

REFERENCES

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Effect of Longitudinal Edge of Paved Surface Drop-Offs on Vehicle Stability

Roger L. Stoughton, Douglas M. Parks, J. Robert Stoker, and Eric F. Nordlin,
Division of Construction, California Department of Transportation

The effect of edge of pavement drop-offs on vehicle stability is reported for 50 tests of professional drivers handling small-, medium-, and large-sized automobiles and pickup trucks off, along, and back onto drop-off heights of 38 mm (1.5 in), 89 mm (3.5 in), and 114 mm (4.5 in) at about 26.8 m/s (60 mph). Tests of two- and four-wheel drop-offs were conducted from an existing 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° or less; vehicle roll angles were 10° or less. A significant jolt and accompanying front-end noise were experienced by the driver 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 the vehicles did not encroach into adjacent traffic lanes. Two nonprofessional drivers participated in a few supplementary tests. They had no difficulties driving over all three drop-off heights at 17.9-20.1 m/s (40-45 mph). The results of these tests were used to help evaluate the California maintenance standards in effect in 1974.

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

This project was initiated

1. To determine the effects of longitudinal drop-offs along a highway and on the stability and controllability of vehicles traveling over the drop-offs at high speeds,
2. To establish maximum tolerable heights for drop-offs,
3. To verify current maintenance standards for allowable drop-off heights.

No attempt was made to study the surprise element in driver reactions to an unexpected drop-off condition.

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

1. Surfaces of a paved shoulder and the unpaved area alongside it,
2. Surfaces of a paved traveled way and an unpaved shoulder,
3. Surfaces of a paved traveled way and a paved shoulder, or
4. 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 during construction, 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 114 mm (4.5 in) used for this project, and sometimes approach several meters, 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 the full width of the traveled way or traveled way and shoulder at one time. There is often a delay before all of the existing pavement can be brought up to the grade of the new pavement blanket.

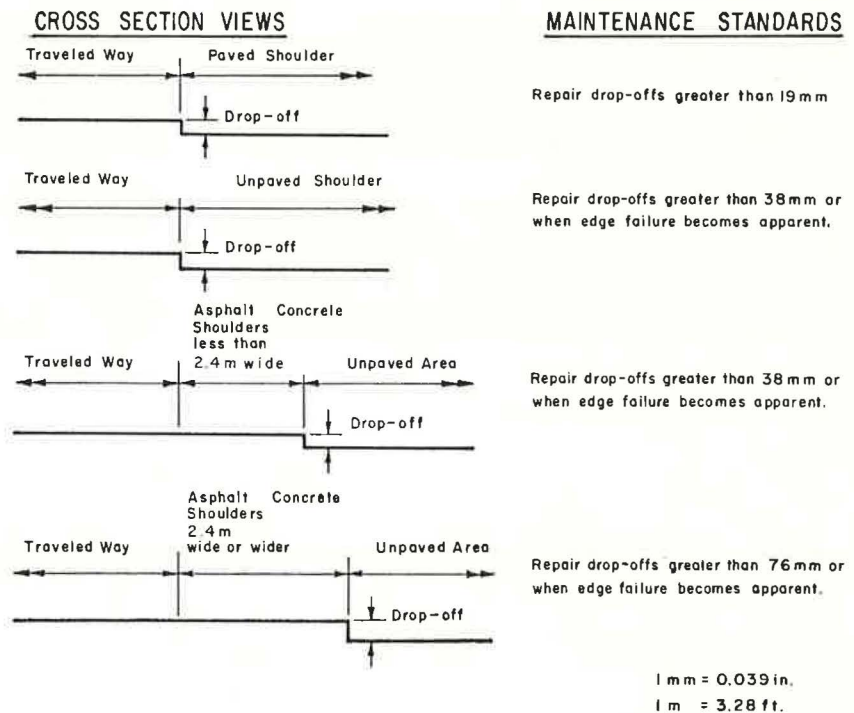
Portions of the California Department of Transportation maintenance manual dated May 15, 1974, specified California's drop-off standards and are illustrated in Figure 1.

