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The Effect Of Longitudinal Edge Of Paved Surface Drop-Off On Vehicle Stability

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E.F. Nordlin, D.M. Parks, R.L Stoughton, and J.R. Stoker

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16. ABSTRACT
The effect of edge of pavement drop-offs on vehicle stability is reported for 50 professional driver tests of a small, medium, and large size passenger car and a pickup truck driven off, along, and back onto drop-off heights of 1 1/2" (38 mm), 3 1/2" (89 mm), and 4 1/2" (114 mm) at about 60 mph (26.8 m/sec). Two and four wheel drop-off tests were conducted from an existed asphalt concrete shoulder onto both compacted soil and asphalt concrete surfaces. The drop-off heights had little effect on vehicle stability: steering wheel angles were generally 60 degrees or less; vehicle roll angles were 10 degrees or less; a significant jolt and accompanying front end noise were experienced by the drivers at the larger drop-off heights; there were no problems with vehicle alignment; less than one wheel revolution was required for the first wheel to mount the drop-off heights; varying amounts of front wheel wobble caused mainly by an irregular drop-off edge were detected; there was virtually no deviation in vehicle trajectory as the vehicles remounted the drop-off edges; and there was no vehicle encroachment into adjacent traffic lanes. Two nonprofessional drivers participated in a few supplementary tests and commented about driving the drop-off heights at 40-45 mph (17.9- 20.1 m/sec).

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Accidents, construction area accidents, construction safety, curbs, maintenance, pavement drop-offs, safety, shoulders, steering, vehicle dynamics, vehicle handling

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STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF STRUCTURES & ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY

March 1976

TL No. 646783

Mr. C. E. Forbes
Chief Engineer

Dear Sir:

I have approved and now submit for your information this final research project report titled:

THE EFFECT OF LONGITUDINAL EDGE OF
PAVED SURFACE DROP-OFF ON VEHICLE STABILITY

Study made by . . . . .Structural Materials Branch

Under the Supervision of. . . . . .E. F. Nordlin, P. E.

Principal Investigator. . . . . . .J. R. Stoker, P. E.

Co-Principal Investigator . . . . .R. L. Stoughton, P. E.

Co-Investigator . . . . .D. M. Parks, P. E.

Report Prepared by . . . . .D. M. Parks, P. E.

Very truly yours,

George A. Hill
GEORGE A. HILL
Chief, Office of Transportation Laboratory

Attachment
DMP:bjs

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Special appreciation is due the following staff members of the Transportation Laboratory who were instrumental in the successful completion of these tests and the preparation of this report:

Lee Wilson	In charge of vehicle preparation; devised drip system to trace path of vehicle; assisted in moving vehicle camera mounts during tests; helped with test site preparation and cleanup.
Jim Keesling	Assembled battery packs for high speed cameras; designed an adjustable mount for interior cameras; in charge of downstream camera; assisted with data reduction, vehicle preparation and cleanup.
Lee Staus	Assisted with data reduction.
Bob Mortensen	In charge of data and documentary photography operated pan cameras during the test series.
Kerry Wilson	Data and documentary photographer; in charge of the operation of all vehicle mounted cameras during the test series; assisted with vehicle preparation.
George Oki	Machine Shop: constructed camera mount and speedometer brackets and fixtures.
Myrna Gumpert Bob Freer	Provided special assistance in expediting service contracts and service agreements.

Appreciation is also due Earl Notestine and Terry Romness from District 03 who made arrangements for the test site and helped with the construction details, and Wayne Grable and his crew from District 03 Maintenance for constructing the test sites.

The concerted efforts of our consultants is also appreciated. Paul O'Shea, our professional driver, offered several valuable suggestions about our test procedures. J. Barry Herron, our cinematographer, assisted by locating some specialized high speed movie equipment, helped design camera mounts used for photographing underneath the vehicle, and assisted with trial runs.

INTRODUCTION

In 1974, the California Department of Transportation (Caltrans) studied some highway accident cases in which a drop-off at the longitudinal edge of pavement was mentioned as a possible contributing factor.

This project was initiated to:

- Determine the effects of longitudinal drop-offs, along a highway, on the stability and controllability of vehicles traveling over drop-offs at high speeds,
- Establish maximum tolerable heights for drop-offs,
- Verify current maintenance standards for allowable drop-off heights,

A longitudinal drop-off, along a highway, exists when there is a difference in height between two adjacent surfaces, either between:

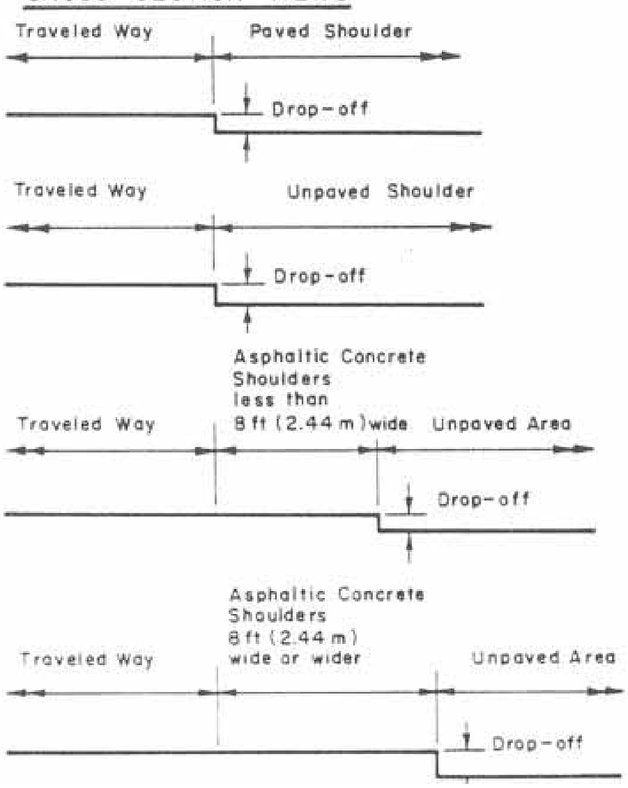
- Surfaces of a paved shoulder and the unpaved area alongside the pavement,
- Surfaces of a paved traveled way and an unpaved shoulder,
- Surfaces of a paved traveled way and a paved shoulder,
- Surfaces of a portion of an existing traveled way with a newly paved blanket overlay and the remaining portion of the existing pavement.

Drop-offs created when new traffic lanes are added to existing traveled ways were not considered for this study. These drop-offs generally exceed the maximum heights of 4 1/2" (114 mm) used for this project and sometimes approach several feet depending on soil conditions at the construction site.

Drop-offs are generally caused by erosion and traffic wear. However, during a pavement blanket overlay operation, a drop-off is frequently caused because the paving equipment cannot pave, in one pass, the full width of the traveled way or traveled way and shoulder at one time. There is often a delay before all the existing pavement can be brought up to the grade of the new pavement blanket.

Portions of Sections 11.01 and 12.01, May 15, 1974, of the Caltrar Maintenance Manual specify California's drop-off standards illustrated as follows:

CROSS SECTION VIEWS



MAINTENANCE STANDARDS

Repair drop-offs greater than 3/4" (19mm)

Repair drop-offs greater than 1 1/2" (38mm) or when edge failure becomes apparent.

Repair drop-offs greater than 1 1/2" (38mm) or when edge failure becomes apparent.

Repair drop-offs greater than 3" (76mm) or when edge failure becomes apparent.

The highway departments from the States of Illinois, New York, Oregon, Texas, and Washington were contacted during the course of this project for their allowable drop-off standards and accident experience records. Comments were as follows:

Illinois

No published standards, but attempts to keep shoulders flush with the pavement.

Post warning signs to alert traffic to shoulder construction.

New York

A 2" (51 mm) maximum drop-off on state highways with a one-way design hourly volume less than 200 vehicles per hour (vph),

A 1 1/2" (38 mm) maximum drop-off for state highways with one-way design hourly volumes of 200-500 vph, and,

A 1" (25 mm) maximum drop-off on expressways with volumes over 500 vph.

Oregon

Requires shoulders to be flush with the traveled way,

Considering a change in their standards to permit up to a 2" (51 mm) maximum drop-off between the traveled way pavement and a gravel shoulder,

Post warning signs to alert traffic to shoulder construction.

Texas

No published standards, but normally try to limit drop-offs to no greater than 2" to 3" (51-76 mm).

In practice provide a minimum 12:1 taper on new overlays between the traveled way pavement and the paved shoulder.

Post warning signs to alert traffic to shoulder constructior

Washington

Requires shoulders to be flush with the traveled way.

Post warning signs indicating "abrupt lane edge" during repaving operations and "shoulder drop-off" at locations where the removal of a shoulder presents a dangerous hazard to traffic.

Require ruts or potholes over 3" (76 mm) deep in gravel or crushed stone shoulders to be filled with stabilized material.

ie of these states, except Oregon, had accident records relatec drop-off conditions. The records from Oregon combined all idents due to chuckholes and drop-offs.

HRIS literature search was made prior to the initiation of thi ject. To date, no known reported research has been conducted determine whether longitudinal drop-offs cause vehicle stabili blems significant enough to endanger motorists who veer entarily off a highway shoulder or other paved surface and try drive back onto the pavement and into their original 12 ft 7 m) lane of travel.

Full scale tests have been conducted by Caltrans(1,2)* and the Texas Transportation Institute(3) on the effects of vehicles going over curbs at various angles. These tests were conducted on curbs with heights ranging from 6" (152 mm) to 12" (305 mm) and also included a few tests over a sloping 4" (102 mm) high curb. It was concluded that these tests did not apply to drop-off conditions of interest in this study which were concerned with near vertical drop-off heights less than 5" (125 mm).

Fifty professional driver tests were conducted to investigate the following basic parameters:

- Drop-off heights of 1 1/2" (38 mm), 3 1/2" (89 mm), and 4 1/2" (114 mm).
- Four different vehicles - a small, medium, and large size passenger car and a pickup truck.
- Vehicles driven by a professional driver from an existing A.C. shoulder onto either an A.C. or a soil surface at velocities of 60 mph (26.8 m/sec) and angles less than 10°.
- Tests where either two wheels or four wheels drop off an existing A.C. shoulder.

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*Numbers underlined in parenthesis refer to a reference list at the end of the report.

CONCLUSIONS AND IMPLEMENTATION

Conclusions

A. Based on the test conditions for this project, the current Caltrans maintenance standards concerning drop-offs from longitudinal edges of pavement are quite reasonable and conservative.

However, before setting overall drop-off standards or standards for specific sites, consideration should also be given to variables not included in this project such as vehicles in poor mechanical condition, driver inexperience or unpreparedness, adverse weather conditions, roadway and shoulder geometry, roadside obstructions or hazards, etc.

