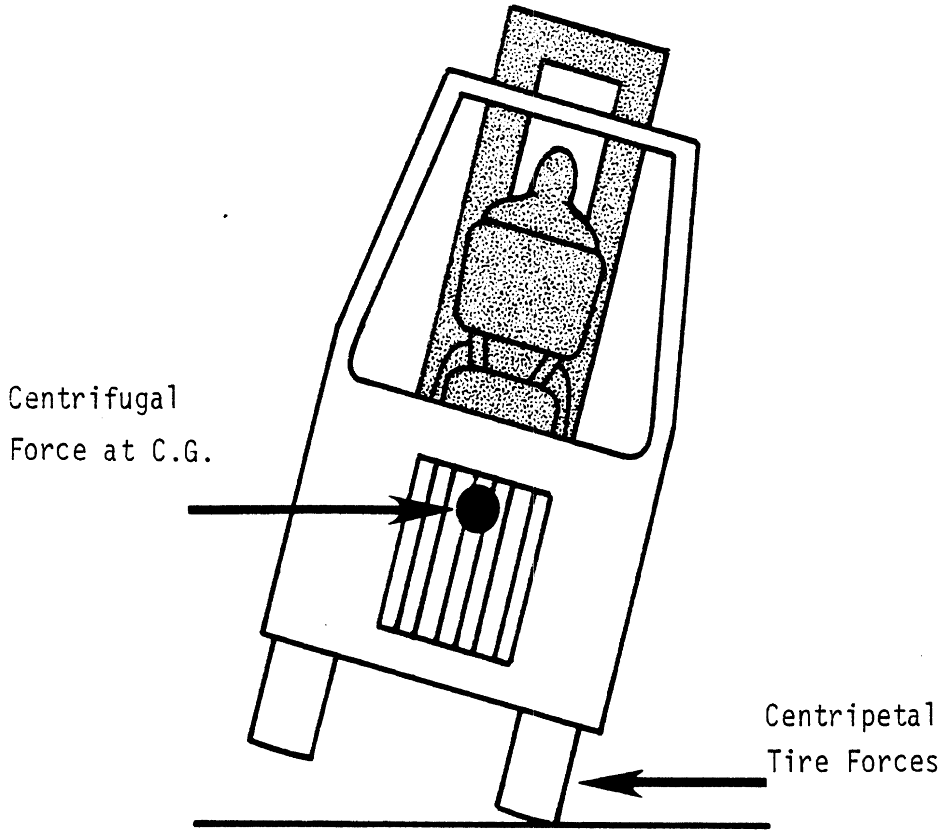

Figure 3-1: Forces Acting on a Vehicle in a Turn

force, which pushes inward and holds him in his curved path and therefore in place in the vehicle, is composed of frictional forces between him and the seat plus any actively applied restraints, such as his grip on the steering wheel. Figure 3-2 illustrates this situation.

3.3 Dynamics of the Severe Maneuvers

Although two severe maneuvers were defined, they will be discussed here as a single entity, because the S-Turn is basically a J-Turn with a largely superficial initial disturbance. It is true that the initial right turn is substantial and is certainly visually impressive. In dynamic terms, however, the test vehicle is a relatively fast-reacting vehicle, such that the effect of this initial disturbance is rather short-lived. This is to say, by the time the left turn is well under way and the actual rollover event is taking place, the effects of the initial (right-hand turn) disturbance have died out and consequently do not appear to substantially influence events during the critical portions of the experiment. Accordingly, the following discussion generally refers to the Severe J-Turn maneuver, this being sufficient to bring out all the salient points.

As indicated above, after the first nine test runs employing the severe test maneuvers, its was clear that these maneuvers were not likely to ever reproduce the desired accident events. The steering input was so extreme that the centrifugal force was not properly directed to eject the passenger from the side of the vehicle; rather, it tended to direct him out the rear opening of the roll cage structure, an ejection mode believed to be unrepresentative of real world incidents.

Figure 3-3 and 3-4 are simplified approximations of the real situation but serve the purpose of this explanation well. As shown in

