PAVEMENT EDGES AND VEHICLE STABILITY - A BASIS FOR MAINTENANCE GUIDELINES

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A Technical Paper for Presentation
at the 61st Annual Meeting of the
Transportation Research Board
Washington, D. C.

January 1983

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ABSTRACT

The repair of pavement edge geometry adjacent to unpaved shoulders is a maintenance activity that requires continuous effort on the part of all state and local agencies. Although it is generally accepted that these roadway discontinuities have some effect of vehicle stability and thus on facility safety, these effects have never been comprehensively quantified. Using research conducted previously by CALTRANS and Systems Technology, Inc., and adding a testing program to supplement and extend the earlier work, a comprehensive treatment of this problem has been developed and is presented here. Recommendations are made for the use of this information to establish maintenance guidelines.

Appropriate use by highway engineers of the information contained here can, in time, make a major impact in reducing accidents influenced by pavement edges. This can be accomplished by reducing unnecessary maintenance and concentrating available maintenance funds on areas having real safety significance.

INTRODUCTION

The repair of unpaved shoulders adjacent to pavement edges as well as the repair of deteriorated pavement edges is a maintenance activity that requires continuous effort on the part of all state and local highway agencies. Although it is generally accepted that pavement edges of excessive height have an effect of vehicle stability and thus on facility safety, this effect has never been comprehensively quantified. As an example of the importance of this factor, it makes a tremendous difference in the maintenance effort required to keep all unpaved shoulders within one inch of the paved surface at the pavement edge as compared to that effort required in keeping the surfaces matching to within two inches.

The research described here, the analysis of available literature and the testing program, allows a realistic evaluation of the influence of pavement edges on automotive safety and further defines the influence of certain critical driver and vehicle factors so the urgency of maintenance can be accurately assessed.

Pavement edges can represent a significant problem to vehicle control, especially since the problem may be worsened and even made critical in some cases by inappropriate forms of caution on the part of drivers. In this most critical situation, the phenomenon can be described by the following hypothetical event.

1. A vehicle is under control in a traffic lane adjacent to a pavement edge where the unpaved shoulder is lower than the pavement elevation.
2. Through inattention, distraction or any other reason, the vehicle is allowed to move or steered into a position with the

right side wheels just off the paved surface. The right side wheels are now to the right of the pavement edge on a surface elevation below that of the main lane.

3. The driver then carefully tries to steer gently back onto the paved surface without <u>reducing speed significantly</u>.
4. The right front wheel encounters the pavement edge preventing it from moving onto the pavement. The driver further increases the steer angle to make the vehicle regain the pavement. The vehicle still does not respond. At this time, there is equilibrium between the cornering forces to the left acting on both front tires and the pavement edge force, acting to the right as shown in Figure 1(a).
5. The critical steer angle is added by the driver, and the right front wheel mounts the paved surface. Suddenly, in less than one wheel revolution, the edge force has disappeared, and the right front cornering force may have doubled due to increases in the available friction on the pavement and the increases in right front wheel load due to cornering. Figure 1(b).
6. The vehicle yaws radically to the left, pivoting about the right rear tire, until that wheel can be dragged up onto the paved surface. The excessive left turn and yaw continues, too rapid in its development for the driver to prevent penetrating the oncoming traffic lane. Figure 1(c).
7. A collision with oncoming vehicles or spin out and vehicle roll may then occur.

Although this phenomenon does occur on highway facilities, in many cases

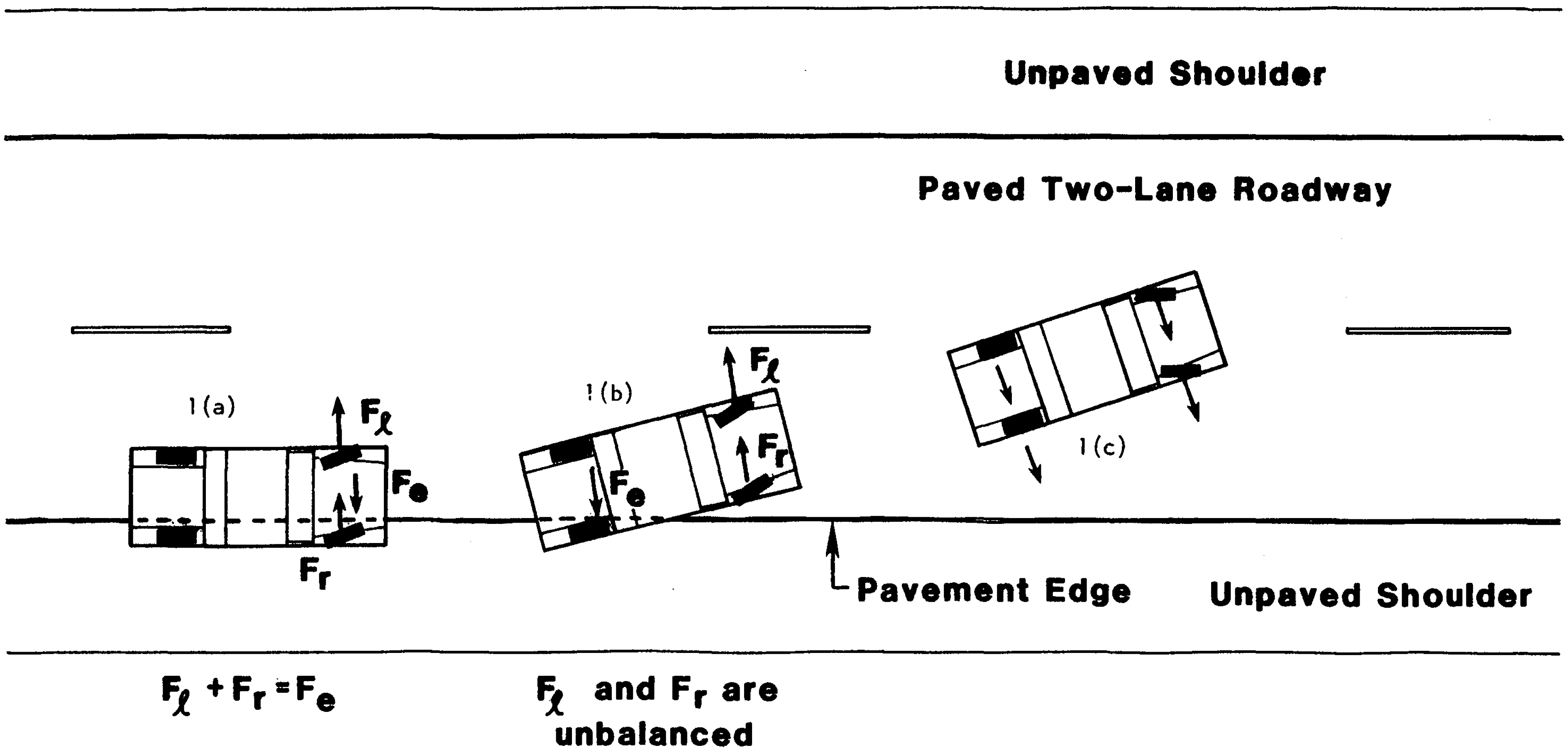


Figure 1. LOSS OF CONTROL PHENOMENON

the same result, vehicle loss of control, may occur without the influence of a pavement edge. A loose or muddy shoulder can have the same effect if the driver oversteers when trying to regain the paved surface. Often it is the oversteering that is the cause when a pavement edge of modest height is blamed.

LITERATURE SURVEY

The qualitative effect of pavement edges, or so-called "lip drop-off" has been to some degree understood for many years. In the Traffic Accident Investigator's Manual (1), published by Northwestern and originally compiled by J. Stannard Baker, the following statement is found: *"Lip drop-off is simply a low shoulder at the edge of a hard pavement. It is important when the shoulder is more than three inches below the pavement . . ."* Based on a telephone conversation with Mr. Baker on September 22, 1982, it was determined that this conclusion was reached by informal testing at Northwestern as early as 1959.