B. For the test conditions of this project, there were virtually no adverse effects on vehicle stability for 50 recorded professional driver tests (including two control tests) of four types of vehicles driven at about 60 mph (26.8 m/sec) during the following consecutive driving maneuvers:

- Driving down off the edge of an existing A.C. shoulder onto either compacted soil or A.C. surfaces from drop-off heights of either 1 1/2 (38 mm), 3 1/2" (89 mm), or 4 1/2" (114 mm), then momentarily
- Driving along the drop-off edge, before
- Driving back up over the drop-off edge and returning to the existing A.C. shoulder.

C. The following specific observations and conclusions were reached as indicators of the stability and controllability of the test vehicles as they traveled over the drop-offs that were studied:

1. Steering - Relatively small steering wheel angles were measured during these maneuvers, usually 60° or less. The driver for these tests handled the steering wheel with minimal effort. At no time did the driver loose control of the steering wheel.

2. Vehicle Roll - Vehicle roll angles did not increase significantly in relation to the height of the drop-offs. A maximum value of 10° was recorded. The driver for these tests did not become disoriented or feel any discomfort during vehicle roll.

3. Noise - There is a significant jolt and accompanying noise associated with driving off and mounting drop-off heights of 3 1/2" (89 mm) and 4 1/2" (114 mm). The driver did not experience any noticeable disturbances during the 1 1/2" (38 mm) drop-off tests.

4. Vehicle Alignment - Front wheel alignment was not measurably affected during the drop-off tests.

5. Tire Scuff - When the vehicles remounted the drop-off edge, the first vehicle wheel to contact the drop-off edge mounted each drop-off height without delay. Photographs of the tire scuff marks taken during the test series show that it takes less than one revolution of the first wheel contacting the edge of the drop-offs before the vehicle climbs back onto the pavement.

6. Wheel Wobble - Varying amounts of front wheel wobble occurred as the first vehicle wheel mounted the 3 1/2" (89 mm) and 4 1/2" (114 mm) drop-off heights. The major cause of wheel wobble (side to side motion) was the interaction of the sidewall of the tire with an irregular pavement drop-off edge. Wheel wobble did not affect the trajectory path of the vehicles during any of the tests.

7. Nonprofessional Drivers - Although a professional conducted all of the 50 tests documented on film for this project, two nonprofessional drivers also did not experience any steering difficulties or stability problems while driving the three drop-off heights at about 40-45 mph (17.9-20.1 m/sec).

8. No Encroachment - During all of the tests, the drivers steered their vehicles back onto the pavement and back into their original 12 ft (3.7 m) lane of travel, nearest the shoulder, without encroaching into the other adjacent traffic lanes.

Implementation

The Offices of Construction and Maintenance should review the findings of this report and their standards on drop-off conditions to determine whether changes are warranted.

The use of signing to warn of possible construction zone hazards or other longitudinal edge of pavement drop-off conditions would be one alternative to establishing maximum drop-off height values for all conditions.

TECHNICAL DISCUSSION

Test Site Location and Construction

The test site was located on an unopened portion of Interstate 80 between Del Paso Park Separation and Overhead and Longview Drive Overcrossing in Sacramento County near Sacramento, California, Figure 1.

FIGURE 1, TEST SITE

Drop-off heights of 4 1/2" (114 mm), 3 1/2" (89 mm), and 1 1/2" (38 mm) were constructed along the edge of an existing 5 ft wide (1.5 m) A.C. shoulder adjacent to a 50 ft wide (15.3 m) unpaved median. Each drop-off height was maintained for a 500 ft (153 m) length with short spaces between the three 500 ft test strips. Field measurements of drop-off heights taken at 10 ft intervals are attached in the Appendix, Table 1A. Each 500 ft (153 m) strip was used for both series of tests, asphalt to soil and A.C. to A.C. After the A.C. to soil tests were completed, an additional

1" to 2" (25 mm to 51 mm) layer of soil was removed from each strip and replaced with a layer of A.C. so that the A.C. to A.C. drop-off tests could be conducted, Figure 2. Originally it was planned that a 5 1/2" (140 mm) drop-off height be used. However, due to the 5.8" (147 mm) minimum ground clearance on the small car it was felt 4 1/2" (114 mm) was the maximum height that could be used without the car bottoming out on the edge of pavement at the drop-off. The longitudinal profile grade for the portion of I-80 used for this project was 0.54%, or nearly level.

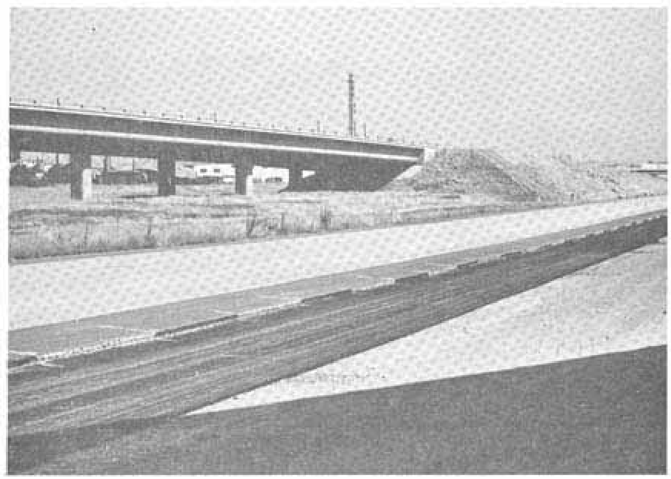


FIGURE 2, A.C. TO A.C. TEST SITE

Two control tests were conducted at sites where there were no drop-offs. Test No. 39, with a medium size vehicle, was performed entirely on the existing PCC pavement adjacent to the drop-off test sites, Figure 2. Test No. 45, with a large size vehicle, was conducted entirely on soil on the other side of the median adjacent to the 1 1/2" (38 mm) drop-off site, Figure 3.

FIGURE 3, CONTROL TEST - NO DROP-OFF, A.C. TO SOIL

Figure 5A in the Appendix shows a layout of the test site, test site widths, and typical cross sections for the existing roadway used for this project.

Test Equipment and Procedure

Four different types of vehicles were used for the test series: a 1971 Ford Pinto, 2520 lbs (1143 kg); a 1971 AMC Matador Sedan, 3840 lbs (1741 kg); a 1970 Chevrolet Brookwood Station Wagon, 4780 lbs (2168 kg); and a 1973 Dodge D100 pickup truck, 4076 lbs (1849 kg), Figures 4, 5, 6, and 7. Other vehicle specifications are included in Table 2A in the Appendix.

FIGURE 4, SMALL SIZE VEHICLE

FIGURE 5, MEDIUM SIZE VEHICLE

FIGURE 6, LARGE SIZE VEHICLE

FIGURE 7, PICKUP TRUCK

Four high speed movie cameras and a normal speed movie camera were used to document each drop-off test: ground mounted pan cameras viewing action perpendicular to the drop-off edge, Figures 8 and 9; a ground mounted downstream camera viewing action parallel to the drop-off edge, Figure 10; a camera mounted inside the vehicle viewing the driver, the rotation of the steering wheel, and a large size speedometer, Figures 11 and 12; and a camera mounted on the front bumper of each vehicle, Figure 13, viewing the action of the vehicle's right front or left front wheel as the wheel dropped off and then mounted the drop-off edge. This camera was moved from the right side to the left side of the vehicle depending on whether two or four wheel drop-off tests were conducted. A normal speed movie camera mounted inside the vehicle, Figure 11, viewing the driver and steering wheel rotation was used for the A.C. to A.C. drop-off tests in addition to the other cameras.

FIGURE 8, PAN CAMERAS

FIGURE 9, PAN CAMERAS IN OPERATION

FIGURE 10, DOWNSTREAM CAMERA

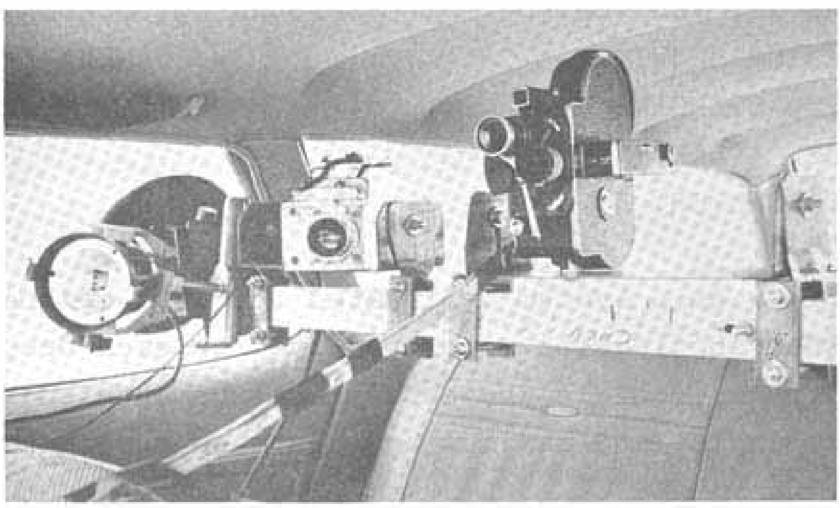


FIGURE 11, INTERIOR VEHICLE CAMERAS

FIGURE 12, VEHICLE INTERIOR SHOWING TAPED STEERING WHEEL & LARGE SPEEDOMETER

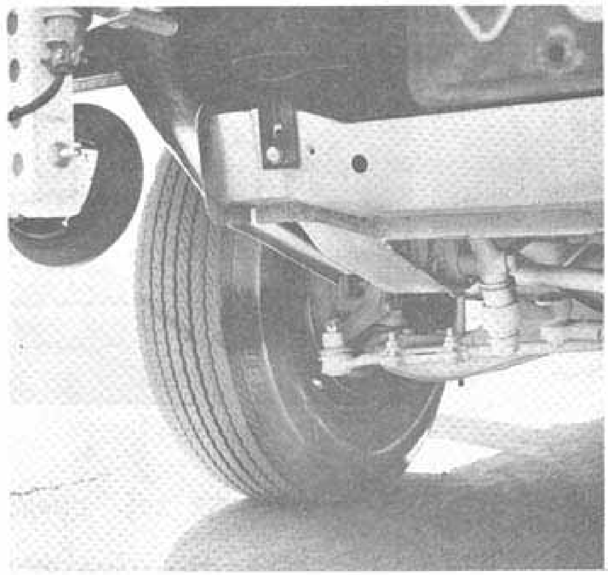


FIGURE 13, BUMPER MOUNTED CAMERA

A gravity flow drip system delineated the path of the right rear wheel of the vehicle with a colored dye for each drop-off test. From this trace, vehicle trajectory measurements such as entrance angle, exit angle, and maximum arc distance were taken after each test.

Photographs were taken after each test of scuff marks on the painte sidewalls of the tires mounting the drop-off heights.

Vehicle track width was measured after each test as a rough check of possible vehicle alignment problems.

The Appendix contains detailed descriptions of the photographic equipment and data collection techniques and the test vehicle equipment.

Test Results

Test parameters, trajectory measurements, maximum vehicle roll angles, maximum steering wheel angles, and vehicle velocities are tabulated separately for the A.C. to soil and the A.C. to A.C. drop-off tests, Tables 1, 2, 3, 4, 5, and 6 attached at the end of this section.