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. New York permitted drop-off heights ranging from 25 mm (1 in) maximum for expressways with volumes over 500 vehicles/h to 51 mm (2 in) maximum for state highways having one-way design volumes of less than 200 vehicles/h. The other states either had no published standards, required shoulders to be flush with the traveled way, or allowed maximum drop-offs of 51-76 mm (2-3 in). Only Oregon had accident records related to drop-off conditions. The records from Oregon combined all accidents due to chuckholes and drop-offs.

A Highway Research Information Service (HRIS) literature search was made prior to the initiation of this project. Before 1974, none of the research reported had been conducted to determine whether longitudinal drop-offs cause vehicle stability problems.

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

Figure 1. 1974 maintenance standards in California.



Fifty tests, using professional drivers, were conducted to investigate the following basic parameters:

1. Drop-off heights of 38 mm (1.5 in), 89 mm (3.5 in), and 114 mm (4.5 in);
2. Four different vehicles—a small-, medium-, and large-sized automobile and a pickup truck;
3. Vehicles driven by a professional driver from an existing asphalt-concrete (AC) shoulder onto either an AC or a soil surface and returned to the AC shoulder at velocities of 26.8 m/s (60 mph) and angles less than 10°; and
4. Tests with either two wheels of the vehicle or four wheels of the vehicle dropping off an existing AC shoulder.

The driver, a former race-car driver, is a private consultant who conducts vehicular impact tests and other automotive research.

TEST SITE LOCATION AND CONSTRUCTION

The test site was located on an unopened portion of I-80 between Del Paso Park Separation and Overhead and Longview Drive Overcrossing in Sacramento County near Sacramento, California (Figure 2).

Drop-off heights of 114 mm (4.5 in), 89 mm (3.5 in), and 38 mm (1.5 in) were constructed along the edge of an existing 1.5-m (5-ft) wide AC shoulder adjacent to a 15.3-m (50-ft) wide unpaved median. Each drop-off height was maintained for a 153-m (500-ft) length with short spaces between the three 153-m test strips. Field measurements of drop-off heights were taken at 3.1-m (10-ft) intervals. Each 153-m strip was used for both series of tests, asphalt-to-soil and AC-to-AC. After the AC-to-soil tests were completed, an additional 25-51 mm (1-2 in) layer of soil was removed from each strip and replaced by a layer of AC so that the AC-to-AC drop-off tests could be conducted (Figure 3). Originally it was planned that a 140-mm (5.5-in) drop-off height be used. However,

Figure 2. Test site.



Figure 3. AC-to-AC test site.



due to the 147-mm (5.8-in) minimum ground clearance on the small automobile we decided that 114 mm was the maximum height that could be used without the automobile 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 percent, or nearly level.

Two control tests were conducted at sites where there were no drop-offs. Test 39, with a medium-sized vehicle, was performed entirely on the existing portland cement concrete (PCC) pavement adjacent to the drop-off test sites. Test 45, with a large-sized vehicle, was conducted entirely on soil on the other side of the

median adjacent to the 38-mm drop-off site.

The tests were conducted from September to October 1974. The test strips were dry and the weather was good for all tests. Figure 4 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. The vehicle specifications are included in Table 1. Each vehicle was tuned and aligned before

Figure 4. Test site and typical camera layout.