Ivey and Griffin (2) dealt with surface discontinuities including pavement edges in a paper published in 1975. Based on 15,968 accidents in the North Carolina accident file, there was an overrepresentation of the key words associated with a shoulder or pavement edge drop (i.e., dropped, soft, curb, and edge). A Delphi study included in this report ranked pavement edge-shoulder drop-off among the top accident related pavement disturbances.

A series of tests reported by Nordlin (3) in the mid-1970's included a range of automobile sizes and edge conditions, from 1.5 to 4.5 inches of drop. Nordlin concluded there was not significant safety hazard in mounting edges up to 4½ inches. This work did not include testing of the scrubbing situation where the offside tire scuffs along the pavement edge prior to receiving the steering input necessary to mount the edge. This scrubbing action is the most critical situation. In further testing at CALTRANS, Stoughton (4) observed the effect of a broken asphaltic concrete pavement edge and muddy shoulder on vehicle stability. The tests included small, medium and large passenger cars and pickup truck driven at speeds up to 60 mph. Again, pavement edge drops of 1½, 3½ and 4½ inches were tested. The primary conclusion Stoughton reached is:

"The pavement drop-offs had little effect on vehicle stability and controllability in all tests." Again the scrubbing situation was not tested.

Klein, et al, (5) produced a report in 1976 which included analyses of accident data, public inquiries through questionnaires and a variety of both open-loop and closed-loop tests. In closed-loop tests, naive drivers were used. Special efforts were made to achieve the edge scrubbing condition. In edge drop tests up to four inches in height, losses of control were encountered at the higher speed levels, generally more than 30 mph. With a well-controlled series of both open- and closed-loop tests, Klein made a major contribution in defining a control difficulty parameter, T_{r_c}, and relating it to a critical speed for each test vehicle. He found a value of about 0.6 seconds for T_{r_c} accurately represented the *"limiting situation for not exceeding the lane boundary after a 4½ inch edge climb."* Referring to Klein's representation (Figure 2), at . . . *"speeds above about 32 mph for the Pinto and the wagon, and above about 44 mph for the Nova, result in values of control difficulty that exceed 0.6 seconds. These same speeds were found to be the critical speed for the lane boundary not being exceeded during the closed-loop test with a 4½ inch drop off."*

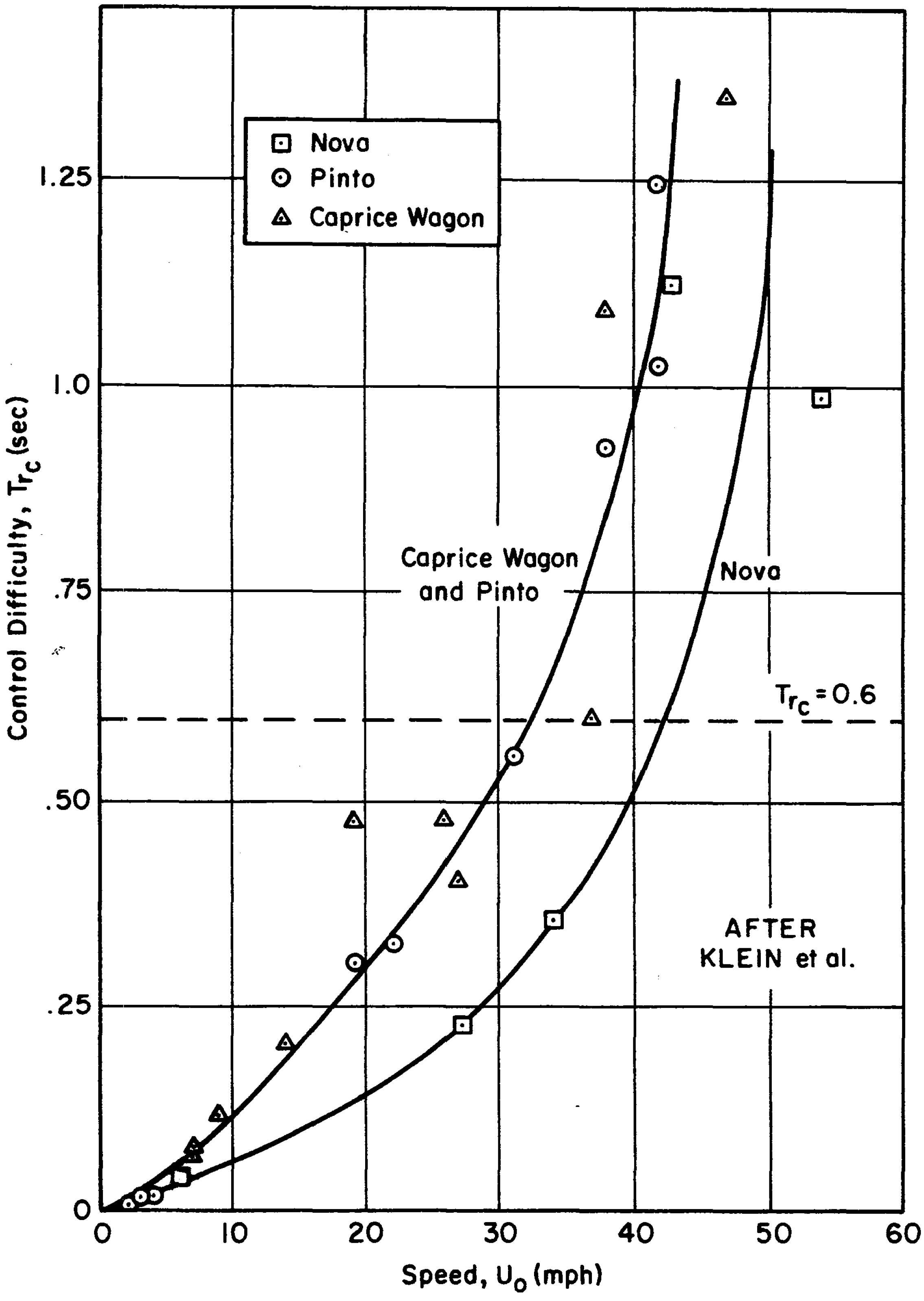

Nova
Pinto
Caprice Wagon
Caprice Wagon and Pinto
Nova
$T_{r_c} = 0.6$
AFTER KLEIN et al.
Control Difficulty, T_{r_c} (sec)
1.25
1.0
.75
.50
.25
0
0
10
20
30
40
50
60
Speed, U_o (mph)

Figure 2

DEFINITION OF T_{r_c} (Control Difficulty Parameter):

$$T_{r_c} = \frac{M\,U_0}{2\,Y_{local}}$$

where: m = vehicle mass

U_0 = forward speed

Y_{local} = local slope of cornering stiffness curve (i.e. the slope of the cornering force vs. slip angle curve at the point the tire mounts the pavement edge)

Fascinatingly, at least to the writers, Klein also found the time between edge mounting of the front and rear tires to be less than 0.6 seconds. It appears 0.6 is the universal constant in pavement edge maneuvers. Another important discovery made by Klein is represented by Figures 3 and 4 showing respectively the relationships between steering wheel angle and steer angle required to climb various edge heights from the scrubbing condition. These curves have the potential for use in describing the maneuver safety, in that the initial relatively linear range (Figure 3 - from 0 to 3 inches, Figure 4 - from 0 to 3 inches) describes a reasonably safe range. As the curves become curvilinear, the maneuver becomes significantly more difficult. As the curves start a precipitous rise, again approaching a straight line, the difficulty becomes extreme.