Steering wheel angle, Tables 5 and 6, is defined as the "angular displacement of the steering wheel measured from the straight-ahead position (position corresponding to zero average steer angle of a pair of steered wheels)"(4).

The A.C. to A.C., 2 wheel drop-off tests at 3 1/2" (89 mm) were eliminated from the test program because the more critical A.C. to soil tests for the same height and wheel condition were uneventful. It was felt that these tests would be redundant.

Photographs of tire scuff marks, Figures 15 and 16, attached at the end of this section, compare sidewall scuff marks with respect to vehicle size and drop-off height for the four wheel A.C. to soil and A.C. to A.C. drop-off tests.

Sequential photographs of the first wheel to mount drop-off heights of 3 1/2" (89 mm) and 4 1/2" (114 mm) for the small, medium and large size vehicles show vehicle wheel interaction with the drop-off edge for the four wheel A.C. to soil and A.C. to A.C. drop-off tests, Figures 17 and 18, attached at the end of this section.

Coefficients of friction for the existing portland cement concrete (PCC) traveled way, the existing A.C. shoulder, and the A.C. surface used for the A.C. to A.C. drop-off tests were measured along the three drop-off test strips with the California Portable Skid Tester, Figure 14.

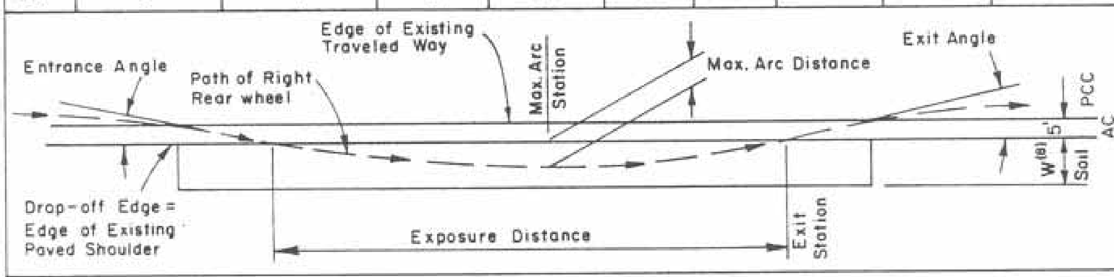
FIGURE 14, CALIFORNIA PORTABLE SKID TESTER

Average values for the coefficients of friction for the three paved surfaces were: 0.42 for the PCC traveled way, 0.44 for the A.C. shoulder, and 0.39 for the A.C. surfaces used for the A.C. to A.C. tests. Actual field measurements and their corresponding ASTM Skid Numbers(5) are listed in the Appendix, Table 3A.

A 30 minute color movie along with a script was assembled to represent the drop-off tests conducted for this project. Documentary coverage of the test site and equipment used for these tests is included.

TABLE 1 TRAJECTORY MEASUREMENTS
ASPHALT CONCRETE TO SOIL DROP-OFF TEST SERIES(1)

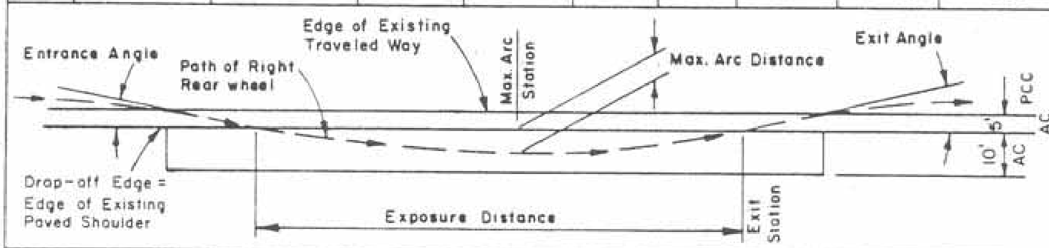
TEST PARAMETERS				VEHICLE TRAJECTORY					
TEST NO.	NOMINAL DROP-OFF HEIGHT in. (7)	NO. OF WHEELS DROPPING-OFF	VEHICLE SIZE (2)	ENTRANCE ANGLE°	MAX. ARC DISTANCE ft (7)	MAX. ARC STATION	EXIT ANGLE°	EXIT STATION	EXPOSURE DISTANCE ft (7)
7	1½	2	S	3.2	3.5	1+90	3.4	3+05	270
1			M	3.4	3.0	1+00	1.1	3+10	329
17			L	2.3	3.2	1+80	2.9	2+97	262
23			P	2.0	4.5	1+80	2.4	3+25	280
8		4	S	4.0	7.3	2+20	5.2	3+70	295
2			M	4.0	8.5	2+30	4.0	4+35	425
18			L	2.6	10.0	2+00	3.1	3+95	361
24			P	4.3	10.1	2+00	3.1	4+30	430
10(3)	3½	2	S	4.6	3.4	1+20	5.7	2+25	190
10(4)			S	4.6	2.4	1+50	4.9	2+31	194
10			S	3.1	2.6	1+20	3.7	2+25	170
4			M	4.9	3.5	1+90	4.3	2+96	216
16			L	4.6	3.5	1+20	2.9	2+56	243
22			P	4.6	3.8	1+50	4.3	3+25	280
9		4	S	3.7	7.8	1+80	4.6	3+35	280
3			M	4.0	8.7	1+50	4.0	3+50	290
15			L	2.3	6.7	2+10	2.3	3+34	300
21			P	5.4	10.3	1+90	2.9	3+33	290
11(5)	4½	2	S	4.7	4.7	1+20	7.8	1+83	183
5			M	5.2	1.8	2+90	4.6	3+41	286
13			L	4.0	4.0	1+30	2.9	3+60	336
19(5)			P	4.6	5.6	1+20	4.2	2+30	196
12		4	S	4.6	9.2	2+20	4.0	3+94	338
6			M	3.5	8.5	1+40	1.4	3+16	291
14			L	4.0	9.4	1+60	2.9	3+94	351
20			P	4.6	10.4	1+90	4.0	3+94	361
45(6)	0	4	L	6.8	8.6	2+10	1.4	3+88	308



(1) Live driver tests.
(2) S = Small car.
M = Medium car.
L = Large car.
P = Pickup truck.
(3) No camera coverage.
(4) No camera coverage of driver.
(5) Three wheels dropped-off.
(6) Control test.
(7) 1 foot = 0.305 meters.
1 inch = 25.4 millimeters.
(8) W = 12 ft. for 1½ & 3½ sites
W = 18 ft. for 4½ site

TABLE 2 TRAJECTORY MEASUREMENTS
ASPHALT CONCRETE TO ASPHALT CONCRETE DROP-OFF TEST SERIES(1)

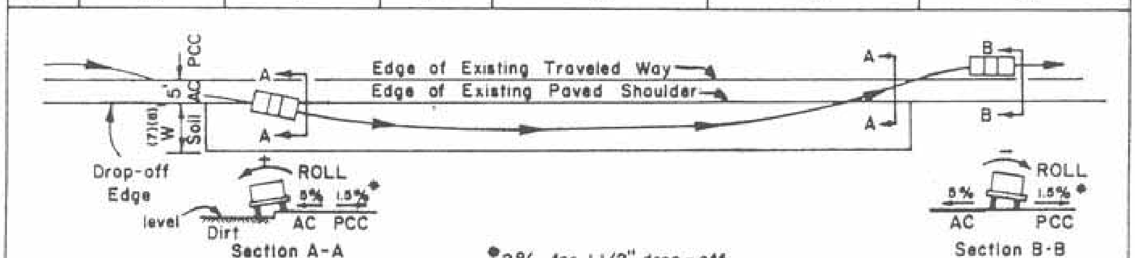
TEST PARAMETERS				VEHICLE TRAJECTORY					
TEST NO.	NOMINAL DROP-OFF HEIGHT in. (6)	NO. OF WHEELS DROPPING-OFF	VEHICLE SIZE (2)	ENTRANCE ANGLE°	MAX. ARC DISTANCE ft (6)	MAX. ARC STATION	EXIT ANGLE°	EXIT STATION	EXPOSURE DISTANCE ft (6)
31	1 1/2	2	S	2.3	1.5	1+30	1.3	3+50	325
36			M	1.1	3.4	1+90	2.3	3+76	314
47			L	4.0	3.6	2+40	2.3	3+93	330
29			P	2.6	3.9	1+40	2.9	3+63	348
32		4	S	4.3	8.0	2+90	5.1	5+00	480
37			M	4.3	7.3	2+20	4.0	4+20	384
46			L	3.4	9.1	2+50	4.6	4+41	382
28			P	4.6	8.2	1+90	4.0	4+01	374
33	3 1/2	4	S	6.8	7.3	1+40	5.2	2+80	260
38			M	6.3	9.0	2+07	2.9	3+92	389
44			L	5.7	8.4	2+00	4.0	3+55	333
27			P	4.6	8.5	1+70	3.0	3+37	315
30	4 1/2	2	S	1.7	2.6	1+20	4.3	3+44	279
35(3)			M	4.3	3.3	0+55	3.7	3+80	382
35			M	2.3	4.5	0+80	3.1	3+73	385
42			L	1.7	4.6	1+20	2.9	3+98	360
25			P	1.7	4.5	1+10	2.3	3+23	300
34		4	S	4.0	7.2	2+60	4.0	4+20	397
40			M	4.0	9.3	2+10	4.3	3+93	404
43			L	3.4	9.7	2+30	6.3	4+43	405
26			P	4.6	9.0	1+80	4.6	4+15	408
41(4)			M	3.4	8.6	1+70	5.7	3+98	408
39(5)	0	4	M	3.1	9.5	2+70	3.9	4+28	428



(1) Live driver tests.
(2) S = Small car.
M = Medium car.
L = Large car.
P = Pickup truck.
(3) Trouble with Bolex camera inside car; driver was driving with one hand on steering wheel.
(4) Radial tire test.
(5) Control test on PCC.
(6) 1 foot = 0.305 meters.
1 inch = 25.4 millimeters.