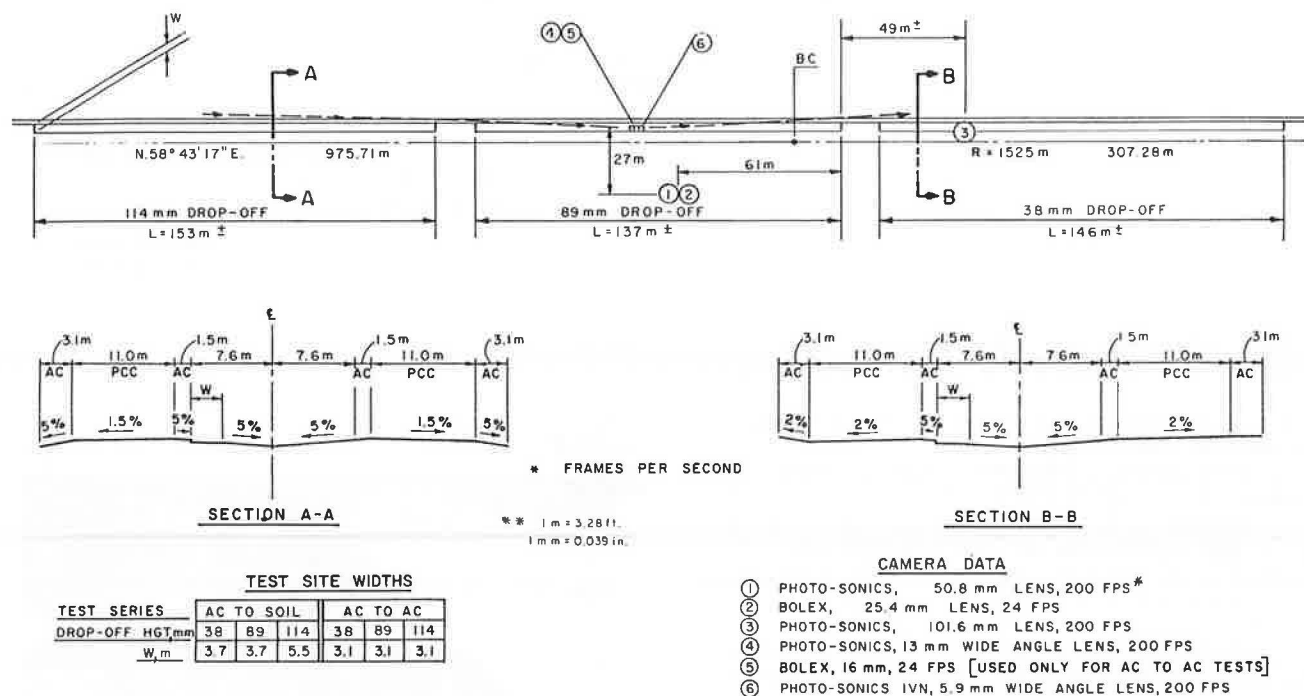


Table 1. Vehicle specifications.

Feature	Automobile				Pickup Truck
	Small	Medium	Large		
Year	1971	1971	1970		1973
Make	Ford	American Motors	Chevrolet		Dodge
Model	Pinto	Matador 4-door sedan	Brookwood station wagon		D100 454 kg
Mass* (kg)	1144	1743	2170		1851
Transmission and no. of forward speeds	Automatic 3	Automatic 3	Automatic 3		Automatic 3
Engine displacement (cm ³)	2000	4980	5740		5210
Shock absorbers	Telescoping	Telescoping	Telescoping		Telescoping
Suspension	Ball joint	Ball joint	Ball joint		Ball joint
Power steering	No	Yes	Yes		No
Steering ratio ^b	22.1	19.4	19.3		30.0
Brake type/power	Drum/no	Drum/no	Drum/yes		Disc, front and 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 polyester	B. F. Goodrich Silvertown HT 4 ply polyester	B. F. Goodrich Silvertown HT 4 ply polyester		Goodyear custom belted 2+2
Average tread depth (mm)	RF 8, LF 8 RR 8, LR 8	RF 6, LF 4 RR 9, LR 8	RF 10, LF 10 RR 8, LR 6		RF 8, LF 8 RR 7, LR 6
Recommended tire pressure (kPa)	221	221	221		221
Wheelbase (m)	2.29	3.00	3.02		3.00
Front tread (m)	1.37	1.53	1.61		1.68
Rear tread (m)	1.40	1.53	1.61		1.63
Distance (km)	65 092	77 629	110 048		13 713
Minimum ground clearance (mm)	147	178	203		203

Note: 1 mm = 0.039 in; 1 m = 3.28 ft; 1 km = 0.62 mile; 1 cm³ = 0.06 in³; 1 kg = 2.21 lb; 1 kPa = 0.145 lbf/in².

*Mass includes 91 kg for the driver and 100 kg of instrumentation.

^bOverall.

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 gauge. 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 before each drop-off test so that tire scuff marks caused by the interaction of the tire with the drop-off edge could be photographed. Tire pressure was checked before each test day and was kept at recommended levels. 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.