Klein has presented by far the most analytically appealing and experimentally comprehensive work done on this subject. The main limitation is that he tested only one, albeit the most critical, pavement edge geometric condition, that of an extreme 90° angle with little edge rounding. The scope limitations of the two principal studies, the non-inclusion of the edge scrubbing condition by Nordlin and the study of only

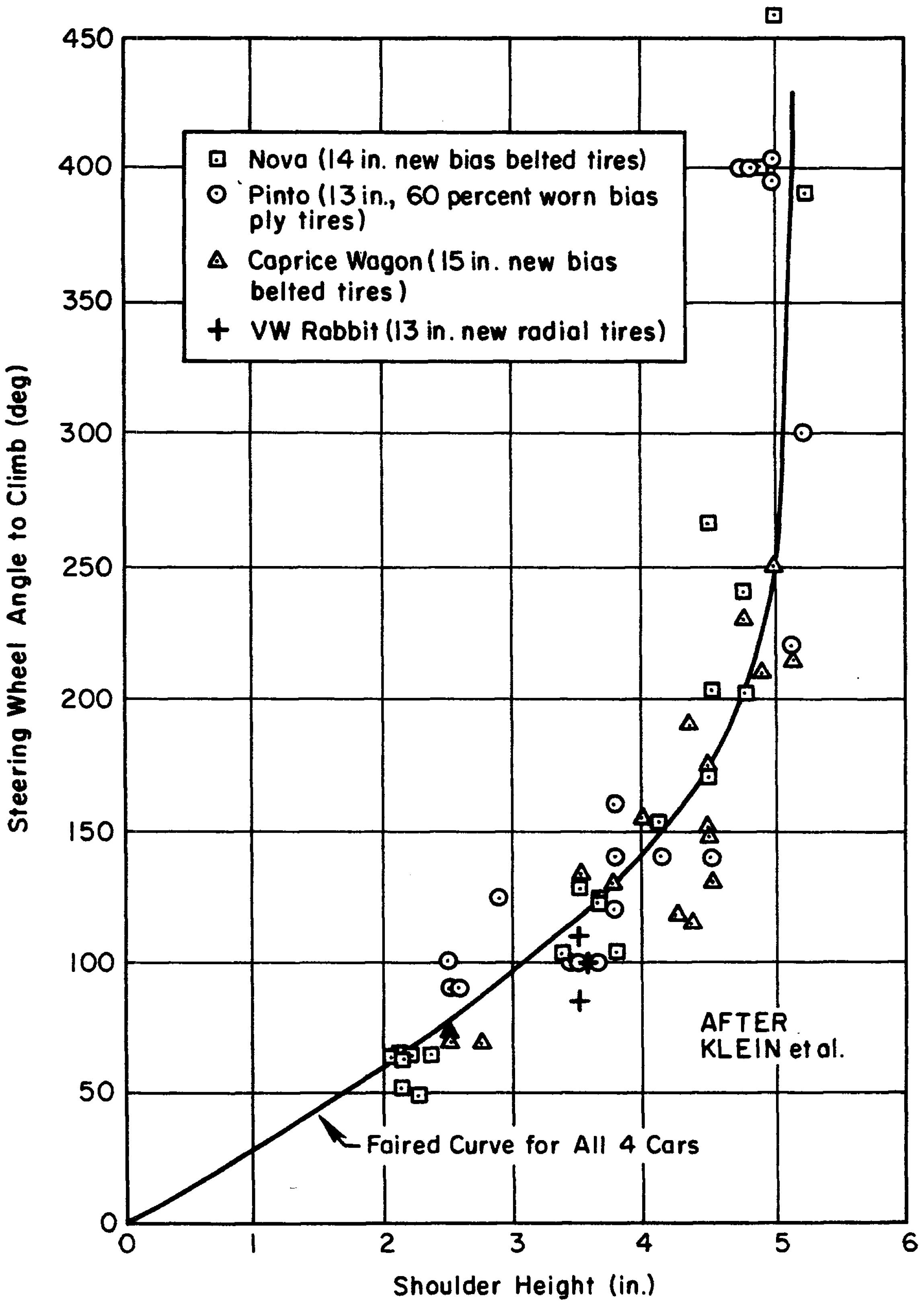
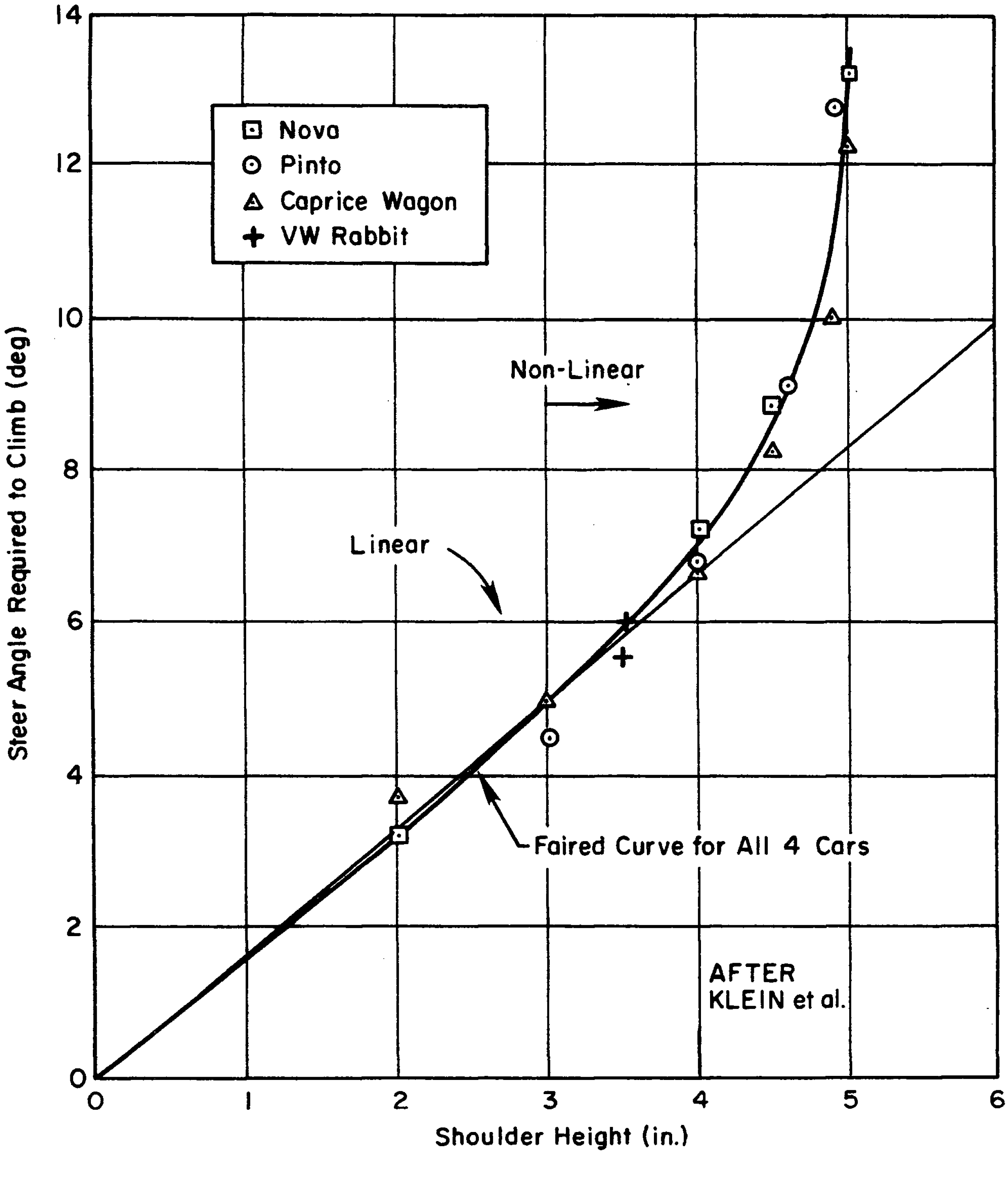