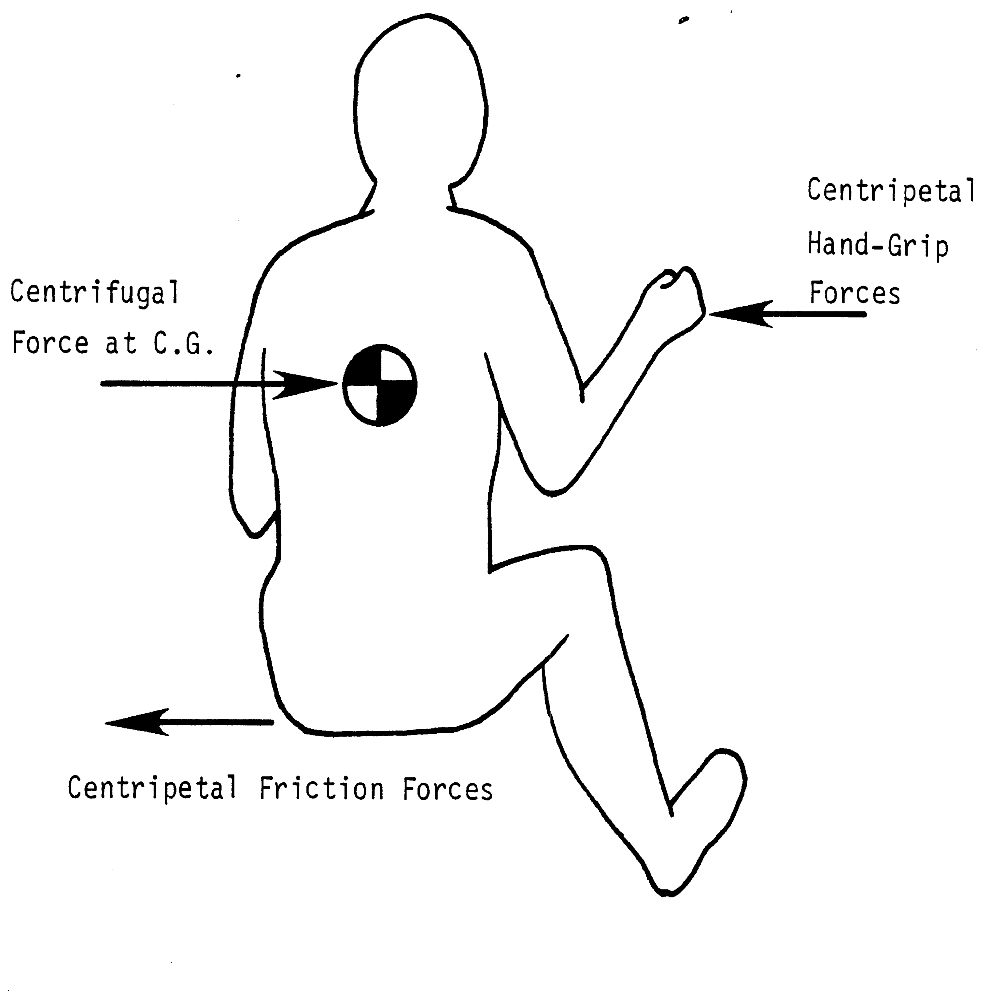

Figure 3-2: Frictional Forces on the Vehicle Operator

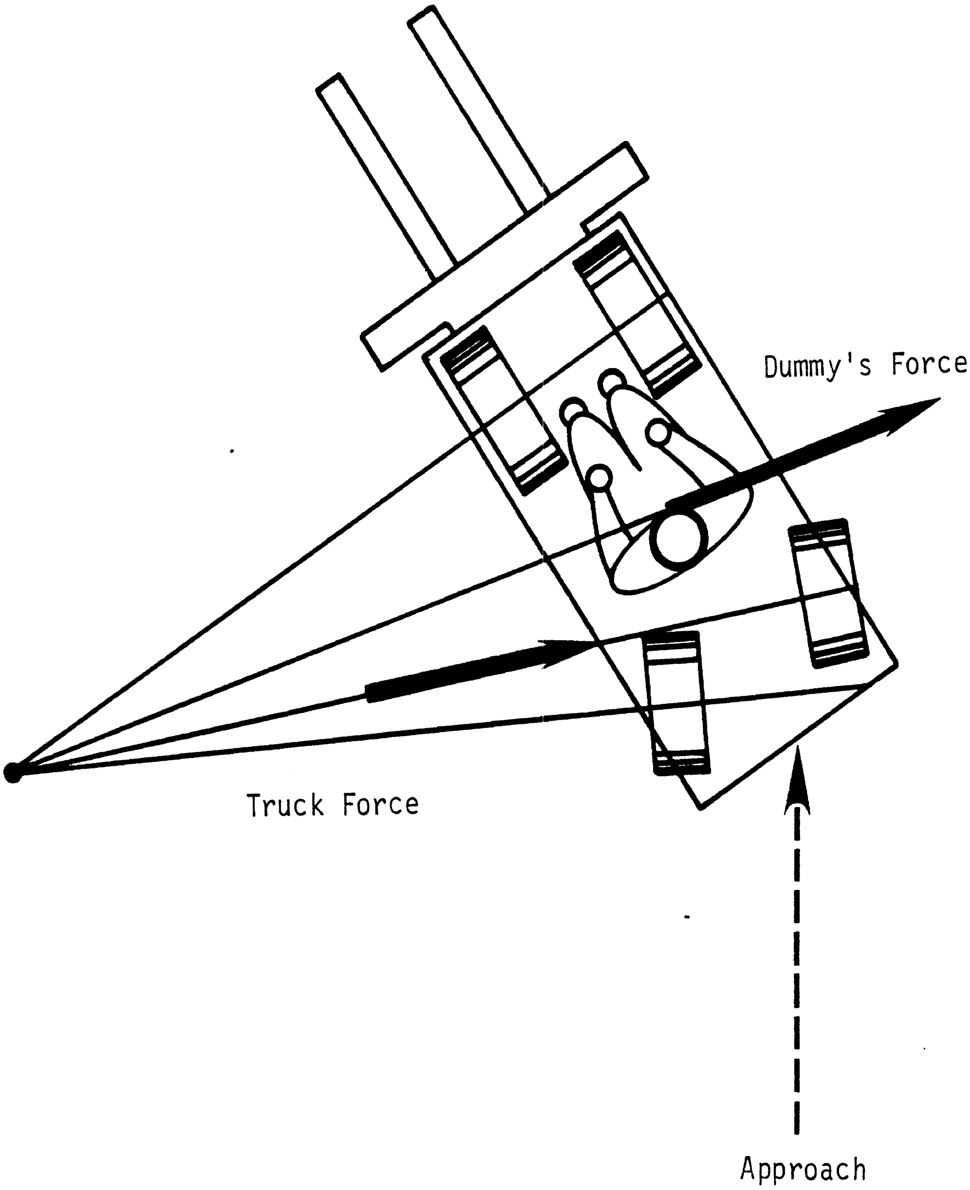

Figure 3-3: Centrifugal Forces in Mild J-Turns

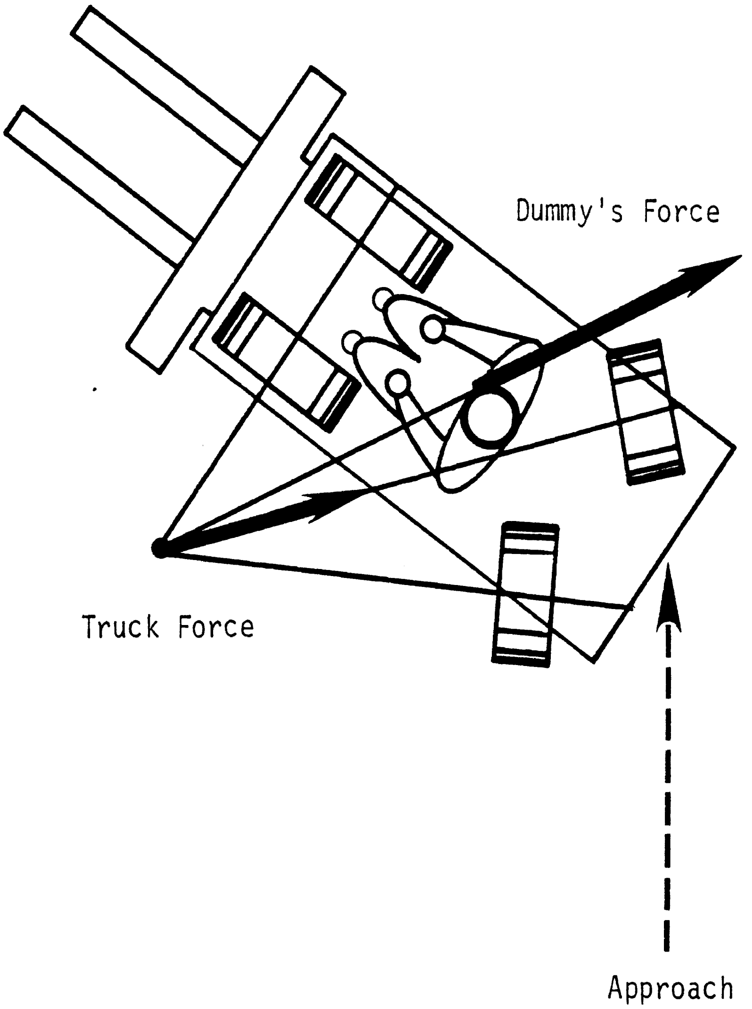

Figure 3-4: Centrifugal Forces in Severe J-Turns

the figures, the center of turn of a vehicle is located at the intersection of lines drawn at right angles to each of the vehicle's wheels. The centrifugal force acting on the vehicle and the operator pushes him away exactly from the center of the turn. Figure 3-3 illustrates the case for a relatively mild turn. The vehicle's wheels are not steered excessively, so the turn center is to one side of the vehicle and the centrifugal force pushes the operator virtually straight out the other side. On the other hand, Figure 3-4 illustrates the case for the Severe J-Turn maneuver. Here, the wheels of the vehicle are turned to a very extreme angle, a capability of forklifts that allows a high level of low-speed maneuverability. As a result, the turn center is not along side the operator, but more in front of him. Thus, centrifugal force pushes him in a more rearward direction. This situation was confirmed by the experiments in which the anthropometric dummy was often ejected through the rear opening of the overhead guard structure while bending the seat backrest backwards.