Figure 5. Vehicle interior showing taped steering wheel and large speedometer.

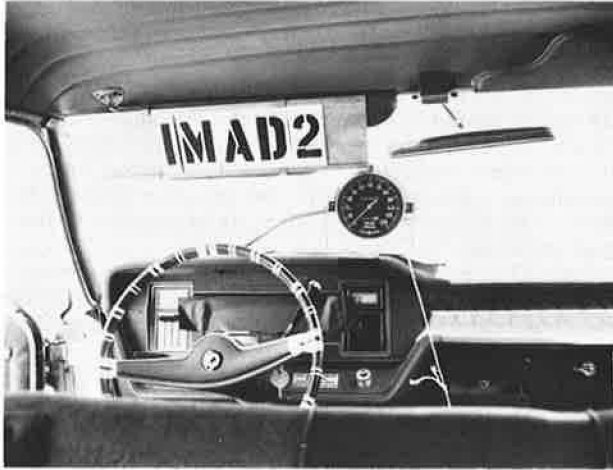


Figure 6. Large-sized vehicle.



Table 2. Trajectory measurements—AC-to-soil drop-off test series.

Nominal Drop-Off Height (mm)	No. of Wheels Dropping Off	Test No.	Vehicle Size ^a	Vehicle Trajectory					Exposure Distance (m)
				Entrance Angle (degrees)	Max. Arc Distance (m)	Station (m)	Exit Angle (degrees)	Exit Station (m)	
38	2	7	S	3.2	1.1	58	3.4	93	82
		1	M	3.4	0.9	31	1.1	95	100
		17	L	2.3	1.0	55	2.9	91	80
		23	P	2.0	1.4	55	2.4	99	85
	4	8	S	4.0	2.2	67	5.2	113	90
		2	M	4.0	2.6	70	4.0	133	130
		18	L	2.6	3.1	61	3.1	120	110
		24	P	4.3	3.1	61	3.1	131	131
	2	10 ^b	S	4.6	1.0	37	5.7	69	58
		10 ^c	S	4.6	0.7	46	4.9	70	59
		10	S	3.1	0.8	37	3.7	69	52
		4	M	4.9	1.1	58	4.3	90	66
		16	L	4.6	1.1	37	2.9	78	74
		22	P	4.6	1.2	46	4.3	99	85
		9	S	3.7	2.4	55	4.6	102	85
		3	M	4.0	2.7	46	4.0	107	88
		15	L	2.3	2.0	64	2.3	102	92
		21	P	5.4	3.1	58	2.9	102	88
114	2	11 ^d	S	4.7	1.4	37	7.8	56	56
		5	M	5.2	0.5	88	4.6	104	87
		13	L	4.0	1.2	4.0	2.9	110	102
		19 ^d	P	4.6	1.7	37	4.2	70	60
	4	12	S	4.6	2.8	67	4.0	120	103
		6	M	3.5	2.6	43	1.4	96	89
		14	L	4.0	2.9	49	2.9	120	107
		20	P	4.6	3.2	58	4.0	120	110
	4	45 ^e	L	6.8	2.6	64	1.4	118	94

Note: 1 mm = 0.039 in; 1 m = 3.28 ft.

^aS = small automobile; M = medium automobile; L = large automobile; P = pickup truck.

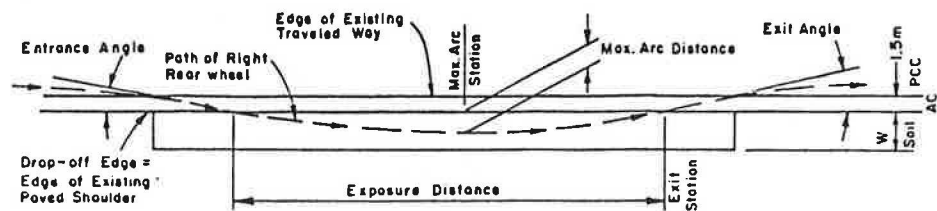
^bNo camera coverage.

^cNo camera coverage of driver.

^dThree wheels dropped off.

^eControl test.