TABLE 3 VEHICLE ROLL ANGLES
ASPHALT CONCRETE TO SOIL DROP-OFF TEST SERIES[1]

TEST PARAMETERS				VEHICLE ROLL ANGLES*		
TEST NO.	NOMINAL DROP-OFF HEIGHT in. (8)	NO. OF WHEELS DROPPING-OFF	VEHICLE SIZE (2)	GOING OFF DROP-OFF	COMING BACK ON EXISTING PAVED SHOULDER	AFTER ALL WHEELS ON TRAVELED WAY
7	1 1/2	2	S	5	4	0
1			M	3	3	0
17			L	3	2	-1
23			P	4	4	0
8		4	S	5	6	NC (9)
2			M	3	3	-1
18			L	3	3	-2
24			P	4	4	0
10 (3)	3 1/2	2	S	6	9	0
10 (4)			S	7	7	-1
10			S	7	8	-1
4			M	7	7	-2
16			L	6	6	-2
22			P	5	6	-1
9		4	S	7	9	0
3			M	5	7	-1
15			L	6	8	-3
21			P	5	6	-1
11 (5)	4 1/2	2	S	9	9	-2
5			M	8	7	-2
13			L	7	7	-1
19 (5)			P	7	7	-3
12		4	S	7	6	0
6			M	7	7	0
14			L	7	7	0
20			P	5	6	-1
45 (6)	0	4	L	0	0	0

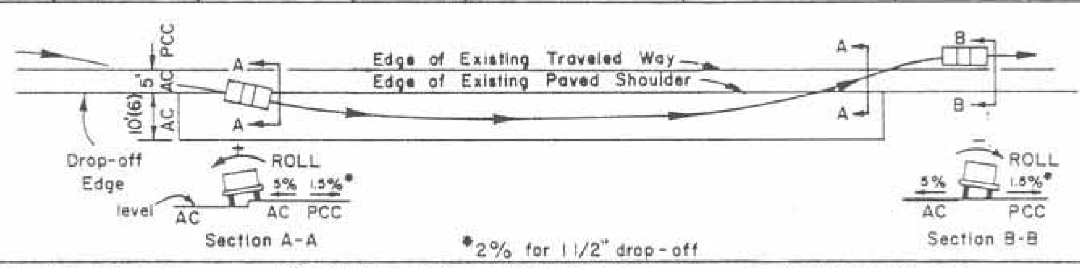


*2% for 1 1/2" drop-off

(1) Live driver tests.
(2) S = Small car.
M = Medium car.
L = Large car.
P = Pickup truck.
(3) No camera coverage.
(4) No camera coverage of driver.
(5) Three wheels dropped-off.
(6) Control test.
(7) W = 12 ft for 1 1/2 & 3 1/2 sites
W = 18 ft for 4 1/2 site
(8) 1 foot = 0.305 meters.
1 inch = 25.4 millimeters.
(9) No film coverage

TABLE 4 VEHICLE ROLL ANGLES
ASPHALT CONCRETE TO ASPHALT CONCRETE DROP-OFF TEST SERIES(1)

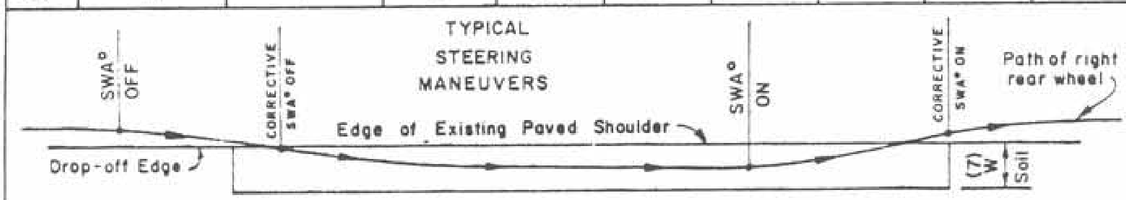
TEST PARAMETERS				VEHICLE ROLL ANGLES°		
TEST NO.	NOMINAL DROP-OFF HEIGHT in. (6)	NO. OF WHEELS DROPPING-OFF	VEHICLE SIZE (2)	GOING OFF DROP-OFF	COMING BACK ON EXISTING PAVED SHOULDER	AFTER ALL WHEELS ON TRAVELED WAY
31	1 1/2	2	S	6	4	0
36			M	2	3	-1
47			L	3	4	NC(7)
29			P	4	3	-1
32		4	S	7	7	NC
37			M	4	4	-2
46			L	2	5	NC
28			P	4	5	-1
33	3 1/2	4	S	7	9	-3
38			M	5	6	NC
44			L	4	6	-4
27			P	5	7	-3
30	4 1/2	2	S	6	8	-3
35(3)			M	10	7	-3
35			M	9	6	-2
42			L	5	5	NC
25			P	8	8	-3
34		4	S	7	8	-2
40			M	8	6	-3
43			L	5	6	NC
26			P	6	6	-1
41(4)			M	7	7	-3
39(5)	0	4	M	-1	2	-1



(1) Live driver tests.
(2) S = Small car
M = Medium car
L = Large car
P = Pickup truck.
(3) Trouble with Bolex camera inside car; driver was driving with one hand on steering wheel.
(4) Radial tire test.
(5) Control test on PCC.
(6) 1 inch = 25.4 mm
(7) No film coverage

TABLE 5 STEERING DATA
ASPHALT CONCRETE TO SOIL DROP-OFF TEST SERIES[1]

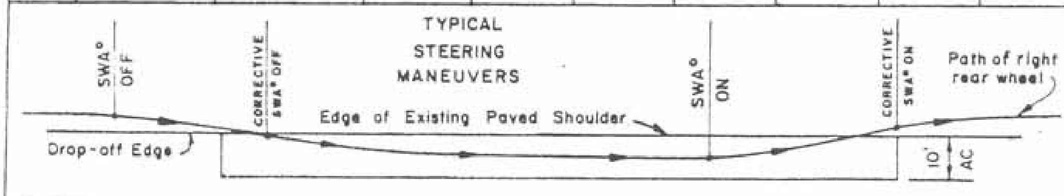
TEST PARAMETERS				STEERING WHEEL ANGLES (SWA°)[8]/VEHICLE VELOCITIES					
TEST NO.	NOMINAL DROP-OFF HEIGHT in (11)	NO. OF WHEELS DROPPING-OFF	VEHICLE SIZE (2)	SWA° OFF	VELOCITY OFF MPH (12)	CORRECTIVE SWA° OFF	SWA° ON	VELOCITY ON MPH (12)	CORRECTIVE SWA° ON
7	1½	2	S	NO FILM COVERAGE (NFC)					
1			M	30R[9]	60	60L[10]	15L	60	8R
17			L	23R	60	53L	38L	60	0
23			P	30R	60	45L	38L	60	23R
8		4	S	15R	65	30L	30L	65	23R
2			M	38R	60	38L	30L	60	15R
18			L	38R	60	53L	45L	60	23R
24			P	45R	60	53L	38L	60	23R
10[3]	3½	2	S	NO FILM COVERAGE					
10[4]			S	30R	55	30L	23L	55	45R
10			S	30R	60	30L	15L	60	45R
4			M	38R	60	38L	30L	60	45R
16			L	30R	55	45L	30L	55	45R
22			P	60R	60	53L	45L	65	53R
9		4	S	30R	60	30L	30L	60	45R
3			M	30R	55	60L	60L	50	45R
15			L	45R	65	60L	83L	60	60R
21			P	75R	60	75L	68L	60	75R
11[5]	4½	2	S	38R	60	45L	75R	55	30R
5			M	45R	55	45L	45L	55	45R
13			L	38R	60	53L	30L	60	NFC
19[5]			P	68R	60	83L	120R	55	45R
12		4	S	30R	60	30L	23L	60	68R
6			M	45R	55	30L	23L	55	30R
14			L	45R	55	53L	30L	55	45R
20			P	75R	60	68L	30L	60	75R
45[6]	0	4	L	45R	55	45L	38L	55	38R



(1) Live driver tests.
(2) S = Small car.
M = Medium car.
L = Large car.
P = Pickup truck
(3) No camera coverage
(4) No camera coverage of driver.
(5) Three wheels dropped-off pvmt.
(6) Control test.
(7) W = 12 ft for 1½ & 3½ sites
W = 18 ft for 4½ site
(8) Maximum; reduced from high speed film.
(9) R = Right or clockwise rotation of steering wheel.
(10) L = Left or counterclockwise rotation of steering wheel.
(11) 1 inch = 25.4 mm
(12) 1 mph = 0.447 m/sec.

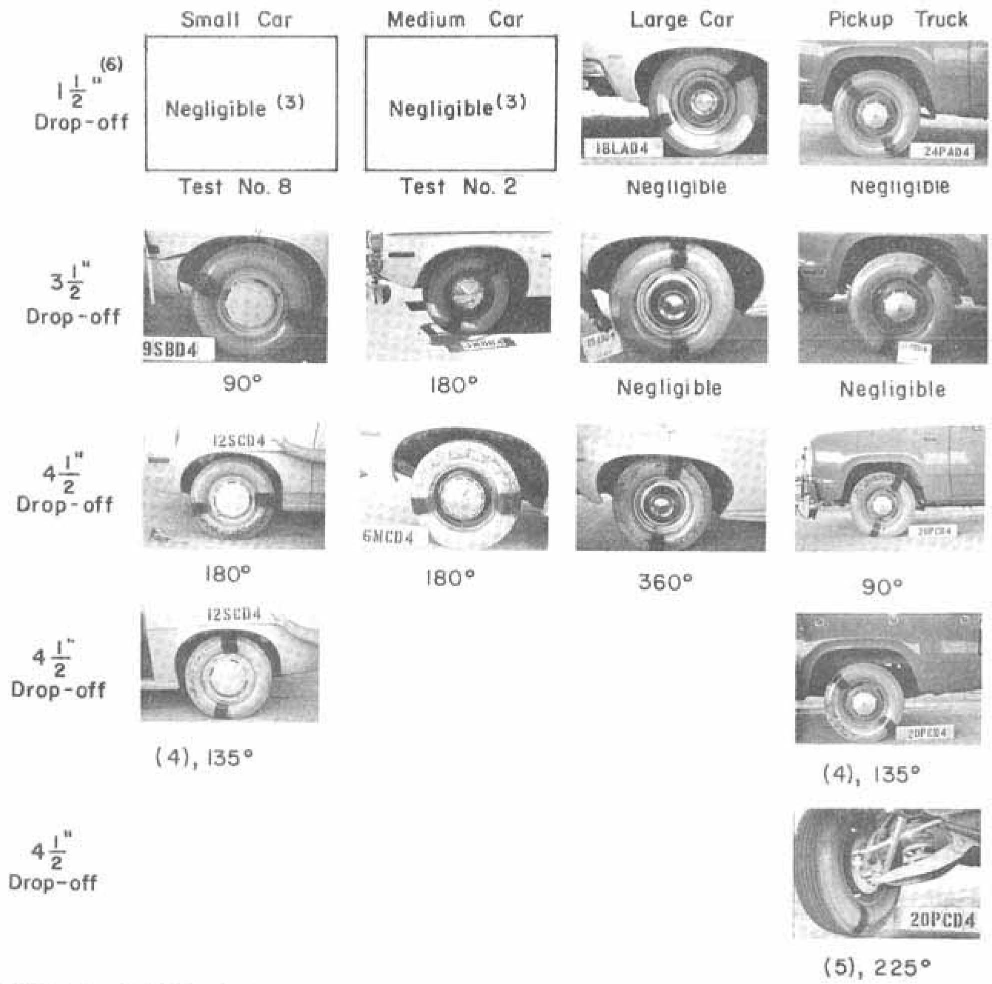
TABLE 6 STEERING DATA
ASPHALT CONCRETE TO ASPHALT CONCRETE DROP-OFF TEST SERIES(1)