3.4 Dynamics of Mild J-Turns

The experience with the severe maneuvers clearly pointed the way toward using milder maneuvers to produce the desired results. Mild, as used here, however, still implies a maneuver that is sufficiently severe to produce rollover. With practice, a steering level just sufficient to produce rollover was determined, and a limited number of experiments using the Mild J-Turn maneuver were begun.

Early runs of this series of tests also failed to produce the desired results. As mentioned in section 2.4, the hands of the dummy were bound to the steering wheel in order to simulate an operator's grip on the wheel. Initially, this bond was so strong as to prevent any ejection under the reduced level of centrifugal force now experienced by the dummy.

Next, the strength of the bonds was reduced, and the experiments were continued. As the turn was initiated, the dummy's centrifugal force was sufficient to overcome the strength of the bonds as well as his frictional coupling to the seat, and he was ejected. However, the severity of the turn was so marginal (with respect to producing rollover) that the rollover event proceeded too slowly. That is to say, relatively early in the turn, the dummy was ejected out the side of the vehicle, landing on the ground, but the vehicle proceeded farther through the turn, leaving the dummy behind, before rolling over.

In the remaining runs, the level of steering was increased somewhat over the minimum necessary for rollover. The final series of experiments were sufficiently variable that three qualitatively different results were obtained:

(1) The rollover event was slightly too slow, producing results much like those described above.

(2) The rollover event was slightly too fast, and the vehicle rolled over before the dummy was ejected. In these cases, the dummy tended to strike its head on the inside-top of the overhead guard when the rollover was nearly complete.

(3) The rollover and ejection events were properly timed so that the dummy was, indeed, caught between the overhead guard and the ground as the vehicle rolled over. In one case, the guard struck the dummy across the mid-section of the trunk. In the other, the guard struck the dummy's head bending the left-most overhead rail of the guard at the strike point.

3.5 General Observations

In sections 3.3 and 3.4, the mild and severe turning maneuvers were addressed separately. However, our experience with the two types of experiments provides a basis for commenting on forklift rollover in general and the likelihood of a rollover resulting in the operator being caught by the guard, as well as on the particular experimental techniques. Our experience strongly indicates that, given the hypothesized passive operator, the likelihood of a rollover event resulting in the particular accident situation of interest is rather si'all. It appears that the event must be rather precisely timed for the operator to be caught between the overhead guard and the ground. If the vehicle rolls over too slowly, the operator can be thrown clear of the vehicle; if it rolls too quickly, the operator may not be ejected at all. Among the broad range of rollover accidents that occur in the real world, probably only a small percentage meet the required timing criteria. Furthermore, the timing of ejection and overhead guard interaction with the dummy would be somewhat different depending on the structural geometry of the guard itself and the mounting position of the seat inside this structure.

The same necessity for relatively precise timing of the rollover makes this accident event somewhat difficult to study experimentally. In the final series of dynamic tests, six runs were conducted in which the steering system controller settings were all the same. Yet of these six tests, two resulted in the dummy being thrown clear; in two others the dummy was not ejected; and in the remaining two the dummy was struck by the guard, once in the head and once in the midsection. This variability results from the peculiar sensitivity to timing and to the inability of the specific steering controller used to provide sufficiently repeatable inputs.

Although some progress was made in understanding the parameters leading to a realistic simulation of field-observed overturn incidents, the variability of the results of the last several tests suggest that additional testing is required to ensure repeatability of the test conditions and results.

3.6 Discussion of Operator Kinematic Response

As noted in the previous sections, there are many factors present in the tests that have an influence on the outcome of the experiment. The timing of the events leading up to dummy motions relative to the truck, the presence (or absence) of arm rests or seatbelts, the geometry of the overhead guard, and the truck motions themselves all combine to influence the sequence of events in any one test. As a result, the occurrence of dummy ejection, the direction of ejection, the attitude of the dummy as it strikes the ground, and the interaction of the dummy with the overhead guard can vary from test to test. It is, therefore, very difficult to obtain repeatable results from the limited number of tests conducted in this study. Although some conclusions may be drawn from these test results, the conclusions must necessarily be test-specific, while general conclusions are usually based on the results of a set of repeatable tests.

Additionally, the construction of the dummy can exert a strong influence on the nature of the dummy/ground interaction. For example, the stiff shoulder structure, used in all automotive test dummies, is not well suited to lateral impact. In some of the dynamic tests, the head of the dummy did not contact the ground even though there was strong shoulder contact (tests Q1 and S3). A human operator would most likely have incurred a head impact under the same conditions due to the lateral flexibility of the human shoulder structure.

These problems are not the result of poor experimental technique, but rather they are due to the general complexity of the truck-overturn/operator-ejection process and the limited state-of-the art in dummy design.

Finally, it should be pointed out that the dummy's response is quantified and reported here as peaks of accelerations at the centers of the head, chest, and pelvis, with the Head Injury Criterion (HIC) as an additional head response indicator. These are all kinematic responses that are meaningfull as injury severity measures only when correlated with clinical observations of injuries. These numbers should, therefore, be interpreted in light of known human tolerance data and the type of impact producing these number. Thus, for example, the HIC may be a valid measure for assessing head injury in blunt head impacts. However, an acceptable HIC level for impacts along one direction, say the anterior-posterior axis of the head, may not be an acceptable level for impacts along other directions, or for other than head impacts. A single indicator of injury level should, therefore, be used only for comparing results of similar tests rather than as an absolute measure of injury severity. In all cases, a well-established human tolerance level, using the same criterion, should be the basis for projecting conclusions from tests conducted with an anthropomorphic dummy to human subjects.

In the following discussion, the test results are grouped into broad categories and descriptions of each test are necessarily brief.

To fully appreciate the complexities of these tests and the variations among them, it is necessary to also view the high-speed movies.