Figure 7. Trajectory measurements—AC-to-soil drop-off test series.



Note: 1 m = 3.28 ft; 1 mm = 0.039 in; W = 3.7 m for 38-mm and 89-mm sites; and W = 5.5 m for 114-mm site.

The perimeter of the steering wheel in each test vehicle was taped every 15°. A black vertical reference line was marked on the white background of a sheet-metal angle bracket taped to the dashboard of the vehicles. When the interior 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. An interior view of the automobile is shown in Figure 5.

A typical view of a test vehicle straddling a drop-off edge is shown in Figure 6. Entrance angles (Table 2, Figure 7) were purposely small to simulate a driver drifting off the edge of the traveled way. Curb jump tests (1-3) showed that vehicles easily traverse curbs

152 mm (6 in) high and greater when impacting at high speeds and larger angles.

Four high-speed movie cameras and a normal-speed movie camera were used to document each drop-off test. The camera positions are shown in Figure 4. Cameras 1 and 2 were mounted on the ground and panned the action. Camera 3 was mounted on the ground downstream of the test and viewed the action parallel to the drop-off edge. Camera 4 was mounted inside the vehicle to view the driver, the rotation of the steering wheel, and a large speedometer mounted on the dash (Figure 5). Camera 6 was mounted on the front bumper of each vehicle to view the action of the vehicle's right-front or left-front wheel as the wheel dropped off and then mounted the drop-off edge (Figure 8). 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. Camera 5, mounted inside the vehicle, viewed the driver and steering wheel rotation for the AC-to-AC drop-off tests in addition to the other cameras.

Over 3350 m (11 000 ft) of movie film was exposed during the tests. Selected tests have been incorporated in a 30-min silent film report, which summarizes the test series.

TEST RESULTS

Test parameters, trajectory measurements, maximum vehicle roll angles, maximum steering wheel angles, and vehicle velocities are tabulated for the AC-to-soil drop-off tests in Tables 2, 3, and 4 and Figures 9 and 10. Data for the AC-to-AC drop-off tests were similar and are not included in this paper, but are included elsewhere (4).

Steering wheel angle (SWA) (Table 4) 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) (5).

Figure 8. Bumper-mounted camera.

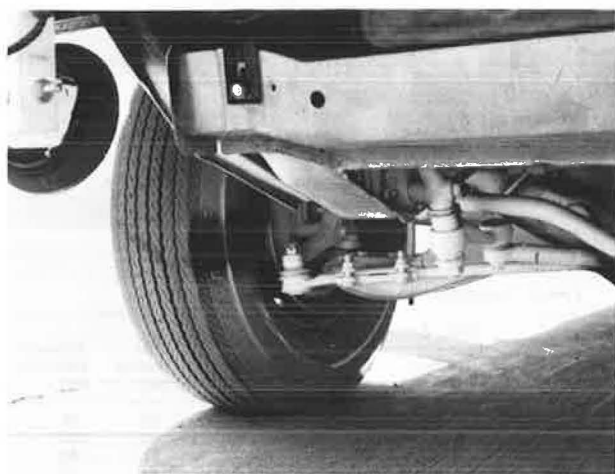


Table 3. Vehicle roll angles—AC-to-soil drop-off test series.

Nominal Drop-Off Height (mm)	No. of Wheels Dropping Off	Test No.	Vehicle Size ^a	Vehicle Roll Angles (degrees)		
				Going Off Drop Off	Coming Back on Existing Paved Shoulder	After All Wheels on Traveled Way
38	2	7	S	5	4	0
		1	M	3	3	0
		17	L	3	2	-1
		23	P	4	4	0
	4	8	S	5	6	- ^b
		2	M	3	3	-1
		18	L	3	3	-2
		24	P	4	4	0
89	2	10 ^c	S	6	9	0
		10 ^d	S	7	7	-1
		10	S	7	8	-1
		4	M	7	7	-2
		16	L	6	6	-2
		22	P	5	6	-1
	4	9	S	7	9	0
		3	M	5	7	-1
		15	L	6	8	-3
		21	P	5	6	-1
	2	11 ^e	S	9	9	-2
		5	M	8	7	-2
		13	L	7	7	-1
		19 ^f	P	7	7	-3
	4	12	S	7	6	0
		6	M	7	7	0
		14	L	7	7	0
		20	P	5	6	-1
0	4	45 ^g	L	0	0	0

Note: 1 mm = 0.039 in.