TEST PARAMETERS				STEERING WHEEL ANGLES (SWA°)(6)/VEHICLE VELOCITIES					
TEST NO.	NOMINAL DROP-OFF HEIGHT in. (10)	NO. OF WHEELS DROPPING-OFF	VEHICLE SIZE (2)	SWA° OFF	VELOCITY OFF MPH (11)	CORRECTIVE SWA° OFF	SWA° ON	VELOCITY ON MPH (11)	CORRECTIVE SWA° ON
31	1 1/2	2	S	NFC(9)	60	36L(7)	23L	60	0
36			M	38R(8)	60	38L	15L	60	38R
47			L	23R	60	45L	38L	60	23R
29			P	45R	60	60L	45L	60	30R
32		4	S	30R	60	53L	38L	60	23R
37			M	38R	60	23L	23L	60	45R
46			L	30R	60	45L	45L	60	30R
28			P	45R	60	60L	45L	60	30R
33	3 1/2	4	S	38R	60	53L	38L	60	45R
38			M	38R	60	53R	15L	60	53R
44			L	38R	60	53L	45L	60	45R
27			P	68R	60	60L	53L	65	45R
30	4 1/2	2	S	30R	60	68L	38L	55	45R
35(3)			M	45R	50	120R	53L	55	75R
35			M	53R	60	38L	30L	60	68R
42			L	38R	60	60L	45L	60	45R
25			P	60R	60	83L	60L	60	60R
34		4	S	38R	55	60L	30L	60	45R
40			M	38R	60	30L	8L	60	45R
43			L	38R	60	53L	45L	60	45R
26			P	60R	60	60L	53L	60	68R
41(4)			M	30R	60	38L	38L	65	53R
39(5)	0	4	M	45R	60	8L	15L	60	38R



(1) Live driver tests
(2) S = Small car
M = Medium car
L = Large car
P = Pickup truck
(3) Trouble with Bolex camera inside car; driver was driving with one hand on steering wheel.
(4) Radial tire test.
(5) Control test on PCC.
(6) Maximum: reduced from high speed film.
(7) L = Left or counterclockwise rotation of steering wheel.
(8) R = Right or clockwise rotation of steering wheel
(9) NFC = No film coverage.
(10) 1 inch = 25.4 mm
(11) 1 mph = 0.447 m/sec

Figure 15 PHOTOS OF TIRE SCUFF MARKS (1) (2)
ASPHALT CONCRETE TO SOIL DROP—OFF TEST SERIES
4 WHEELS DROPPING-OFF SHOULDER



(1) Photos of left front tire are shown unless otherwise noted.

(2) Test identification code shown in photos
Example: 18 LAD 4
18 = Test No.
L = Large car; S = Small car; M = Medium car; P = Pickup truck
A = 1 1/2" Nominal Drop-off height; B = 3 1/2" Drop-off; C = 4 1/2" Drop-off
D = Dirt, ie. Dropping-off to Soil Surface
4 = No. of wheels Dropping-off

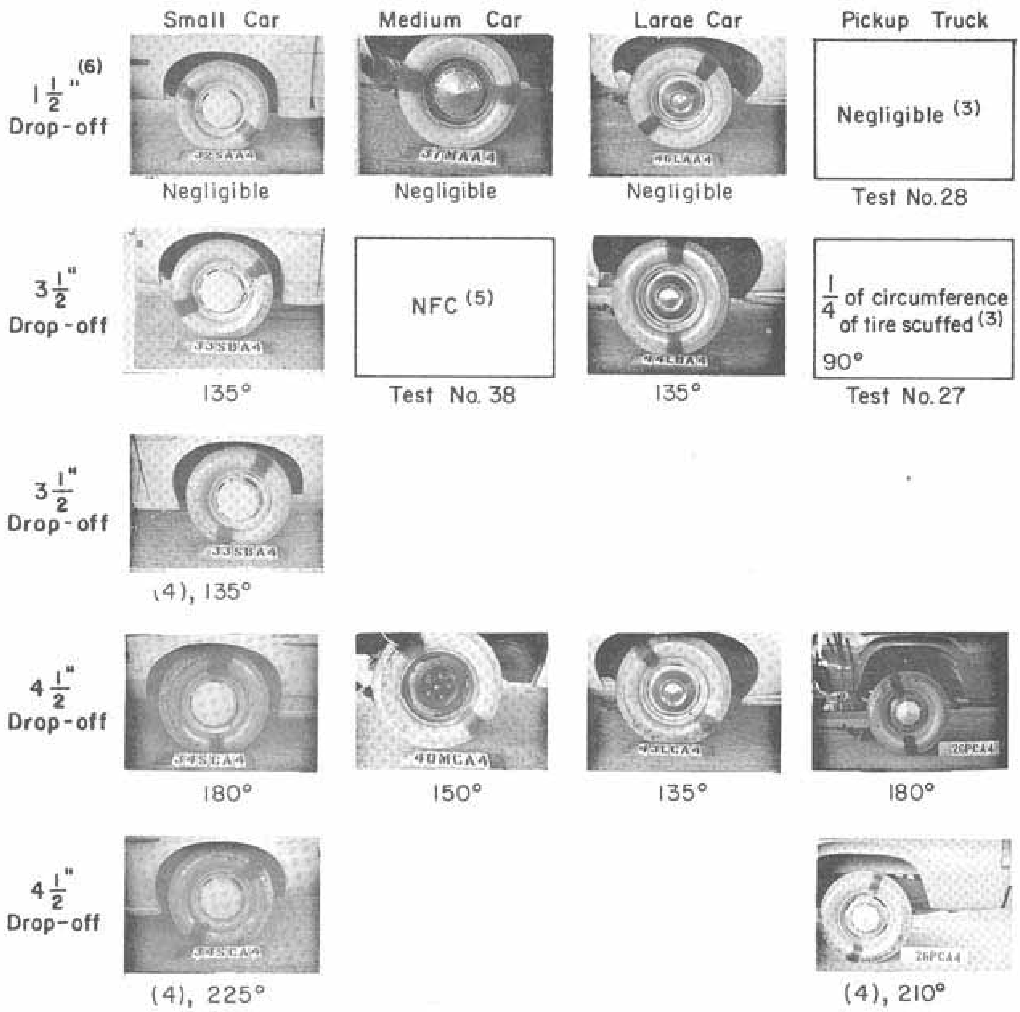
(3) As shown in high speed film

(4) Left rear tire

(5) Right front tire

(6) 1 inch = 25.4 millimeters

Figure 16 PHOTOS OF TIRE SCUFF MARKS (1) (2)
ASPHALT CONCRETE TO ASPHALT CONCRETE DROP–OFF TEST SERIES
4 WHEELS DROPPING-OFF SHOULDER



(1) Photos of left front tire are shown unless otherwise noted.

(2) Test identification code shown in photos
Example: 32SAA4
32 = Test No.
L = Large car; S = Small car; M = Medium car; P = Pickup truck
A = 1 1/2" Nominal Drop-off height; B = 3 1/2" Drop-off; C = 4 1/2" Drop-off
A = Asphalt, ie. Dropping-off to Asphalt Concrete Surface
4 = No. of wheels Dropping-off

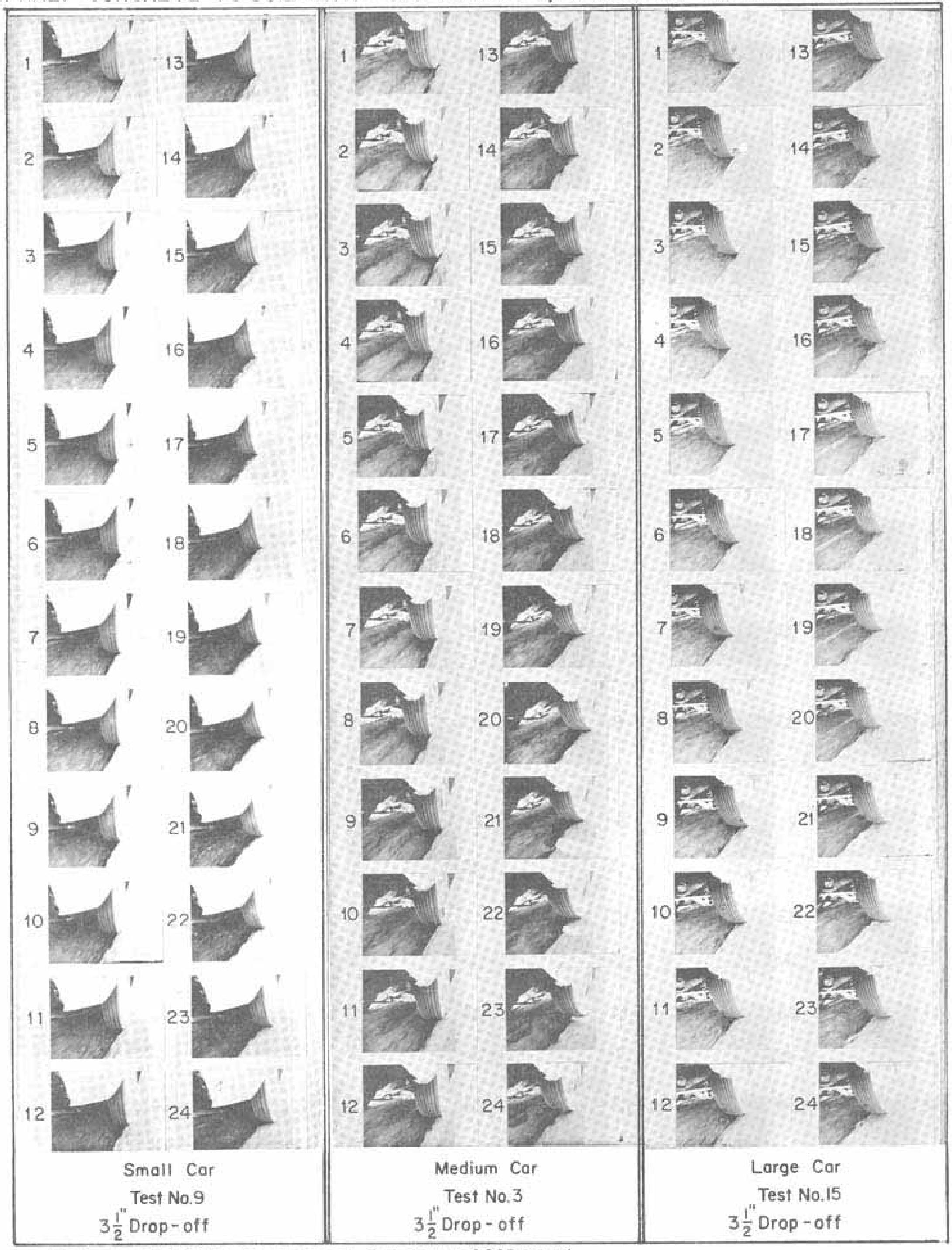
(3) As shown in high speed film

(4) Left rear tire

(5) NFC = No film coverage

(6) 1 inch = 25.4 millimeters

Figure 17 SEQUENTIAL PHOTOS[(1)(2)] OF LEFT FRONT TIRE MOUNTING DROP-OFF EDGE ASPHALT CONCRETE TO SOIL DROP-OFF SERIES[(3)]; 4 WHEELS DROPPED-OFF SHOULDER



(1) Film speed = 200 frames per second. Each frame = 0.005 second
(2) Photos progress downward on page. (3) Live driver tests

Discussion of Test Results

1. Vehicle Stability and Controllability

There will be no attempt to define vehicle stability and controllability rigorously in this report. For the purposes of this study, vehicle stability can be divided into the following two components:

- As the vehicles traveled through the prescribed course, they were stable if all their mechanical systems and parts responded in a predictable, nonerratic manner and were undamaged. This is meant to imply there was no skidding; no excessive rocking, rolling, or vibration; no deviation from the intended path of travel; and no loss of contact with the pavement.