3.6.1 <u>Operator Restrained by Seatbelts</u>. These were tests Q1, Q2 and Q3. The seatbelt installation on the test vehicle used belt anchor points that were widely spaced and not close to the sides of the vehicle seat. This was because there were no suitable anchor point structures near the seat edges. The resulting belt configuration tended to restrict lateral motion of the dummy's pelvis less than closer-spaced anchor points would have done. During the overturning of the truck, the dummy moved laterally with the truck until the side of the truck struck the ground. Following truck side impact, however, the dummy continued to translate laterally rather than pivoting around the lap belt, as would have occurred with a more laterally restrictive belt.

The contact of the dummy with the ground produced three different head impact situations that were the result of dummy characteristics, vehicle dynamics, and coupling of the dummy to the vehicle through the seatbelt. In test Q1, the head did not hit the ground due to the combination of dummy orientation at impact and shoulder stiffness. In test Q2, the dummy appeared to be more tightly coupled with the vehicle, and the head impacted the ground with a peak acceleration of 245 g. In the third test, Q3, the dummy orientation at impact produced a more severe head impact (417 g) with the ground. The peak chest and pelvic accelerations were similar in all three tests. It is very likely that a more realistic (less stiff) dummy shoulder structure would have resulted in head/ground impact in test Q1, just as it would have in tests Q2 and Q3.

3.6.2 Operator Remained with Truck. These were tests V3, V4, U2, U4, and V1. All of the these produced characteristically lower head accelerations (112 - 275 g) than any other tests in which head/ground contact occurred. At the same time, the chest accelerations were slightly higher (32 - 56 g), and the pelvic accelerations were much higher (41 - 106) than those of the belted dummy.

In two of the cases (V3 and V4), the dummy remained with the truck because of head contact with the overhead guard early in the rollover. This was probably due to the forward leaning attitude of the dummy and/or to its altered initial position caused by the S-turn maneuver used in these tests. The other three tests (U2, U4 and V1) used a large turning radius with the result that the dummy moved with the truck until it struck the ground.

As in the seatbelted dummy tests, the influence of the dummy shoulder in modifying the head impact dynamics cannot be overlooked. A more realistic shoulder could very well have changed the severity of the head impacts in these tests also.

3.6.3 Operator Ejected from Rear. These were tests R1, R2, R3, S1, S2, S3, and U1, in which the final position of the dummy showed ejection from the rear opening of the overhead structure. All of these tests involved an upright dummy and a 6-foot radius turn. The tests were characterized by high head accelerations (298 - 925 g), except in S3 when no head/ground contact occurred, as well as high chest accelerations (35 - 83 g) and high pelvic accelerations (96 - 202 g). As noted in Section 3.3, the severe nature of the 6-foot radius turn produced a dynamic situation that forced the passive dummy to move rearward during the turn, resulting in the dummy being partially ejected from the vehicle through the rear of the overhead guard structure. As the vehicle overturned, the dummy also moved sideways, resulting in the dummy contacting the ground rearward of the guard. Again, the influence of the dummy shoulder was evident in affecting the head impacts.

Because this ejection mode is not obvserved in most real world incidents, the severe J-turn was deemed to be unrealistic as a simulation of real world events. Consequently, the data produced in the severe J-turn tests with or without the seatbelts should not be used as the basis for making conclusions as to the effectiveness of seatbelts in realistic accident situations.

3.6.4 Operator Ejected from Side. These were tests S5, S6, S7, S8, S9, and S10, in which the dummy was ejected from the side opening of the overhead structure. These tests, which made up the final series, were all 15-foot radius turns. The wider turn in this maneuver allowed the dummy sufficient time to reach a higher velocity relative to the vehicle and thus impact the ground in an attitude that resulted in severe head/ground interaction. This situation produced high head accelerations, indicating greater head impact velocities than those associated with ejections through the rear of the guard. In test S9, the dummy was retained from initial ejection by contact with the overhead guard, but the nature of the final dummy/ground interaction was still one of ejection rather than staying with the vehicle. The chest accelerations were more consistent (44 - 57 g) here than were those of the rear ejections, but the average values were similar between the two types of ejection. The pelvic accelerations were somewhat lower (18 - 129 g) in these side ejections than in the rear ejection cases.

In addition to severe ground contacts in these tests, two cases (S8 and S10) of overhead guard interaction with the dummy were produced. In test S8, the guard contacted the abdomen of the dummy after the dummy had ejected. In test S10, the guard struck the dummy head shortly after the head had hit the ground. The loading produced on the dummy by the guard did not involve as high acceleration values as the ground contacts produced. The nature of loading, however, was more that of crushing than impact.

Because of time and budget constraints, testing was halted after test S10. Thus, no further tests were conducted to investigate the effectiveness of seatbelts or any other restraining or protective devices under conditions similar to those of the last six tests. Given additional time and money, effort should first be focused on refining the tests procedures to produce repeatable test results, before testing the effectivenes of restraint systems and/or protective devices.

3.7 Comparison of Results from Phases I and II

The tests conducted in this Phase II program have been discussed in the previous sections. Of the four categories of tests, there were three that can be compared to the results of the Phase I program. They are (1) seatbelted operator (dummy) tests, (2) tests in which the unrestrained operator (dummy) remained with the truck, and (3) the tests in which the operator (dummy) was ejected through the rear of the overhead guard structure. The fourth test category in which the operator (dummy) was ejected through the side of the overhead guard structure, was unique to the Phase II program. Phase I also had a noncomparable category in which the dummy was retained by a chest strap.

The data are summarized for both Phase II and Phase I in Table 3-1. For the seatbelted dummies, the head accelerations were more consistent in Phase I, while the chest accelerations were more consistent in Phase II. Both phases had consistent pelvic acceleration values, while the Phase II results tended to be higher, probably due to the wider belt anchor spacing in those tests.

For the category of tests in which the unrestrained operator remained with the truck, both phases exhibited similar peak values in head, chest, and pelvic accelerations, but the HIC values in Phase I were higher. This indicates a longer time duration of the head accelerations in those tests. Tests in the third category, involving rear ejection, were generally comparable in peak accelerations and in HIC, with the exception of head accelerations in tests S3 and U1.