^aS = small automobile; M = medium automobile; L = large automobile; P = pickup truck.

^bNo film coverage.

^cNo camera coverage.

^dNo camera coverage of driver.

^eThree wheels dropped off.

^fControl test.

Table 4. Steering data—AC-to-soil drop-off test series.

Nominal Drop-Off Height (mm)	No. of Wheels Dropping Off	Test No.	Vehicle Size ^b	SWA ^a /Vehicle Velocities					
				SWA Off ^c (degrees)	Velocity Off (m/s)	Corrective SWA Off ^d (degrees)	SWA On (degrees)	Velocity On (m/s)	Corrective SWA On (degrees)
38	2	7	S	No film coverage					
		1	M	30R	26.8	60L	15L	26.8	8R
		17	L	23R	26.8	53L	38L	26.8	0
	4	23	P	30R	26.8	45L	38L	26.8	23R
		8	S	15R	29.1	30L	30L	29.1	23R
		2	M	38R	26.8	38L	30L	26.8	15R
		18	L	38R	26.8	53L	45L	26.8	23R
		24	P	45R	26.8	53L	38L	26.8	23R
	2	10 ^e	S	No film coverage					
		10 ^f	S	30R	24.6	30L	23L	24.6	45R
		10	S	30R	26.8	30L	15L	26.8	45R
		4	M	38R	26.8	38L	30L	26.8	45R
		16	L	30R	24.6	45L	30L	24.6	45R
		22	P	60R	26.8	53L	45L	29.1	53R
		9	S	30R	26.8	30L	30L	26.8	45R
		3	M	30R	24.6	60L	60L	22.4	45R
		15	L	45R	29.1	60L	83L	26.8	60R
		21	P	75R	26.8	75L	68L	26.8	75R
114	2	11 ^g	S	38R	26.8	45L	75R	24.6	30R
		5	M	45R	24.6	45L	45L	24.6	45R
		13	L	38R	26.8	53L	30L	26.8	45R
		19 ^h	P	68R	26.8	83L	120R	24.6	45R
	4	12	S	30R	26.8	30L	23L	26.8	68R
		6	M	45R	24.6	30L	23L	24.6	30R
		14	L	45R	24.6	53L	30L	24.6	45R
		20	P	75R	26.8	68L	30L	26.8	75R
	4	45 ⁱ	L	45R	24.6	45L	38L	24.6	38R

Note: 1 mm = 0.039 in; 1 m/s = 2.24 mph.

^aMaximum degrees, reduced from high-speed film.

^bS = small automobile; M = medium automobile; L = large automobile; P = pickup truck.

^cR = clockwise rotation of steering wheel.

^dL = counterclockwise rotation of steering wheel.

^eNo camera coverage.

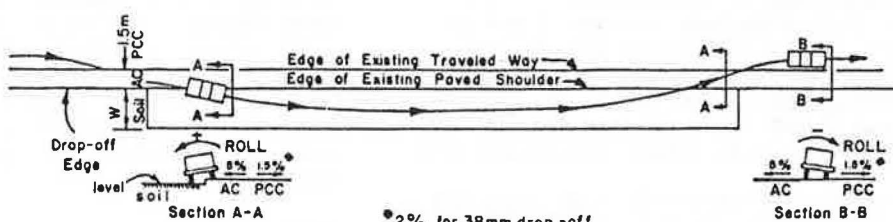
^fNo camera coverage of driver.

^gThree wheels dropped off pavement.

^hControl test.

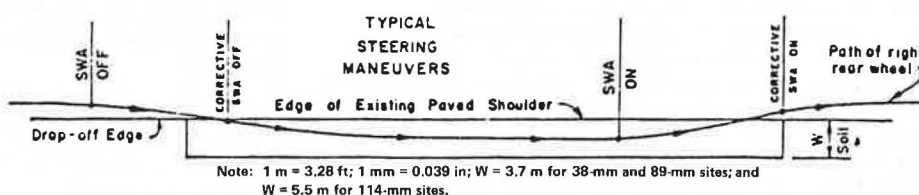
ⁱNo film coverage.