Nova (14 in. new bias belted tires)
Pinto (13 in., 60 percent worn bias ply tires)
Caprice Wagon (15 in. new bias belted tires)
VW Rabbit (13 in. new radial tires)
Steering Wheel Angle to Climb (deg)
Shoulder Height (in.)
AFTER KLEIN et al.
Faired Curve for All 4 Cars
450
400
350
300
250
200
150
100
50
0
0
1
2
3
4
5
6

Figure 3



Nova
Pinto
Caprice Wagon
VW Rabbit
Non-Linear
Linear
Faired Curve for All 4 Cars
AFTER
KLEIN et al.
Steer Angle Required to Climb (deg)
Shoulder Height (in.)
0
2
4
6
8
10
12
14
0
1
2
3
4
5
6

Figure 4

one pavement edge geometry by Klein, is why the present work is necessary. The current testing work plan was designed to compliment the earlier studies.

TEST PROGRAM

A comprehensive Test Program was developed to evaluate the effects of edge conditions based on a variety of drop off heights, vehicles, tires, drivers, speeds, and positions. The conditions chosen do not represent every conceivable condition involving an edge condition. This would produce a very large and unwieldy test matrix. The variables for this initial full scale testing program were chosen as representative of those typically found on the highways today, which would extend the information already developed by Nordlin (3) and Klein (5).

EDGE HEIGHT AND SHAPE

In order to obtain a sufficient number of data points without allowing the test matrix to become too massive, three shoulder to pavement heights were chosen. They were 1½ inch, 3 inch, and 4½ inch with a construction tolerance of ±¼ inch measured at intervals of 10 feet.

To evaluate these heights a 500 foot test course was constructed at the TTI Proving Grounds adjacent to an existing concrete runway. To produce a soil shoulder, the vegetation and top soil were first removed from the runway edge approximately 20 feet wide. Next a sandy loam was added, graded for drainage, and finally rolled. With the soil at the level of the existing concrete, a 1½ inch pad of asphalt, 12 feet wide and 500 feet long, was applied to the concrete, producing an asphalt-soil interface with a 1½ inch height.

The edge was left unmodified, as it was installed, to provide a typical edge condition or shape, with approximately a 1½ inch radius edge. The nominal shape of this edge is shown in Figure 5(a) with slight vari-

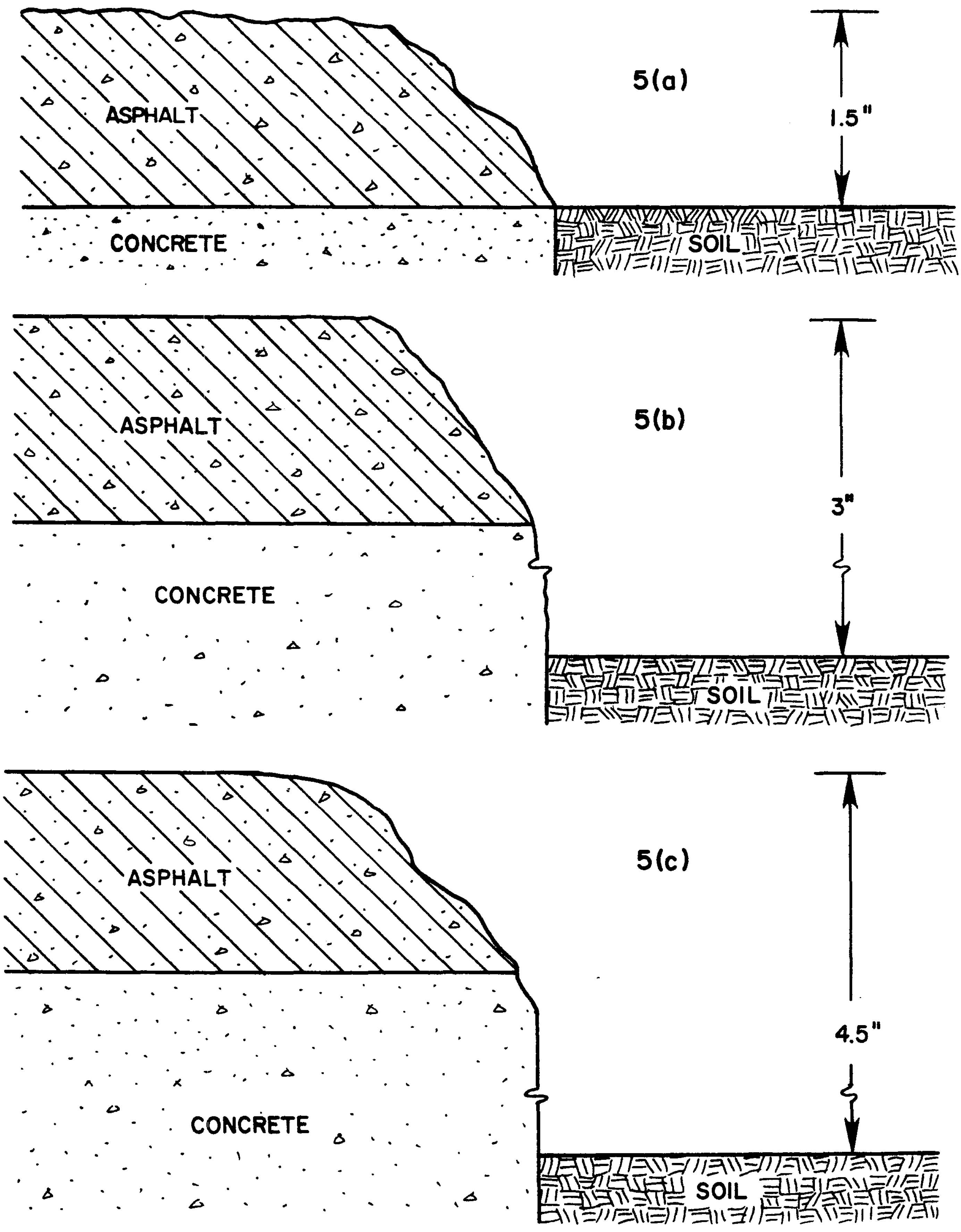


Figure 5. EDGE PROFILES

ations occurring over the length of the test course.

Upon completion of the 1½ inch test runs the soil was cut down 1½ inches and regraded producing a 3 inch edge height condition with the same asphalt shape as the 1½ inch condition, and a vertical face 1½ inch below that, as shown in Figure 5(b). The 4½ inch condition was produced in the same manner, by removing 1½ inches of soil and regrading as shown in Figure 5(c). To gain some insite into edge shape, at the 4½ inch condition the first half of the course was modified (Figure 6) to produce a sharper edge with approximately a 0.75 inch radius. By using an epoxy base paving material, with aggregate similar to the asphalt pavement, the required edge was finally produced by grinding to the desired contour and texture. The unmodified test course is shown in Figure 7 in the 4½ inch condition with the mini-compact test vehicle.

VEHICLES

Passenger automobiles and a pickup truck were tested. To evaluate the effect of weight, suspension system and wheel size, a mini-compact, intermediate and a full size automobile were tested along with a standard size pickup. These vehicles, described in Table 1, provide an adequate range of weights, varying from 1668 lbs to 4713 lbs, with wheel sizes from 12 to 15 inches. Before testing, each vehicle was set up to manufacturers specifications with respect to the suspension and steering system, and periodically inspected during the course of the testing. Each vehicle was equipped with a roll bar and racing lap and shoulder belts to provide an added margin of safety for the test drivers.