- As the drivers steered their vehicles through the prescribed course, no heroic efforts were required. This is meant to imply that steering did not require undue physical effort, excessive or tricky steering wheel input was unnecessary, and the drivers were not unduly bounced or thrown around in their seats.

The test data presented relates to the above criteria. The first criterion is discussed in this section of this report and the second in following sections.

A good qualitative evaluation of vehicle stability and controllabilit can best be obtained by viewing the behavior of the driver and the vehicle in the test movies. The following facts were developed from observation of the actual tests, from review of the test film and from verbal reports by the test car driver:

a. Wheel Wobble - The first wheel to mount the larger drop-off heights wobbled from side to side in varying amounts as the wheel passed over the drop-off edge. Some differences in wobble are attributed to differences in:

- Steering geometry i.e., caster, camber, steering axis inclination, toe-in, and toe-out,
- Vehicle mass,
- Tire size and condition,
- Vehicle velocity,
- Lateral acceleration,
- Exit angle.

A frame by frame analysis of movie coverage from the camera attached to the front bumper of the vehicle indicated that an irregular pavement drop-off edge is a major cause of wheel wobble, Figure 18, Test No. 6. However, the irregular edge did not prevent the wheel from mounting the drop-off heights during any of the tests.

Even though wheel wobble occurred, vehicle stability was not adversely affected. Also, overall vehicle trajectory was not affected by wheel wobble. Wheel wobble was absorbed by the steering and suspension systems of each vehicle.

b. Tire Scuffing - Photographs of tire scuff marks, Figures 15 and 16, indicate how easily and quickly the first wheel of each vehicle mounted drop-off edges up to 4 1/2" (114 mm) high. Less than one full wheel revolution was required for the lead wheel to mount the drop-offs.

Only photographs for the four wheel drop-off tests are shown in Figures 15 and 16 because the inside sidewall of the tires for the two wheel drop-off tests could not be conveniently photographed without removal of the wheel. However, scuff marks are visible in the high-speed movies of the two wheel drop-off tests.

The length of the scuff marks for both the two wheel and four wheel drop-off tests were not significantly different.

In a few tests, some of the tires were completely scuffed, namely; the left rear tires for Test Nos. 11 and 19, and the left front, Figure 15, and left rear tires for Test No. 14. During Test No. 14, an irregular drop-off edge was the major factor causing the scuffing, Figure 18.

During Test Nos. 11 and 19, intended as two wheel drop-off tests, the left rear wheel also momentarily dropped-off and sideswiped the drop-off edge.

Radial tires were used on the medium size vehicle in Test No. 41. These tires had no different effect on the steering performance of the vehicle than the polyester or belted tires used in the other tests.

c. Three Wheel Off Tests - The events which came closest to causing any loss of vehicle control occurred during Tests 11 and 19 (4 1/2" (114 mm) drop-off; A.C. to soil) when there was some rear wheel sideslipping and three wheels dropped off instead of the intended two. However, the driver was able to drive the vehicles back onto the roadway surface without losing control and without any abnormal difficulty. The lower coefficient of friction for the soil drop-off surface as compared to the A.C. drop-off surface made it easier for the vehicles to slip. Vehicle roll angles for these tests, 9° and 7° respectively, were not excessive. During

Test 11, after return to the pavement surface, the driver encroached into the adjacent traffic lane to avoid hitting a traffic cone and possibly damaging the movie camera mounted on the front bumper of the vehicle. The traffic cone was positioned to mark the edge of the traffic lane and the end of the drop-off site.

d. Curved Roadway - The 1 1/2" (38 mm) test strip was constructed on a 5000 ft (1525 m) radius curve along the test site, Figure 5A. The vehicles were not affected by this gradual curve during any of the two or four wheel drop-off tests conducted at this height.

e. Power vs. Manual Steering - "In a car equipped with power steering, hydraulic power does about 80% of the work. This power not only helps to turn the wheels from a straight-ahead position, it also helps hold the wheels on the course selected by the driver regardless of whether this course is straight-ahead or turned to negotiate a curve."(8) To offset this tendency of holding a selected course, positive caster is provided on vehicles with power steering to produce good returnability.

In contrast, "a small amount of negative caster is used on cars equipped with manual steering to reduce steering effort. In addition, steering axis inclination provides all the directional stability and returnability needed on a car equipped with a manual steering gear".(8)

The medium and large size vehicles used for this test series were equipped with power steering while the small size vehicle and the pickup truck were equipped with manual steering.

Even though steering torques were not measured during this test series, there were no trends in the test results to indicate whether power steering affected vehicle stability in any of the tests.

2. Control Tests

Test Nos. 39 and 45, medium and large size vehicles, were conducted on Portland Cement Concrete (PCC) and soil surfaces respectively. There were no drop-offs at these sites.

The driving maneuvers performed during these two tests were similar to those performed during the actual drop-off tests. The results from these tests were useful when comparing the effects of drop-offs versus no drop-off for similar surface conditions on vehicle stability.

The results from the control test on PCC, Test No. 39, could only approximate those for A.C. surfaces. An A.C. pavement surface wide enough for a control test was not available.

3. Parameters Not Studied

Before establishing parameters for this test series, it became apparent that many factors could have some effect on the tests:

- Tires (type, tread depth, inflation pressure),
- Front end alignment,
- Condition of engine,
- Surface texture and condition of test sites,
- Weather.

Therefore, before any tests were conducted, all tires on each vehicle were inspected for type, tread depth, and inflation pressure; all front ends were aligned; the engine in each vehicle was tuned; and the surfaces of each test site were inspected for irregularities and swept. All tests were conducted in good weather, i.e., all test sites were dry.

It is questionable whether it is reasonable to set one or two maximum drop-off heights as a standard for all highway locations. Before limits for maximum drop-off heights can be set, parameters other than those studied for this project should be considered such as bald tires, minimum road clearances, wet or muddy soil shoulders, surfaces with loose dirt or gravel, driver inexperience, the presence of fixed objects or drainage facilities beyond the edge of the shoulder, curves, grades, night driving, smooth highway surfaces, the element of driver surprise, etc.

4. Professional Driver Comments

Comments were solicited from the unbelted professional driver after each drop-off test. The driver was instructed to:

- Ease off each drop-off height,
- To drive momentarily along the drop-off edge,
- To ease back onto the shoulder and back into his lane of travel.

Throughout his maneuvers, the driver maintained a velocity of 60 mph (26.8 m/sec).

1 1/2" (38 mm) Drop-Off - The driver did not experience any riding discomfort or difficulty steering the test vehicles for the two and four wheel drop-off tests from either A.C. to soil or A.C. to A.C. surfaces. Each of the vehicles recovered smoothly and there were no vehicle stability problems.

3 1/2" (89 mm) Drop-off - The driver did not have any difficulty steering the vehicles during the four wheel drop-off tests. There was no steering wheel jerk.

The driver was noticeably jolted and he heard front end noises while driving over this drop-off height. Each of the vehicles recovered smoothly and there were no vehicle stability problems.

4 1/2" (114 mm) Drop-off - The driver felt a significant jolt and heard front end noises during the two and four wheel A.C. to A.C. drop-off tests. During Test Nos. 11 and 19, small car and pickup truck, three wheels dropped-off. However, the sideslip motion of both vehicles was tolerable. There was no steering wheel jerk during any of these tests. The driver did not have any difficult driving back onto the roadway.

5. Nonprofessional Driver Comments

A.C. to Soil Drop-offs (1 1/2" (38 mm), 3 1/2" (89 mm) 4 1/2" (114 mm))- A Caltrans engineer drove both the medium and large size vehicles over each drop-off at about 40 mph (17.9 m/sec). He did not experience any loss of steering control and had no trouble driving back onto the roadway for these heights. Front end noise was louder for the 4 1/2" (114 mm) drop-off than either the 3 1/2" (89 mm) or 1 1/2" (38 mm) drop-offs.

He also rode as a passenger when the other nonprofessional driver, a Caltrans stenographer, drove over the same drop-off heights. He did not notice any steering wheel disturbances during her maneuvers.

The Caltrans stenographer's comments were similar to those from the engineer. She did not experience any difficulty steering either the medium or large size vehicles. She estimated her velocity at 45 mph (20.1 m/sec). She also recognized a loud front end noise during the 3 1/2" (89 mm) and 4 1/2" (114 mm) drop-off tests.

A.C. to A.C. Drop-offs (1 1/2" (38mm), 3 1/2" (89 mm), 4 1/2" (114 mm)) - Both nonprofessional drivers drove the large size vehicle over the three A.C. to A.C. drop-off heights. Each driver commented that it was easier to drive over the A.C. to A.C. drop-offs than the A.C. to soil drop-offs. Neither driver experienced any control problems. The stenographer felt that the front end noise was somewhat reduced for the A.C. to A.C. tests.

The nonprofessional driver drop-off tests were not documented on film.

6. Driver Education Programs

"Approximately 800 driver safety programs have been initiated to show drivers how to anticipate highway emergencies and how to react to them swiftly and safely"(6). Off-road recovery instruction is a part of some of these driver education programs.

At the Research Center of Liberty Mutual in Hopkinton, Massachusetts, drivers are instructed to drop two wheels off a 4" (102 mm) concrete drop-off onto a 6 ft (1.8 m) wide A.C. roadway covered with a layer of small stone to simulate a reasonably unstable shoulder condition. Training stresses maintaining contact with the roadway as much as possible.

Off-road recovery is also included in General Motors Corporation's Advanced Driver Education Program conducted at General Motors Proving Ground in Milford, Michigan. Drivers are taught to straddle a 4" (102 mm) concrete drop-off edge, to drive along the shoulder, and then use approximately 90° of steering input to properly align themselves before driving back onto the roadway surface. Upon hearing or feeling the front tire impact the drop-off edge, drivers immediately countersteer to a straight-ahead position.

These driver education programs are an indication that non-professional drivers can readily traverse drop-off heights up to 4" (102 mm) in height even when the off-pavement surface is less stable than those used in this test series.