Figure 9. Vehicle roll angles—AC-to-soil drop-off test series.



Note: 1 m = 3.28 ft; 1 mm = 0.039 in; W = 3.7 m for 38-mm sites; and W = 5.5 m for 114-mm site.

Figure 10. Steering data—AC-to-soil drop-off test series.



Note: 1 m = 3.28 ft; 1 mm = 0.039 in; W = 3.7 m for 38-mm and 89-mm sites; and W = 5.5 m for 114-mm sites.

Coefficients of friction for the existing PCC traveled way, the existing AC shoulder, and the AC surface used for the AC-to-AC drop-off tests were measured along the three drop-off test strips with the 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 AC shoulder, and 0.39 for the AC surfaces used for the AC-to-AC test. These correspond to American Society for Testing and Materials (ASTM) skid numbers of 49, 51, and 47, respectively.

CONCLUSIONS

This paper does not attempt to define vehicle stability and controllability rigorously. For the purposes of this study, they were described as follows:

1. Stability—All of the mechanical systems and

parts of the vehicle responded in a predictable, non-erratic manner and were undamaged. This is meant to imply that 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.

2. Controllability—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 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:

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, which included control with

the thumb and forefinger only of both hands in some tests. At no time did the driver lose 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, which is far from an impending rollover condition. 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 89 mm (3.5 in) and 114 mm (4.5 in). The driver did not experience any noticeable disturbances during the 38-mm (1.5-in) 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. Results were similar for two-wheel and four-wheel tests.

6. Wheel wobble—Varying amounts of front-wheel wobble occurred as the first vehicle wheel mounted the 89-mm and 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 tests documented on film for this project, two nonprofessional drivers stated they also did not experience any steering difficulties or stability problems while driving the three drop-off heights at about 17.9–20.1 m/s (40–45 mph). No data were taken from these tests, which were not part of the work plan.

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

9. Three-wheel off tests—The events which came closest to causing any loss of vehicle control occurred during tests 11 and 19 (114-mm drop-off, AC 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 vehicle 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 AC drop-off surface made it easier for the vehicles to slip. Loose material on a shoulder should be considered a shoulder problem, not a drop-off problem. Vehicle roll angles for these tests (9° and 7° , respectively) were not excessive.

10. Curved roadway—The 38-mm (1.5-in) drop-off test strip was constructed on a 1525-m (5000-ft) radius curve to the left along the test site (Figure 3). The vehicles were not affected by this gradual curve during any of the two- or four-wheel drop-off tests conducted at this height.

11. Power steering—The medium- and large-sized vehicles used for this test series were equipped with power steering, and the small-sized 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 that power steering affected vehicle stability in any of the tests.

12. Recent tests—Three tests involved a professional driver in a pickup truck traveling 26.8 m/s (60 mph). They were conducted in March 1978, to investigate vehicle stability and controllability while traversing a crumbling edge, 51-mm (2-in) high drop-off (nominal) on an AC shoulder next to a muddy shoulder. One test was a control test with no drop-off encountered; in the other two tests the two right wheels of the truck traversed the drop-off. It was concluded that there were no changes in the conclusions from the original series of 50 drop-off tests (6).

13. Summary statement—For the test conditions studied, the edge of pavement drop-offs per se did not throw the vehicles out of control or into an unstable condition or require any unusual control methods by the driver to get the automobile off and on the drop-off.

MAINTENANCE STANDARDS

Before setting overall drop-off standards or standards for specific sites, consideration should 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. Hence, the test results alone were insufficient to establish a maximum tolerable drop-off height for all conditions.

Based on the test conditions for this project, the 1974 California Department of Transportation maintenance standards concerning drop-offs were considered to be quite reasonable and conservative. Since 1974 the approach to maintaining the lateral support at the edge of pavement and shoulder maintenance has been changed somewhat in California, and no specific maximum allowable drop-off heights are included in the maintenance standards.

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