TABLE 3-1: COMPARISON OF PHASES I AND II TEST RESULTS

Results of Phase II					Results of Phase I				
Test Code	HIC	Peak Acc G's			Test Code	HIC	Peak Acc G's		
		HED	CST	PLV			HED	CST	PLV
OPERATOR RESTRAINED BY SEATBELTS									
Q1	132	73	28	28	F2	525	210	246	25
Q2	606	245	29	30	F5	780	230	18	19
Q3	1636	417	33	21	F9	870	252	29	19
UNRESTRAINED OPERATOR REMAINED WITH TRUCK									
V3	376	116	32	49					
V4	272	112	46	71	E4	872	188	35	44
V2	414	275	33	54	E5	997	233	25	61
U3	686	198	56	41					
V1	277	146	39	106					
UNRESTRAINED OPERATOR EJECTED FROM REAR									
R1	1166	363	50	181					
R2	1766	439	62	96					
R3	709	298	35	165	E6	1438	319	60	219
S1	790	371	83	202	E8	1786	342	49	450
S2	1646	415	39	99	E10	1813	330	51	154
S3	71	96	54	189					
U1	4299	925	52	99					

4.0 STATIC DOCK-RELATED TEST SERIES

In this series of tests, another forklift truck was made to overturn from a simulated 4-foot high dock onto the pavement of the test site. Additional tests were conducted in some cases because of loss of camera coverage or loss of instrumentation of the dummy's head. Other intended tests were completely eliminated because of severe damage to the mast and, toward the end of the series, because of extensive damage to the overhead guard and the counterweight. Of the tests conducted, 12 were considered "successful" and are therefore reported here.

4.1 Test Site

The static tests were conducted in the same HSRI parking lot where the dynamic ones were conducted, but in a different area. The existing dock, which is essentially 15 feet wide with about a 30-foot long ramp, had to be modified to raise it to the requested 52-inch height. The edge of the ramp was protected with steel angles to minimize the friction of the lift truck counterweight during some overturn modes. The apron in front of the dock was paved, and a 10x10-foot gridwork was painted on the pavement in 1x1-foot squares.

Two high-speed movie cameras were also used in this series, along with the hand-held zoom movie camera. Because of the layout of the dock and test site with respect to the sun, no additional lighting was necessary here. The locations of the cameras were changed for every category of tests to provide the best coverage. Thus, for the rear drop-off series , one overhead camera was used with a wide-angle lens at a distance of approximately 16 feet, directly looking down on the truck, as shown in Figure 4-1. For the lateral series, one camera was placed directly in front of the test pad. The other camera in both series was located to the side and aimed parallel to the dock's edge.

4.2 Equipment, Instrumentation, and Processing

A lift truck with a non-functional engine was used. For one test mode, the truck hydraulic lines that control the mast vertical and tilt motion were modified to be actuated externally by the hydraulic system on an HSRI crane. The steer wheel mechanism was also modified to be locked into one extreme position for another test mode. Finally, the brakes on the stationary front wheels were repaired to be used in a third mode of testing.

The test subject was the same anthropomorphic dummy used in the dynamic test series and described in section 2.2.

The instrumentation packages used for the dynamic series of tests were also used for the these dock-related static tests, except for the six force and moment transducers on the steering column. These were described earlier in section 2.3.

Finally, the same data handling procedures and software were used in this static test series as those used in the dynamic one. These were described earlier in section 2.4. The only differences were that no steering column signals were processed, and that the synchronization signal could not be reliably included in the processing.

4.3 Description of Static Tests

There were three modes of overturns in the dock-related static tests. The first was the rear drop-off overturn in which the lift truck rear (steer) wheels were on the dock, while the front wheels were locked

Figure 4-1: Initial Forklift Position for Rear Drop-Off Test

on a movable trailer parked against the edge of the dock. (See Figure 4-1.) As the trailer pulled away from the dock with the front wheels locked on the trailer surface, the lift truck was dragged over the dock's edge and was made to overturn backwards on the pavement below.

The second mode was a longitudinal forward overturn test in which the lift truck was parked on the dock with the front wheels right at the edge. The forks were loaded with a 3000-pound steel block (maximum rated capacity) and then lifted to the maximum height. The mast was remotely tilted forward until there was enough imbalance to cause the truck to overturn longitudinally forward onto the pavement, 4 feet below. Only one test was conducted in this mode, since the mast was damaged and could not be operated without extensive repairs.

The third mode was the lateral overturn tests, in which the unloaded lift truck was parked alongside the edge of the dock with the steer wheels turned maximally for a left turn, causing it to fall off the edge and overturn on its right side. This was first done with all four wheels on the dock and with a push from the crane along the direction of the steer wheels. However, after the right rear wheel dropped off the edge, the forklift sat on its undercarriage and did not overturn. Instead the truck slid along the edge of the dock. Figure 4-2 illustrates this position. Subsequent tests were conducted using that initial position, i.e., with the right rear wheel off the edge while all other tires remained on the dock. The truck was made to overturn with the aid of another operating lift truck that lifted the left side of the test truck, as shown in Figure 4-3, causing it to overturn on the pavement, 4 feet below.