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APPENDIX

Test Vehicle Equipment and Preparation

The speedometer cable from each test vehicle was disconnected and connected to a speedometer with a larger face, a 6" (13 mm) diameter Police Special, attached to a bracket secured to the dashboard of the vehicle. The larger speedometer was used so that the velocity of each vehicle could be monitored during the tests by movie cameras mounted inside the test vehicle. This larger speedometer was calibrated for each test vehicle prior to the drop-off tests.

A vehicle drip system delineated the path of the right rear wheel of each vehicle by leaving a trace of colored dye during the tests. A one gallon can with a stopcock was secured to the front seat of each vehicle, Figure 1A. A rubber hose attached to the drip can extended back to a position in front of the right rear wheel of each vehicle, Figure 2A.

The drip can was attached on the outside of the pickup truck in front of the right rear wheel well.

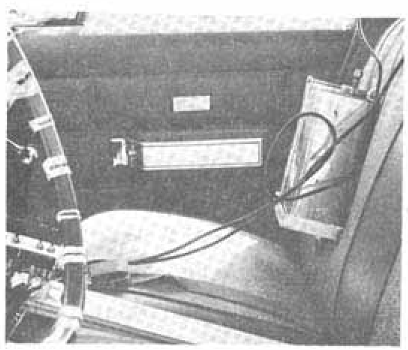


FIGURE 1A, DRIP CAN

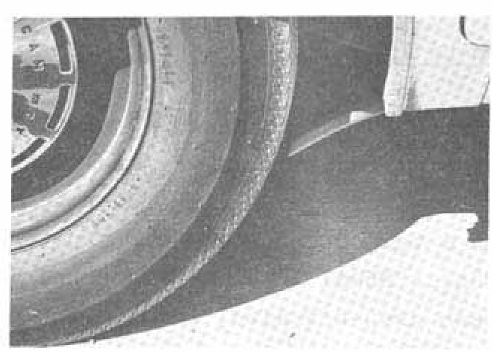


FIGURE 2A, DRIP HOSE

The perimeter of the steering wheel in each test vehicle was taped every 15°. A black vertical reference line was marked on the whit background of a sheet metal angle bracket taped to the dashboard of the vehicles. When the interior high speed Photo-Sonics 1B camera was bore sighted, the vertical reference line was adjusted to line up with the tape on the steering wheel corresponding to a zero steering wheel angle. These taped angle markings were used to measure the angles through which the steering wheel was turned during each test.

Each vehicle was tuned and aligned before being used for the drop-off tests. The alignment was checked after each test run by measuring the wheel track of the vehicles with an adjustable gage. Toe-in and toe-out alignment problems could be detected by this method. These problems are early indicators of more extensive alignment problems.

The sidewalls of the tires on the test vehicles were painted befor each drop-off test so that tire scuff marks caused by the interaction of the tire with the drop-off edge could be photographed. Vehicle tire pressure was checked before each test day, and was kept at recommended levels.

Photo Instrumentation

Data film was obtained by high speed cinematography through the u of six 16mm cameras, Figure 5A at the back of the Appendix: a Photo-Sonics Model 1B (200 fps) and a Bolex (24 fps) were mounted on a tripod and located to the side of the drop-off sites, a Phot Sonics Model 1B on a tripod was located downstream and offset fro each drop-off site; a Photo-Sonics Actionmaster 200 Model 1VN (20 fps) was mounted on the right front side of the vehicle's bumper for all tests where only two wheels dropped off the A.C. pavement edge and on the left front side of the vehicle's bumper for tests where all wheels dropped off the asphalt concrete pavement edge; a Photo-Sonics Model 1B and a Bolex camera were mounted inside the vehicle on an adjustable cross-arm attached to the back seat windows by two Super Grips, 10" (254 mm) diameter flexible rubber edge grips activated by withdrawing air with a built-in plunger to attain sufficient surface tension. The Bolex camera mounted inside the vehicle was used only for the A.C. to A.C. drop-off tests. For all drop-off tests using the pickup truck, the interior cameras were mounted in the bed of the truck, Figure 3A.

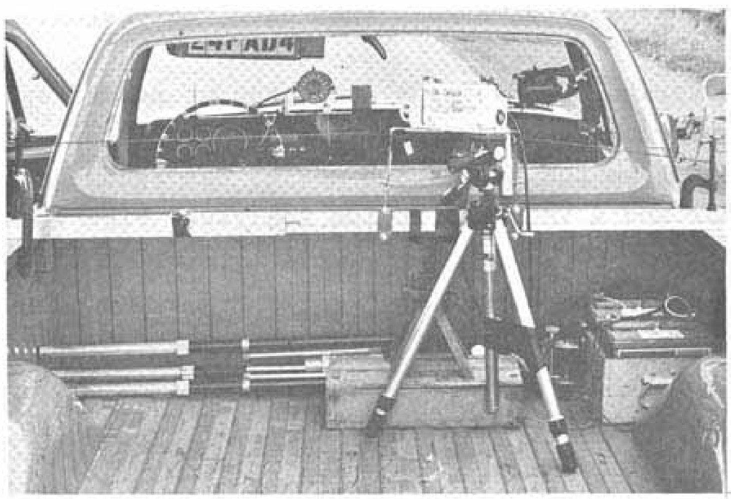


FIGURE 3A, INTERIOR CAMERAS MOUNTED IN PICKUP TRUCK

All the high speed cameras were equipped with timing light generators which exposed reddish timing pips on the film at a rate of 1000 per second. The pips were used to determine camera frame rates and to establish time-sequence relationships.

Two Mini Pro 650 watt heads provided light for the cameras mounted inside the vehicles. The rear window of each test vehicle, except the pickup truck, was covered before each test to blockout exterior light and reflection. The rear window of the pickup truck was removed to avoid photographing through glass.

Power for the three Photo-Sonics Model 1B cameras was supplied by two 12 volt batteries for each camera. The two light sources and the Photo-Sonics Actionmaster 200 Model 1VN camera were each powered by a 30-volt battery belt. The Photo-Sonics Model 1B mounted inside the vehicle and the Photo-Sonics Model 1VN along with the two interior lights were actuated by four toggle switches mounted on a board and secured to the front seat of the test vehicle. The interior Bolex camera was turned on by pulling a metal strap attached to the camera. Both the pan cameras and the downstream camera were actuated by cameramen when each test began.

Documentary coverage of the tests consisted of normal speed movies and still photographs taken before, during, and after each drop-off test. Data from the high speed movies was reduced on a 16mm movie projector and a Vanguard Motion Analyzer, Figure 4A.

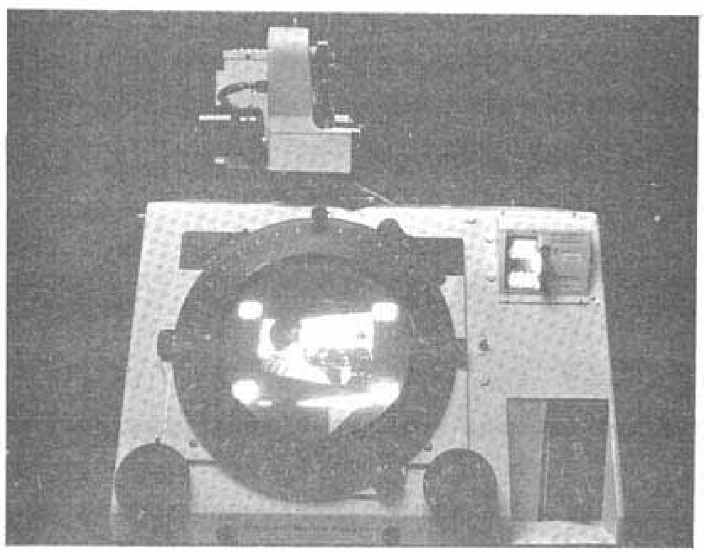


FIGURE 4A, VANGUARD MOTION ANALYZER

Procedures for instrumenting the test vehicles and the test sites to assist in the reduction of movie data are listed as follows:

1. Butterfly targets were attached to the side of the vehicles, in view of the pan cameras, to detect excessive pitching during the tests.

2. Steering wheel angles were reduced from movie data by counting tape marks attached to the steering wheel as explained previously in Test Vehicle Equipment and Preparation.

3. A test identification coding system was devised to identify each test parameter: test number, vehicle size, drop-off height, drop-off surface, and the number of wheels dropping off each drop-off height. The identification code was visible in all camera views except the wheel coverage during each drop-off test. The code appears at the beginning of each test for the wheel coverage.

4. Each test strip was stationed every 10 feet (3.1 m) with numbers painted on the A.C. shoulder pavement, and the drop-off edge was painted every other 10 ft (3.1 m) section along the entire length of each test strip.

5. The 6 inch (13 mm) diameter speedometer on the dashboard of each test vehicle was positioned to be in view of the interior high speed movie camera. The velocity of the test vehicle was monitored during each drop-off test.

6. Vehicle roll angles were measured from the roadway surface to the top edge of the front windshield, delineated by black tape.

TABLE 1A DROP-OFF HEIGHT FIELD MEASUREMENTS in.