TIRES

To determine the effect of tire construction, the intermediate and

SIZE		MINI COMPACT		INTERMEDIATE		FULL SIZE		PICKUP TRUCK	
YEAR		1977		1974		1977		1976	
MAKE		HONDA		CHEVROLET		PLYMOUTH		FORD	
MODEL		CIVIC		NOVA		GRAND FURY		F150 CUSTOM	
MASS(a)	FRONT	L 519	R 514	859	883	L 1347	R 1323	1259	1289
	REAR	L 306	R 329	773	731	1019	1024	872	889
	TOTAL	1668		3246		4713		4309	
ENGINE DISPL.		75.5 CID		250 CI		440 CI		390 CID	
SHOCK ABSORBERS		TELESCOPING		TELESCOPING		TELESCOPING		TELESCOPING	
SUSPENSION		STRUT		BALL JOINTS		BALL JOINTS		KING PINS	
POWER STEERING		NO		NO		YES		YES	
STEERING RATIO		18.2:1		36:1		21.2:1		21.8:1	
BRAKE TYPE/POWER		FT DISC REAR DRUM/NO		DRUM/NO		FT DISC REAR DRUM/YES		FT DISC REAR DRUM/YES	
AIR CONDITIONER		NO		NO		YES		YES	
TIRE SIZE AND TYPE		P155/80R12		P195/75R14		PZ25/75R15		L78-15	
		GOODYEAR TIEMPO		GOODYEAR POLY STEEL		GOODYEAR VIVA		GOODYEAR POLYGLAS	
AVE. TREAD DEPTH		LF 9/32	RF 9/32	LF 11/32	RF 11/32	LF 10/32	RF 10/32	LF 11/32	RF 11/32
		LR 9/32	RR 9/32	LR 11/32	RR 11/32	LR 10/32	RR 10/32	LR 11/32	RR 11/32
RECOMMENDED TIRE PRESSURE		FRONT	24	FRONT	24	FRONT	30	FRONT	30
		REAR	24	REAR	24	REAR	30	REAR	36
WHEELBASE		86.5"		111.25		122		132.75	
FRONT TRACK		51.5"		59.25		63.875"		65	
REAR TRACK		50.75"		59.5		63.625"		64.5	
MILEAGE		70122		07077		78651		65270	
MINIMUM GROUND CLEARANCE mm		5.25"		6.25"		7.25"		8.75"	

(a) Mass Less Driver and Instruments

Table 1. Vehicle Descriptions

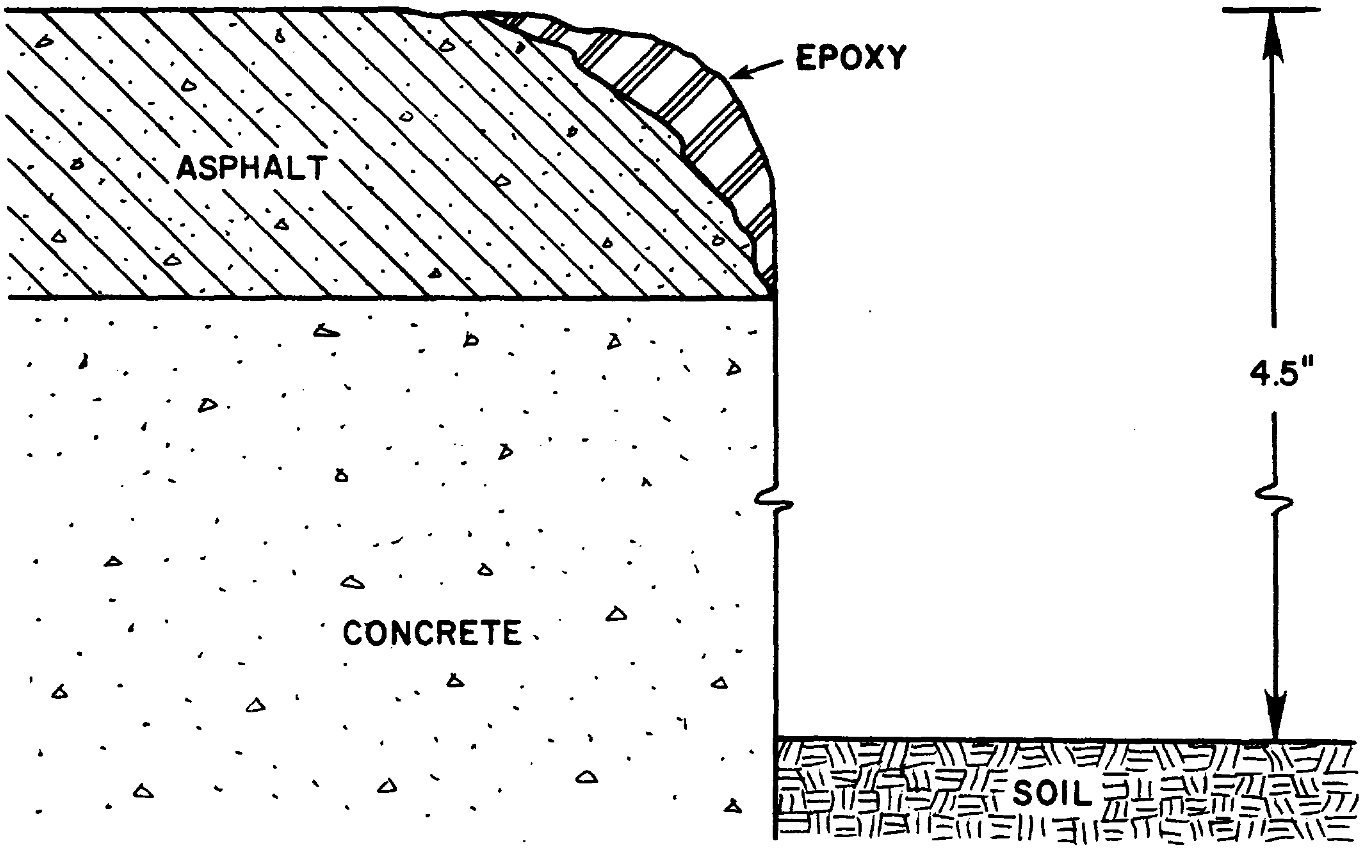
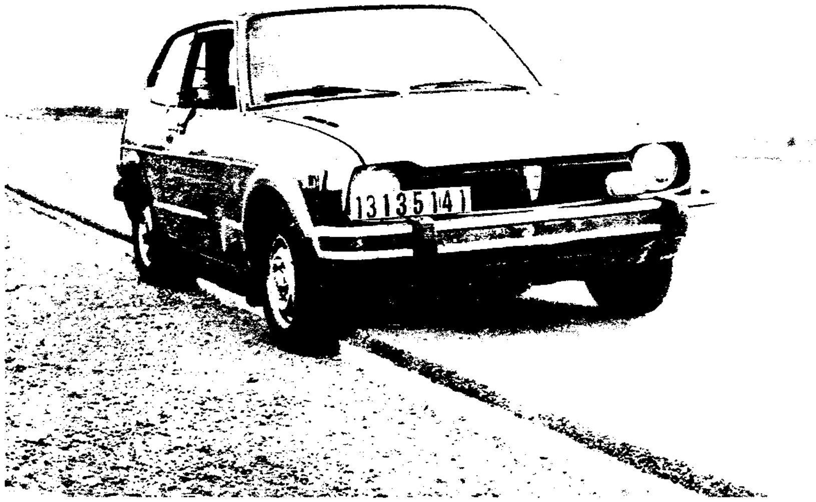


Figure 6. MODIFIED 4.5 INCH PROFILE



A

B

Figure 7. 4.5 in Test Course with Minicompact.

full sized sedans were tested with both bias ply and radial tires. The other two vehicles were tested with only radial tires. Only full tread tires were considered in this testing, since smooth or damaged tires could be considered a special case for future investigation. In all cases, the tire inflation was adjusted to recommended cold pressures just before testing.