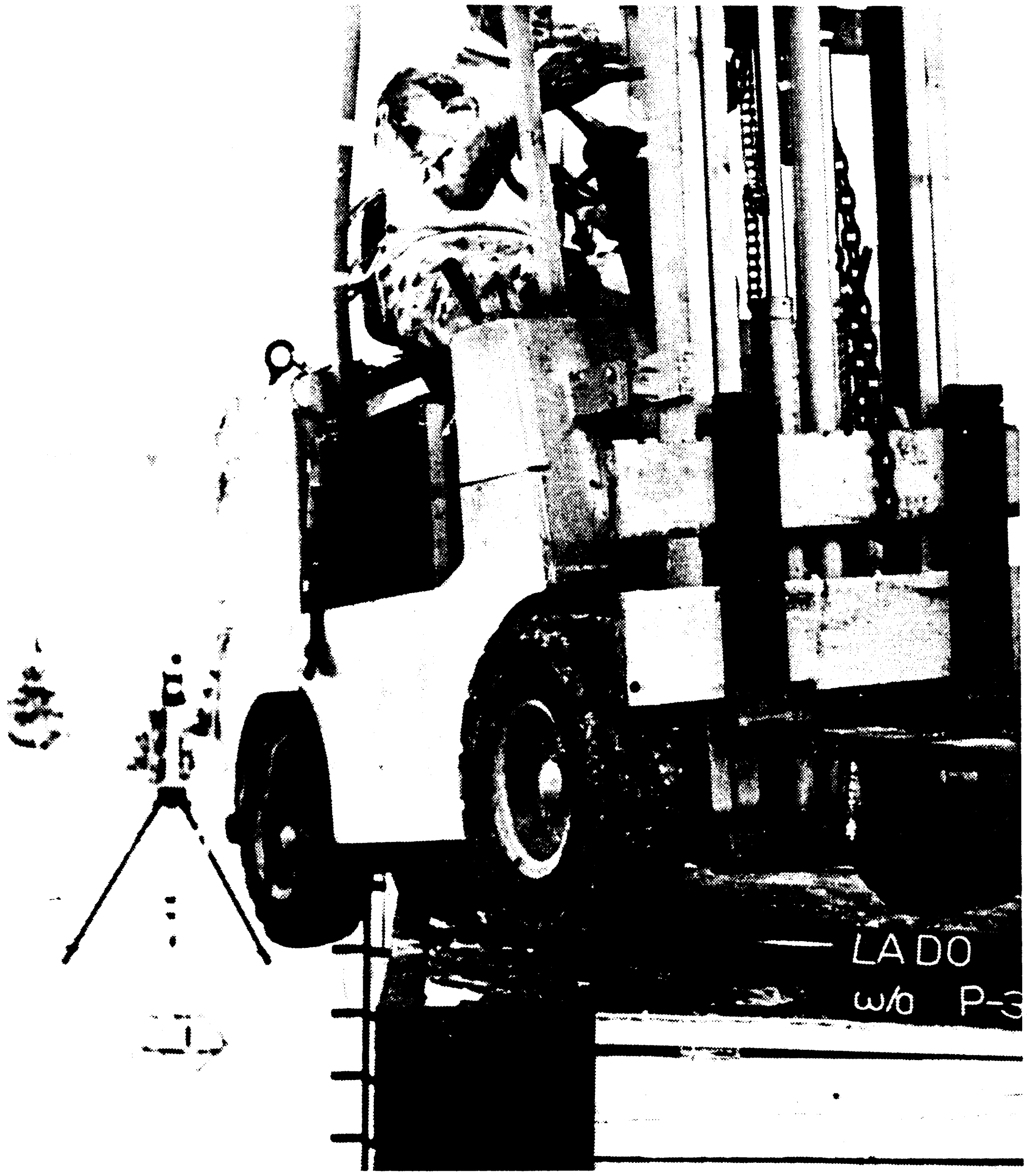

Figure 4-2: Modified Initial Position for Lateral Overturn Static Test

Figure 4-3: Initiating the Lateral Overturn Off the Dock

There were 12 successful dock-related tests conducted in Phase II and reported here. In all these tests the dummy was seated in a slightly forward-leaning posture, and its wrists were tied to the steering wheel using a double strand of 20-pound fishing line. The test conditions, which were varied for each mode, were the presence or absence of the same restraining devices used in the dynamic series, namely, the seatbelts and the armrests. Table 4-1 lists these 12 dock-related static tests.

TABLE 4-1: SUMMARY OF DOCK-RELATED STATIC TEST RESULTS

Test Code	Test Conditions
	7 Tests in Rear Drop-Off Mode (trailer pulling away from dock)
L2, L3, L4, L5...	With seatbelts, no armrests
M1, M2, M3.......	Unrestrained (no seatbelts, no armrests)
	1 Test in Longitudinal Overturn (max. load, max. height, tilting forward)
J2...............	With seatbelts, no armrests
	4 Tests in Lateral Overturn Mode
N2, N3...........	With seatbelts, no armrests
P1, P2...........	Unrestrained (no seatbelts, no armrests)

4.4 Results of Static Tests

The results from 10 successful dock-related static tests are summarized in Table 4-2. Detailed results of data processing are assembled in Appendix B, and are briefly described in the following subsections.

TABLE 4-2: SUMMARY OF STATIC TESTS RESULTS

Test	Seatbelts	HIC	Peak Resultant g's			Observations
			Head	Chest	Pelvis	
L3	w	377	175	143	147	No direct head impact
L4	w	3598	405	79	55	
L5	w	2883	539	23	28	
M1	w/o	7657	676	25	70	
M2	w/o	4584	631	19	18	
M3	w/o	172	78	87	127	No direct head impact
N2	w	5886	756	29	56	
N3	w	6292	712	42	31	
P1	w/o	196	134	87	33	
P2	w/o	7192	792	159	54	

4.4.1 <u>Results of Rear Drop-Off Test</u>. These were the L-tests (with seatbelts) and the M-tests (without seatbelts.) Both movies and signals were lost in test L1, while only head signals were lost in test L2.

Review of the high-speed movies revealed a consistent pattern of events in these simulated accidents. First, the truck rotated (in pitch) backward while the front wheels moved away from the dock along with the moving trailer. As the counterweight fell off the dock, the overhead guard hit the edge of the dock first. During this backward pitch, the dummy stayed upright with respect to the vertical, making it appear as if its body pitched forward relative to the truck. Once the overhead guard hit the dock, the dummy then fell back in the seat, pushed on the seatback, and struck the edge of the dock across the shoulders or on the back of the head, depending on several factors that included how far the truck had moved away from the dock. All motion stopped when the impact forces on the overhead guard pushed the reclined truck back into an upright position, moving the seated dummy forward inside the overhead cage.

In test L2, most of the impact was received by the shoulders, while the head rotated backward in a "whiplash" motion. No head signals were processed from this run. In test L3, the dummy's back at the time of truck/dock impact was rotated about 45 degrees from the seatback, and the dummy was a few inches off the seat. At impact, the dummy fell into the seat producing a peak pelvic acceleration of 147 g. The dummy then struck the edge of the dock across the shoulders producing a peak 143 g acceleration in the chest. The head motion was primarily a rearward pitch with no apparent hard impact with the ground, resulting in peak head acceleration of 175 g and a HIC value of 377.

Slightly different kinematics were produced in tests L4 and L5. In both these tests, the location of the dummy/dock strike was the back of the head and not across the shoulders. The results of these two tests averaged 3240 for the HIC, and 472 g, 45 g, and 39 g for the peak resultant head, chest, and pelvic accelerations, respectively. Unlike other L-tests, all motion of the truck and dummy stopped at the position shown in Figure 4-4. This photograph is included to demonstrate head strike against the edge of the dock.

The M-tests used an unrestrained dummy and produced results similar to the L-tests. Tests M1 and M2 produced a strike on the back of the dummy's head, at the location shown in Figure 4-5. The HIC values were 7657 and 4584. Peak accelerations from these two tests were 676 g and 631 g for the head, 25 g and 19 g for the chest, and 70 g and 18 g for the pelvis. Finally, test M3 produced a strike across the shoulders against the dock's edge, resulting in accelerations of 87 g in the chest