	ASPHALT CONCRETE TO SOIL DROP-OFFS			ASPHALT CONCRETE TO ASPHALT CONCRETE DROP-OFFS		
STATION(1)	1 1/2 (2)	3 1/2	4 1/2	1 1/2	3 1/2	4 1/2
0+00	1 (3)	3 1/2	4 1/2	1 1/2	2 1/2	4
+10	1 1/2	4 1/4	4 1/2	1 1/2	3 1/2	4
+20	1 1/2	3 1/4	4	1 1/4	3 1/4	3 1/2
+30	2	3 1/2	4	2	3 1/4	4 1/4
+40	2	2 3/4	4 1/4	1 3/4	2 1/2	4
+50	2 1/2	3 3/4	4 1/4	1 3/4	3	4
+60	2 1/2	4	4 1/2	2	3 1/2	4
+70	2 1/2	4	4 1/4	1 1/4	3 3/4	3
+80	1 3/4	3 3/4	4 1/4	1 1/4	3 3/4	3 1/4
+90	1 1/2	4 1/4	4	1 1/4	3 1/2	3 1/2
1+00	1	4	4 1/2	1 1/4	3 1/4	3 3/4
+10	1 1/2	3 1/2	4	1	3 1/4	3 3/4
+20	1 1/2	4	4	1	3 1/4	4
+30	1 1/2	3 1/2	4 1/4	1	3	3 3/4
+40	1 3/4	4	4 1/2	1 1/4	3	3 1/2
+50	2	3 3/4	4 3/4	1 1/4	3	3 1/2
+60	1 3/4	3 3/4	4 1/4	1 1/2	3 1/4	3 1/4
+70	2 1/4	4	4	1 1/2	3 1/2	3 1/4
+80	1 1/2	3 3/4	4	1 1/2	3 1/4	3 1/4
+90	1 3/4	4	4 1/2	1 1/2	4	3 3/4
2+00	1 3/4	4 1/2	4 1/4	1 3/4	4 1/4	4 1/4
+10	1 3/4	4 3/4	4 1/2	1 1/2	4	4 1/4
+20	1 1/2	4 1/2	4 1/2	1 1/4	3 3/4	4 1/4
+30	1 3/4	4 3/4	4 1/2	1 1/4	4	4 1/4
+40	1 3/4	4 1/2	4 1/2	1 1/2	3 3/4	4 3/4
+50	1 1/4	3 1/2	4 1/2	1 1/2	3 1/2	4 3/4
+60	1 1/4	3 3/4	4 1/4	1 1/2	3 1/4	4 1/2
+70	1 1/4	4	4	1 1/2	3 1/2	4
+80	1 1/2	4	4 1/2	1 1/2	4	3 3/4
+90	1 1/2	4	4 1/2	1	3 3/4	4 1/2
3+00	1 3/4	4 1/2	4 1/4	1 1/4	3 3/4	4 1/2
+10	1 3/4	4	4 1/4	1 1/4	3 3/4	4 1/4
+20	1 1/2	4	4 1/4	1 1/4	4	4
+30	1 1/4	4	4 1/2	1	4	3 3/4
+40	1 1/4	3 3/4	4	1	3 1/2	3 3/4
+50	1 1/4	3 1/2	4	1	3 3/4	4
+60	1 1/4	3 1/2	4	1	3 3/4	4
+70	1 1/2	3 3/4	4 1/4	1	3 1/2	4 1/2
+80	1 1/2	3 1/2	4 1/4	1 1/2	3 1/2	4 1/2
+90	1 1/4	3 1/2	4 1/2	1	3 1/2	4 1/4
4+00	1 1/4	3 1/2	4 1/4	1	3 1/2	4 1/4
+10	1 1/4	3 1/2	4 1/2	1	3	4
+20	2	3 1/2	4 1/2	2 1/2	3	4
+30	1 1/4	3 1/4	4 1/2	2 1/2	3 1/2	4
+40	1 1/4	3 1/2	4 1/2	2	4	4
+50	2 1/2	2 3/4	4 1/2	2	2 1/2	4 1/4
+60	1 3/4		4 1/2	1 1/2		4
+70	1 1/2		4 1/2	1		4
+80	1 1/2		4 1/4	1		4
+90			4 1/2			4 1/4
5+00			4			3

(1) EACH TEST SITE WAS STATIONED INDEPENDENTLY.
(2) NOMINAL DROP-OFF HEIGHT.
(3) 1 INCH = 25.4 MILLIMETERS.

TABLE 2A VEHICLE SPECIFICATIONS

SIZE	SMALL CAR	MEDIUM CAR	LARGE CAR	PICKUP TRUCK
YEAR	1971	1971	1970	1973
MAKE	FORD	AMC	CHEVROLET	DODGE
MODEL	PINTO	MATADOR 4D SEDAN	BROOKWOOD STATION WAGON	D100 $\frac{1}{2}$ TON
WEIGHT(1) LBS(2)	2520	3840	4780	4076
TRANSMISSION & NO. OF FORWARD SPEEDS	AUTO. 3	AUTO. 3	AUTO. 3	AUTO. 3
ENGINE DISPL. IN^{3}(3)	122	304	350	318
SHOCK ABSORBERS	TELESCOPING	TELESCOPING	TELESCOPING	TELESCOPING
SUSPENSION	BALL JOINT	BALL JOINT	BALL JOINT	BALL JOINT
POWER STEERING	NO	YES	YES	NO
STEERING RATIO(5)	22.1	19.4	19.3	30.0
BRAKE TYPE / POWER	DRUM / NO	DRUM / NO	DRUM / YES	DISC-FRONT & DRUM-REAR / YES
AIR CONDITIONER	NO	NO	YES	YES
TIRE SIZE	B78X13	E78X14	H78X15	G78X15
TIRE TYPE	B.F. GOODRICH CUSTOM LONG MILER 4 PLY POLY	B.F. GOODRICH SILVERTOWN HT 4 PLY POLY	B.F. GOODRICH SILVERTOWN HT 4 PLY POLY	GOODYEAR CUSTOM BELTED 2 + 2
AVE. TREAD DEPTH IN.	RF $\frac{10}{32}$ LF $\frac{10}{32}$ RR $\frac{10}{32}$ LR $\frac{10}{32}$	RF $\frac{8}{32}$ LF $\frac{5}{32}$ RR $\frac{11}{32}$ LR $\frac{10}{32}$	RF $\frac{12}{32}$ LF $\frac{12}{32}$ RR $\frac{10}{32}$ LR $\frac{7}{32}$	RF $\frac{10}{32}$ LF $\frac{10}{32}$ RR $\frac{9}{32}$ LR $\frac{8}{32}$
RECOMMENDED TIRE PRESSURE PSI(4)	32	32	32	32
WHEELBASE IN.	90	118	119	118
FRONT TREAD IN.	54	60	63.5	66
REAR TREAD IN.	55	60	63.5	64
MILEAGE MI.	40,430	48,217	68,353	8,515
MINIMUM GROUND CLEARANCE IN.	5.8	7.0	8.0	8.0

(1) Weight includes 200 lb driver and 220 lbs of instrumentation.

(2) 1 lbm = 2.205 kg

(3) 1 inch = 25.4 millimeters

(4) 1 psi = 6.89 N/m^2

(5) Overall

TABLE 3A PAVEMENT SURFACE SKID RESISTANCE MEASUREMENTS

SURFACE	LOCATION (1)(2)		% GRADE	COEFFICIENT OF FRICTION (5)			ASTM SKID NO.
	STATION FT.	POSITION		MEASURED	CORRECTED (4)	AVERAGE	
PCC	C8	OWT (3)	-2	0.46	0.40		
	C200		-1	0.48	0.43		
	C400		-.5	0.47	0.44	0.42	49.3
	B45		-.5	0.42	0.39		
	B212		-.5	0.48	0.45		
Existing A.C. Shldr.	C28	Edge of drop-off	-2	0.52	0.45		
	C205		-1	0.44	0.40		
	C203		-1	0.40	0.36		
	C415		-1	0.43	0.39		
	B15		-1	0.51	0.45	0.44	51.0
	B192		-.5	0.51	0.47		
	A25		-.5	0.50	0.47		
	A200		-.5	0.50	0.47		
	A443		-.5	0.52	0.49		
New AC	A393	Middle of surface	+1	0.42	0.41		
	A165		+1	0.40	0.39	0.39	46.9
	B265		+1	0.38	0.37		
	C335		+1	0.40	0.39		

(1) A = $1\frac{1}{2}''$ Drop-off site

B = $3\frac{1}{2}''$ Drop-off site

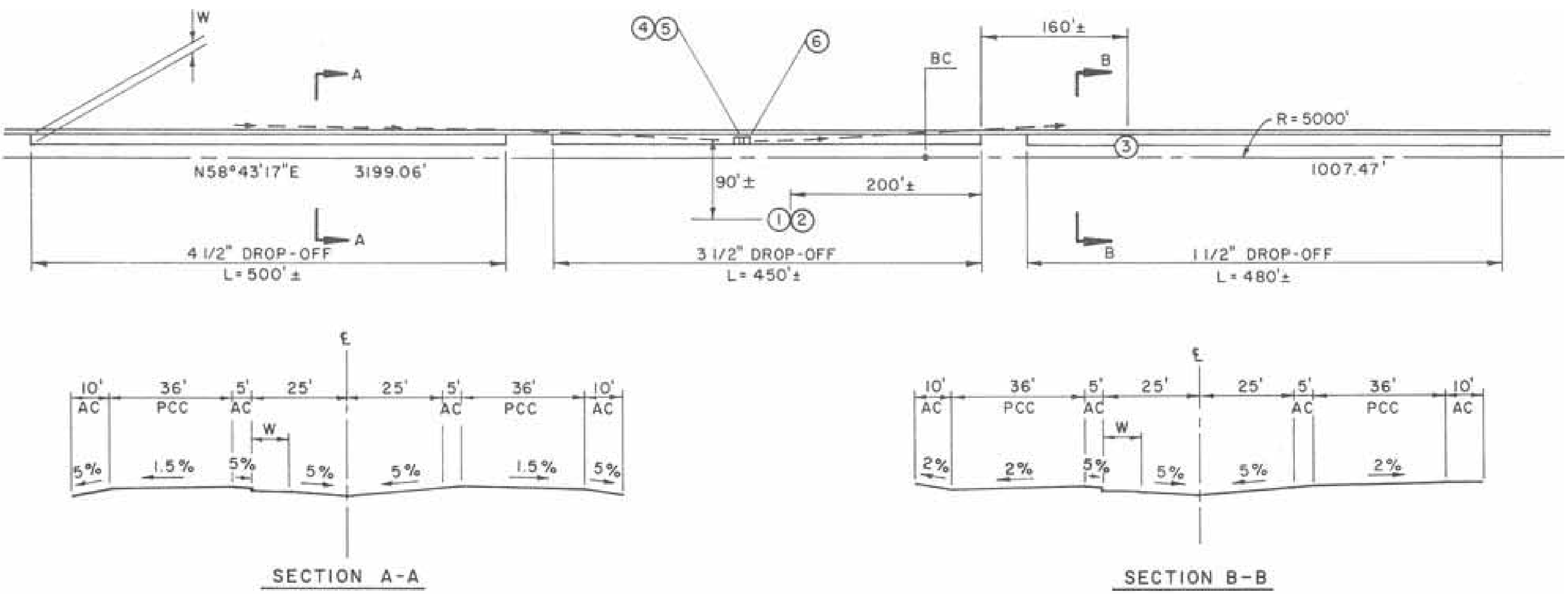
C = $4\frac{1}{2}''$ Drop-off site

(2) 1 ft. = 0.305 meters

(3) OWT = Outside wheel track

(4) Corrected for grade and calibration of test machine.

(5) Measured with the California Portable Skid Tester.



TEST SITE WIDTHS

TEST SERIES	AC TO SOIL			AC TO AC		
DROP-OFF HGT in.	1 1/2	3 1/2	4 1/2	1 1/2	3 1/2	4 1/2
W ft.	12	12	18	10	10	10

CAMERA DATA

① PHOTO-SONICS, 2" (50.8 mm) LENS, 200 FPS *
② BOLEX, 1" (25.4 mm) LENS, 24 FPS
③ PHOTO-SONICS, 4" (101.6 mm) LENS, 200 FPS
④ PHOTO-SONICS, 13 mm WIDE ANGLE LENS, 200 FPS
⑤ BOLEX, 16 mm, 24 FPS [USED ONLY FOR AC TO AC TESTS]
⑥ PHOTO-SONICS 1VN, 5.9 mm WIDE ANGLE LENS, 200 FPS

* FRAMES PER SECOND

TEST SITE & TYPICAL CAMERA LAYOUT **

FIGURE 5A

** 1 FOOT = 0.305 METERS
1 INCH = 25.4 MILLIMETERS