DRIVERS

Closed loop tests are those where the driver is free to steer or brake as needed to maintain stability. Driver skill level is a variable notoriously difficult to assess. To evaluate the effect of skill level, four drivers were chosen. These drivers were:

1. Professional - Teaches High Performance Driving Techniques
2. Semi-Professional - Technician Who Occasionally Performs Duties As Test Vehicle Driver
3. Typical Male - Construction Supervisor With No Special Driving Skills
4. Typical Female - Technician With No Special Driving Skills

Only Driver #1 drove the complete matrix of tests since it was felt his skills were required for any tests involving a potentially hazardous situation. Driver #2 performed all tests up to the 4½ inch drop off condition. Drivers #3 and #4 conducted a selected number of runs at the 1½ inch and 3 inch edge height.

TEST SPEEDS

To evaluate the effect of vehicle speed, each condition was run at 35, 45, and 55 mph. These values were chosen to cover the spectrum of speeds that may be encountered in a typical edge recovery situation.

VEHICLE POSITIONS

Once a vehicle has left the roadway and has a wheel or wheels on the shoulder, several modes of returning to the roadway are possible. Three of these modes were investigated during this study. The first is the scrubbing condition where the driver allows the vehicle to move laterally toward the roadway at a very slow rate until a tire contacts the roadway-shoulder lip. At that time lateral motion stops and the tire is in intimate contact with the roadway edge (scrubbing) while continuing to travel forward. To mount the edge the driver is required to input an increasing amount of steering toward the roadway. The second condition is where the right front and rear wheels are well on the shoulder while the other two wheels are still on the roadway. The driver then steers to the left at a comfortable level so as to produce a lateral velocity high enough to preclude any continuous scrubbing condition as the vehicle returns to the roadway. In the third condition, the vehicle returns to the roadway the same as in the second condition except that all wheels are on the shoulder before the return maneuver is initiated.

PHOTOGRAPHY

To document each test run and to provide a means of obtaining certain measurements, two standard speed 16 mm motion picture cameras were used. The first camera was operated from the rear doors of a van. The van preceded the test vehicle by about 50 feet, remaining on the asphalt roadway. The second camera was located on the passenger door, aimed toward the driver, who would start and stop the filming by means of a remote switch. This switch also lit a small lamp in the windshield, visable to both cameras, for synchronization. To document the run condition, an eight digit changeable slate was installed on the right front bumper and on the drivers window which were both changed to reflect the current condition of each run. The meaning of each of the digits on the slate is shown in Table 2.

ELECTRONIC INSTRUMENTATION

To quantify certain dynamic parameters during the testing, electronic instrumentation was installed in the intermediate size vehicle. It was felt that it would be more efficient in this investigation to hold the vehicle variable constant, while evaluating all other combinations of variables.

The parameters measured by instrumentation were:

PARAMETER	FULL SCALE	RESOLUTION
VELOCITY	100 mph	0.2 mph
LATERAL ACCELERATION	± 2 g	0.01 g
YAW RATE	±70°/sec	0.2°/sec
WHEEL ANGLE	±20°	0.1°

These data were transmitted to the central base station for recording by means of an FM-FM Telemetry Radio Link. In addition to the aforementioned data, the test driver activated a switch just prior to the run providing a signal which initiated computerized data processing

SUBJECTIVE RATING SYSTEM

In addition to the photographic and electronic data, a system was developed to allow the driver to express the severity of each test run immediately upon completion. The system consisted of a numerical ranking from one to ten. One (1) was no detectable effect and ten (10) was a com-

DIGIT	1	2	3	4	5	6	7	8
MEANING	VEHICLE	EDGE CONDITION	RECOVERY CONDITION	VEHICLE SPEED		DRIVER	TIRES	RUN #

(1) VEHICLE:
1. Mini-compact (Honda)
2. Intermediate (Nova)
3. Full Size (Plymouth)
4. Pickup Truck (Ford F150)

(2) EDGE CONDITION:
1. 1½ Inch Drop off
2. 3 Inch Drop off
3. 4½ Inch Drop off
4. 6 Inch Drop off

(3) RECOVERY CONDITION:
1. Right wheels 3' off pavement
2. Right wheels scrubbing
3. Vehicle fully on shoulder

(4-5) VEHICLE SPEED: Test speed in MPH

(6) DRIVER:
1. Professional
2. Untrained female
3. Semi-professional
4. Untrained male

(7) TIRES:
1. PZ25/75R15 Goodyear
2. Belted H78-15 Goodyear
3. E78-14 Firestone
4. P155/80R12 Goodyear
5. L78-15 Cushion belted Goodyear
6. P195/75R14 Goodyear Poly Steel

(8) RUN #: Sequential run Numbers under Same conditions

Table 2. TEST RUN INDENTIFICATION KEY

plete loss of control. To assist the driver in assigning a number to their impression, an aid was prepared for their referral when deciding on an appropriate value. This aid is shown below.

SEVERITY CODE:

1. Undetectable	6. Extra Effort
2. Very Mild	7. Tire Slip (Slight lateral skidding)
3. Mild	8. Cross C. L. & Returned
4. Definite Jerk	9. Crossed C. L., No Return
5. Effort Required	10. Loss of Control (Spin Out)

Even though this system is subjective and prone to variability from driver to driver, it proved a good indicator when confined to any one driver's reactions to the entire matrix of tests. This rating value was later used as the dependent variable when sorting by computer on various combinations of conditions.

TEST RUNS

Each driver was instructed to maintain a certain distance behind the photo van. The photo van driver would maintain the test speed by calibrated speedometer, allowing the test driver to concentrate on maneuvering the vehicle. Each run would allow enough run-up room so that speed and separation distance could be accurately maintained. Just before reaching the beginning of the course, the driver would leave the roadway and assume the required position with respect to the shoulder edge. Once stabilized, the test driver would attempt to return to the delineated 12 foot roadway lane in the prescribed manner. If any run deviated from the pre set-up condition, it was repeated at the direction of the test supervisor. The test supervisor also had the option of terminating a series of runs, should the risk to the driver become significant. Over 300 test runs were made during the course of this study and are summarized in Table 3.

Table 3. Summary of Test Runs

DRIVER	VEHICLE	1.5"	3.0"	4.5"	Scrubbing	Half Vehicle Off	Full Vehicle Off	35 mph	45 mph	55 mph	Radial	Bias
Professional	Mini Compact	X	X	X	X	X	X	X	X	X	X	
	Intermediate	X	X	X	X	X	X	X	X	X	X	X
	Full-sized	X	X	X	X	X	X	X	X	X	X	X
	Pickup	X	X	X	X	X	X	X	X	X		X
Semi-Professional	Mini Compact	X	X		X	X	X	X	X	X	X	
	Intermediate	X	X		X	X	X	X	X	X	X	X
	Full-sized	X	X		X	X	X	X	X	X	X	X
	Pickup	X	X		X	X	X	X	X	X		X
Untrained Female	Mini Compact											
	Intermediate											
	Full-sized											
	Pickup	X						X	X	X		X
Untrained Male	Mini Compact		X		X	X	X	X	X	X	X	
	Intermediate		X		X	X	X	X	X	X	X	X
	Full-sized		X		X	X	X	X	X	X	X	X
	Pickup		X		X	X	X	X	X	X		X

TEST DATA ORGANIZATION

In order to evaluate the degree of influence or sensitivity, each variable in the test matrix has with respect to safety, a method of rapidly searching for certain conditions was developed. This system involved a Hewlett Packard HP-85 computer and disk drives running standard Information Management Pac software. With this system, each variable (vehicle, driver, ect.) associated with each run was entered into the data base along with the subjective severity rating associated with that run. This then resulted in over 300 records that could be scanned for a certain variable or combination of variables. In that way, the severity or average severity for all requested runs could be obtained.