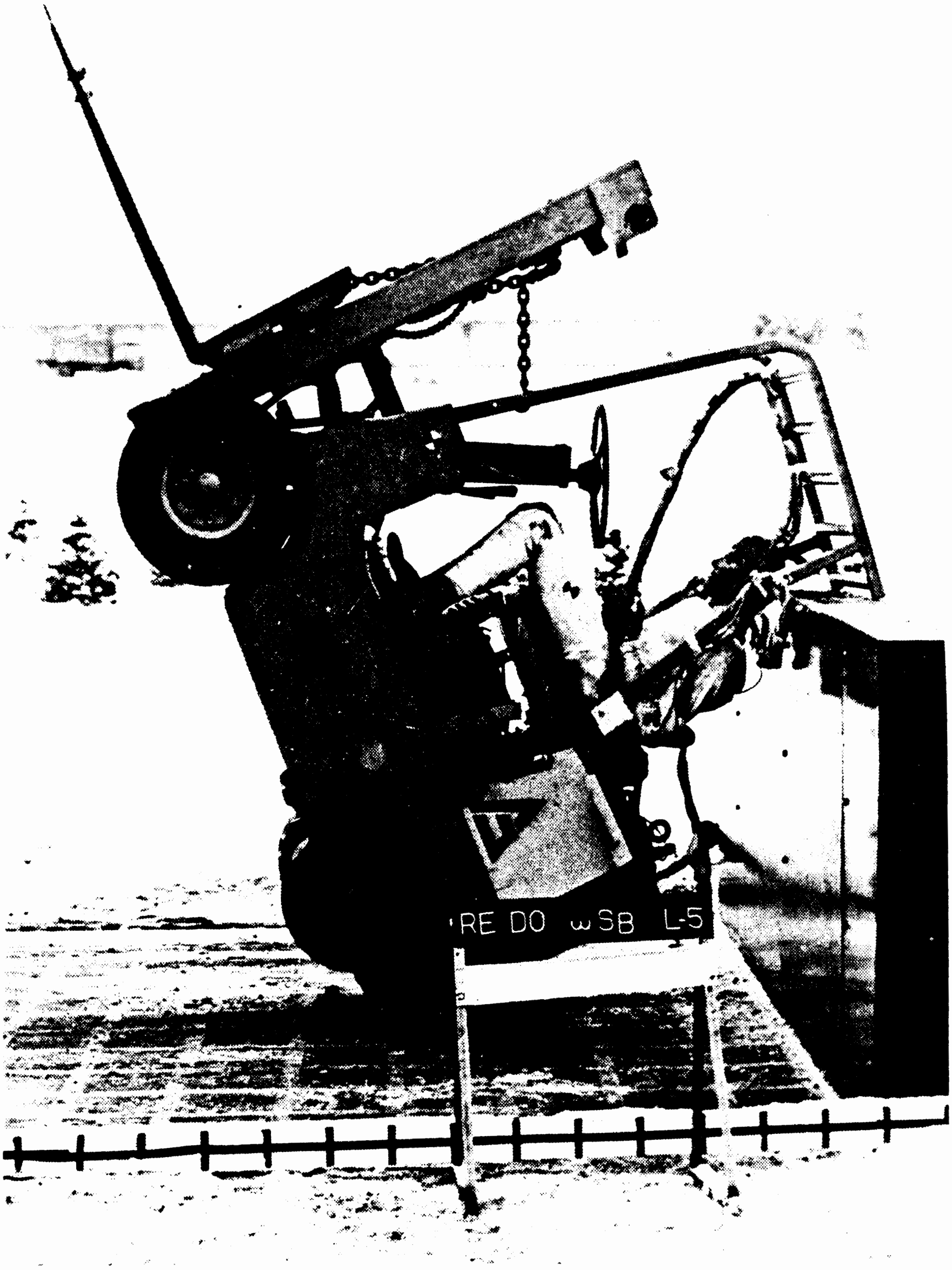

Figure 4-4: Final Position of Rear Drop-Off Test L5

and 127 g in the pelvis, while the head acceleration peak was 78 g with a HIC value of 172.

4.4.2 <u>Results of Lateral Dock Overturns</u>. These were the N-tests (with seatbelts) and P-tests (without seatbelts). Signals from test P3 were not processed, but movies from N2, N3, P1, P2, and P3 were obtained and reviewed. The film review revealed that, as the truck was tipped over the dock's edge starting with the right-rear wheel already off the edge, the counterweight impacted the ground first on its right-rear corner. At impact, the dummy began its ejection directly out the rear opening of the overhead guard at about a 45 degree angle with respect to the truck's long axis. Once the counterweight impacted the ground and stopped the truck's fall, the dummy continued its fall until it exited from the rear and struck the ground either head first or shoulders first. The truck then pivoted about the counterweight corner and landed on its right side. Only in test P1 did the truck land on its side before the dummy impacted the ground. Figures 4-6 and 4-7 show two different final positions of the dummy from tests N2 and P3.

Results of tests N2, N3, and P2, which had similar dummy and truck kinematics, averaged a HIC value of 6457, and peak accelerations of 753 g, 77 g, and 47 g for the head, chest and pelvis, respectively. The HIC value from test P1 was 196, and the peak accelerations from these tests were 134 g, 87 g, and 33 g for the head, chest, and pelvis.

4.4.3 <u>Results of Longitudinal Dock Overturn</u>. Only one test was run, test J-2. The signals were not processed, but the movies showed that, with the maximally loaded and raised forks, the truck overturned longitudinally and fell forward on the pavement below the dock. At its maximum rotation, the truck's long axis was pointing directly into the