Many different combinations of variables were evaluated. The more relevant ones are presented in bar charts. The value of 5, on the severity code varying from one to ten, was selected as the boundary between safe operation and the beginning of a trend leading to progressively less safe conditions. It was above this value that each driver considered the level of effort and concentration greater than normally required in typical driving. This assessment was made on an individual basis.

DISCUSSION OF RESULTS

To evaluate the effect of the three edge heights in two modes of returning to the roadway (scrubbing and a smooth return), average severities were obtained using the professional driver. Only this driver was used for these data since he completed the entire test matrix. Figure 8 shows the average values for each of the conditions, when smoothly returning to the roadway from a position where the vehicle is about half on the earth shoulder and half on the pavement. As can be seen, there is very little difference, either between vehicles or between the 3 inch and 4.5 inch heights. Figure 9 shows the same series of tests except the pre-return condition is changed. In this case the right wheels are in intimate contact with the pavement edge, scrubbing condition, before return to pavement is attempted. Once again the difference in vehicles is quite small, but the effect of edge height is pronounced in the 4.5 inch tests with the maneuver severity for all vehicles extending into the upper half, or the critical severity range.

To determine the influence of driver skill level, average severity levels were obtained from three drivers (professional, semi-professional and the untrained male). Data from all vehicles at each test speed on the 3 inch edge height were summarized. As can be seen in Figure 10, the average values for each driver under each pre-return condition were fundamentally equal. The exception is the untrained male with the full vehicle on the shoulder. This is a typical result believed to be due to the relatively rough shoulder surface.

Since both bias and radial tires were tested on the intermediate and full sized vehicles, a comparison was possible using the identical condi-