Figure 4-5: Location of Dock's Edge Strike on Dummy's Head

Figure 4-6: Final Dummy Position in Test N2

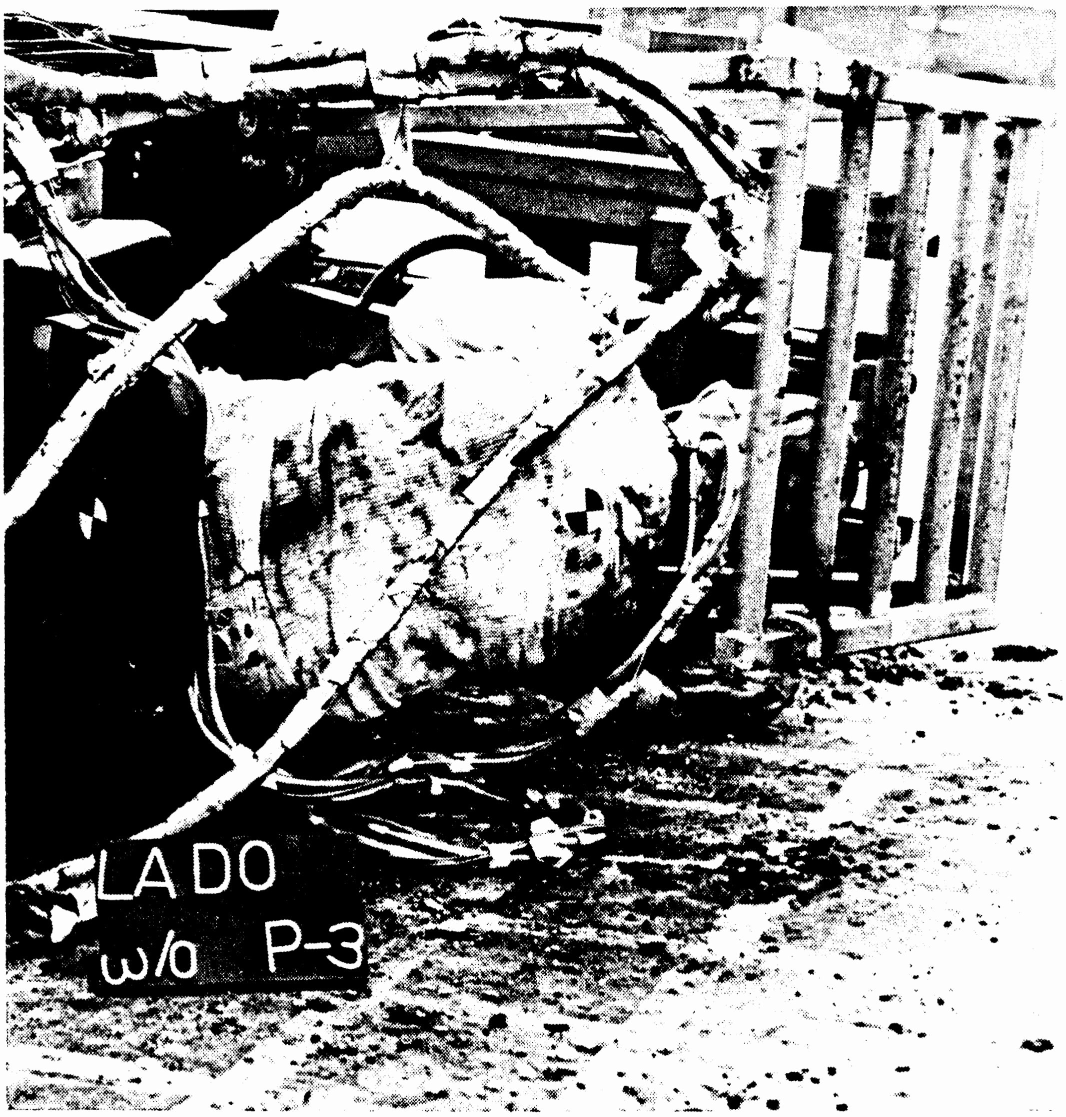

Figure 4-7: Final Dummy Position in Test P3

ground. The dummy remained in the seat because of the load on its back by the seatback. As the truck bounced back to an upright position, the dummy was kept in the seat by the seatbelt.

5.0 DISCUSSION OF STATIC TESTS

The first and third modes were intended to simulate realistic forklift operator maneuvers and operating situations. The third lateral overturn mode could occur when the operator, having found himself driving too close to the edge of the pathway from which his vehicle could fall, would attempt to steer away from the dangerous edge. However, because of the rear-wheel steer arrangement of forklift trucks, in so doing he would actually make the rear-end move forward along the turned rear-wheel path and toward the edge of the dock, causing rather than preventing the accident.

The question arises as to the validity of the test procedure used in the second mode (lateral overturn). This test procedure assumes virtually no dynamic motion of the vehicle before it rolls off the dock. If the procedure is intended to simulate an accident in which the forklift is moving forward at a very low speed, so that it would leave the dock from a virtually static initial condition, then the procedure provides a reasonable simulation.

Conversely, if these tests are intended to simulate a situation in which the forklift is traveling at a significant speed prior to the fall, then the procedure is not valid. A vehicle traveling at speed and having initiated a turn prior to the moment of fall, would depart the dock surface with considerable rotational momentum in yaw (turning). The vehicle would continue to rotate in yaw as it moved through space and would finally strike the ground in a significantly different attitude than occurred in these tests. The vehicle would probably strike the ground rear-end first or even rotate sufficiently to strike the left side, as opposed to striking the right side or right-rear as occurred in the actual tests.

In all of the static dock-related tests where the transducer signals were processed, severe accelerations due either to head or chest contact were observed. This is indicative of the harsh environment associated with the dock and surrounding pavement structures. In particular, the dock's edge presented a serious problem for rear drop-off tests regardless of whether the seatbelts were used or not. Given the particular model of the test truck, the overhead guard rear legs were the first ones to strike the edge of the dock, followed by the dummy's head or its shoulders during its rearward rotation. It is likely that a different model truck, in which the overhead structure rear legs are mounted further back, would have resulted in an earlier dock/guard interaction, possibly changing the nature of dummy interaction with the dock's edge. In any case, the use of seat belts as the sole restraint device may not be sufficient to reduce the severity of this type of impact.

6.0 SUMMARY OF CONCLUSIONS

Throughout this report, comments were made about the tests conducted in Phase II of the Operator Restraint Testing Program, the problems encountered in the testing procedure, and the dynamics and kinematics of both the forklift truck and the dummy simulating the truck operator. In this section, the conclusions drawn from the tests and the test results are summarized.

(1) Given some latitude in experimenting with the test conditions and configurations, it was possible to produce, in Phase II, some interactions between the dummy and the truck that were not obtained in Phase I. The experimental procedures, however, remain unreliable in producing repeatable results.

(2) When Phase II tests had similar test conditions to those in Phase I, the results of tests from both phases were comparable. This was the case for the nine severe J-turns conducted in Phase II.

(3) None of the severe J-turn tests produced a realistic side ejection of the dummy, while side ejection occurred in the last six mild J-turn tests. However, seatbelts were not used in these realistic mild J-turn tests. Additional testing using the mild J-turn should be carried out first without seatbelts to refine the testing procedures, then with seatbelts and/or other restraint devices to investigate their effectiveness.

(4) Ejection of the dummy from the side opening of the overhead structure occurs in mild J-turns of about a 15-foot radius at about 12 mph truck speed.

(5) Interaction of the passive dummy with the overhead guard during side ejection is affected by the rate of truck rollover, by the type and presence of restraints, and by the truck motion itself.

(6) The presence of the armrest had negligeable effect on the rear-ejection of the dummy. It did, however, seem to influence the orientation and position of the dummy during its impact in side ejection.

(7) Simulation of active participation of the operator was limited to tying the dummy's wrists to the steering wheels. To the extent that the strength of those ties may not accurately represent the operator grip on the steering wheel, the results obtained from this technique may not be realistic.

(8) The static lateral overturn off the dock is a realistic simulation of slow-moving vehicles. It is not, however, a reasonable simulation if the truck is moving at higher speeds when it overturns off the dock.

(9) The rear drop-off static test was the most realistic of the dock-related accident simulations. In most of these tests, the back of the dummy's head or its shoulder struck the edge of the dock, producing high of chest and/or head accelerations. In these tests, the seatbelt did not seem to affect the dummy's motion.

(10) The severity of the dummy's kinematic response is affected by the occurrence of ejection, by the direction and angle of ejection, and by the location of interaction of the dummy with the ground and/or the overhead guard structure. The construction of the dummy may also be a factor in determining the severity of kinematic response, particularly head response.

(11) The HIC and peak accelerations were used to describe the dummy's kinematic response to enable comparisons of impact severity among various tests. Multiple injury criteria and well-established human tolerance levels for these criteria, combined with results from repeatable tests, are essential for projecting any conclusions from the dummy test results to human subjects.

(12) The data produced in Phase II is not adequate to formulate definitive conclusions about the efficacy of the restraint systems tested in this phase.