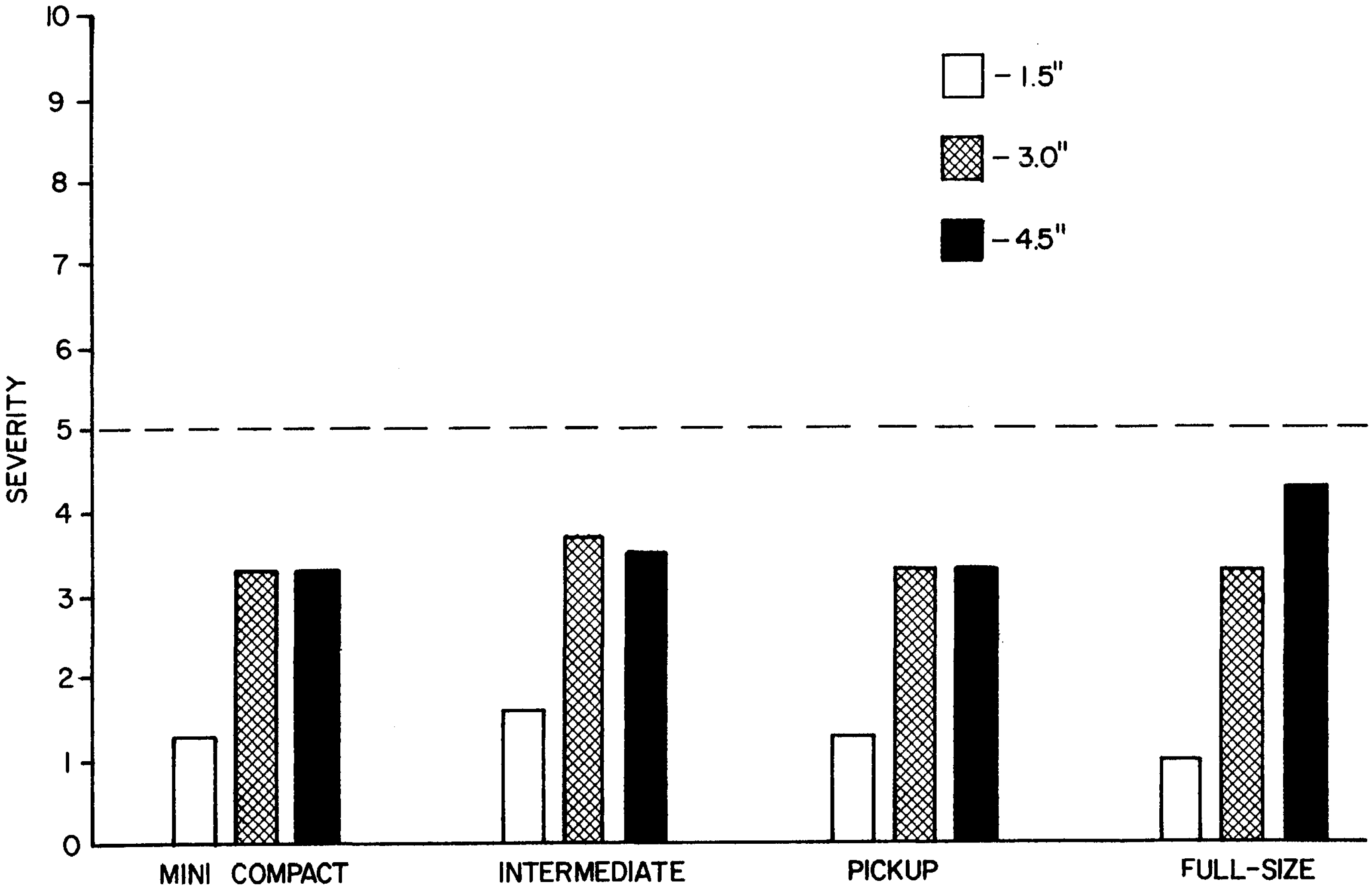


Figure 8. VEHICLE COMPARISON
Nonscrubbing Condition
Driver 1
34, 45 & 55 mph

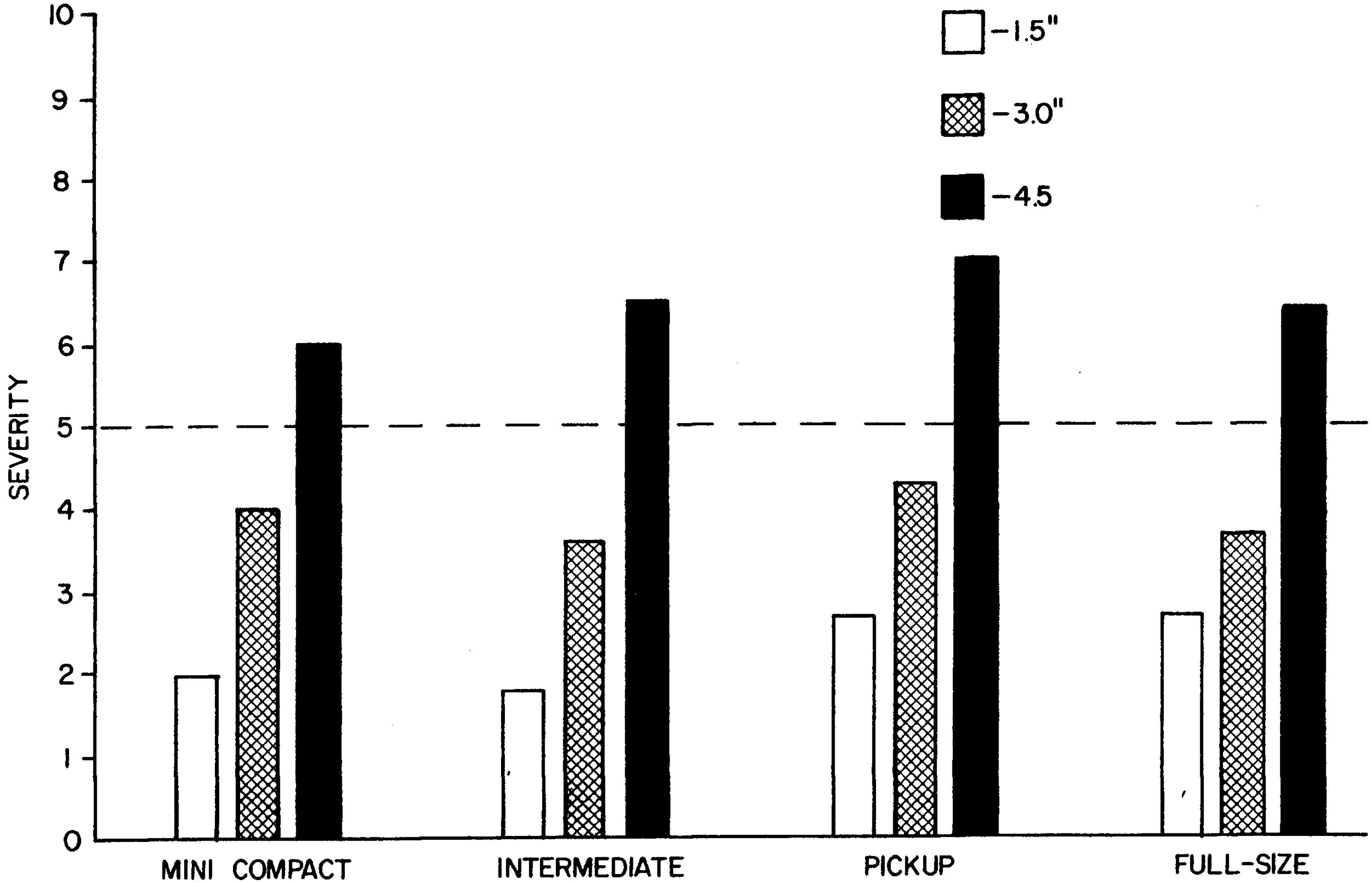


Figure 9. VEHICLE COMPARISON
Scrubbing Condition
Driver 1
35, 45 & 55 mph

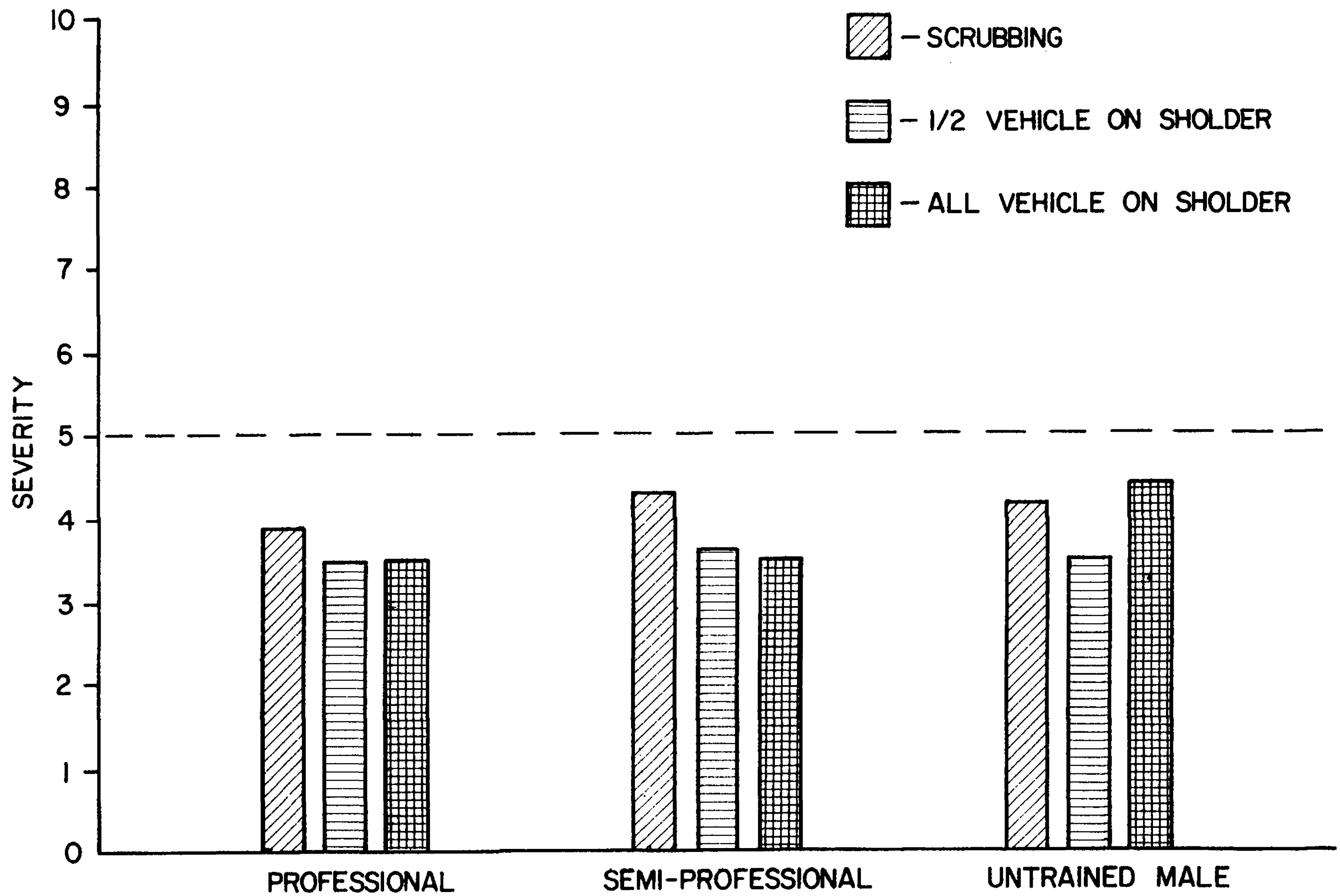


Figure 10. DRIVER COMPARISON
Average Severity - 3 in. Drop Off
All Vehicles at 35, 45 & 55 mph

tions of each test speed, the professional driver and intermediate vehicle at the various edge heights. Only the scrubbing condition was considered for this comparison since it involves tire construction much more than the other two conditions. The modified 4.5 inch edge (0.75 inch radius) was also used in this comparison. Figure 11 shows a slight difference between the radial and bias ply, with the bias ply producing slightly higher severity levels at all heights. Once again, the pronounced increase in severity at the 4.5 inch level is apparent, with only a slightly higher level due to the relatively sharp edge.

Finally the effect of speed at which the vehicle returned to the roadway was considered in Figure 12. Only the runs made by the professional driver were evaluated to maximize the scope of the comparison. Also, only the scrubbing condition was considered since it has been shown to lead to the most hazardous conditions. All vehicles were averaged since vehicle differences were shown to be small. As Figure 12 shows, a nearly linear increase in severity occurs as the speed is increased within each edge height condition. As before, the 4.5 inch edge height is a potentially unsafe condition, even at the 35 mph speed. Also note the 45 mph and 55 mph are above the critical speeds found by Klein (5).

LATERAL ACCELERATIONS

To quantitatively assess the dynamic reaction of the vehicle to the various test conditions, the more important vehicle parameters were measured and recorded on the intermediate size vehicle. These measurements provide additional insight into forces acting on the vehicle, forces the driver must accommodate if stability is to be maintained. One of the more important reactions measured is lateral acceleration. This is a meas-

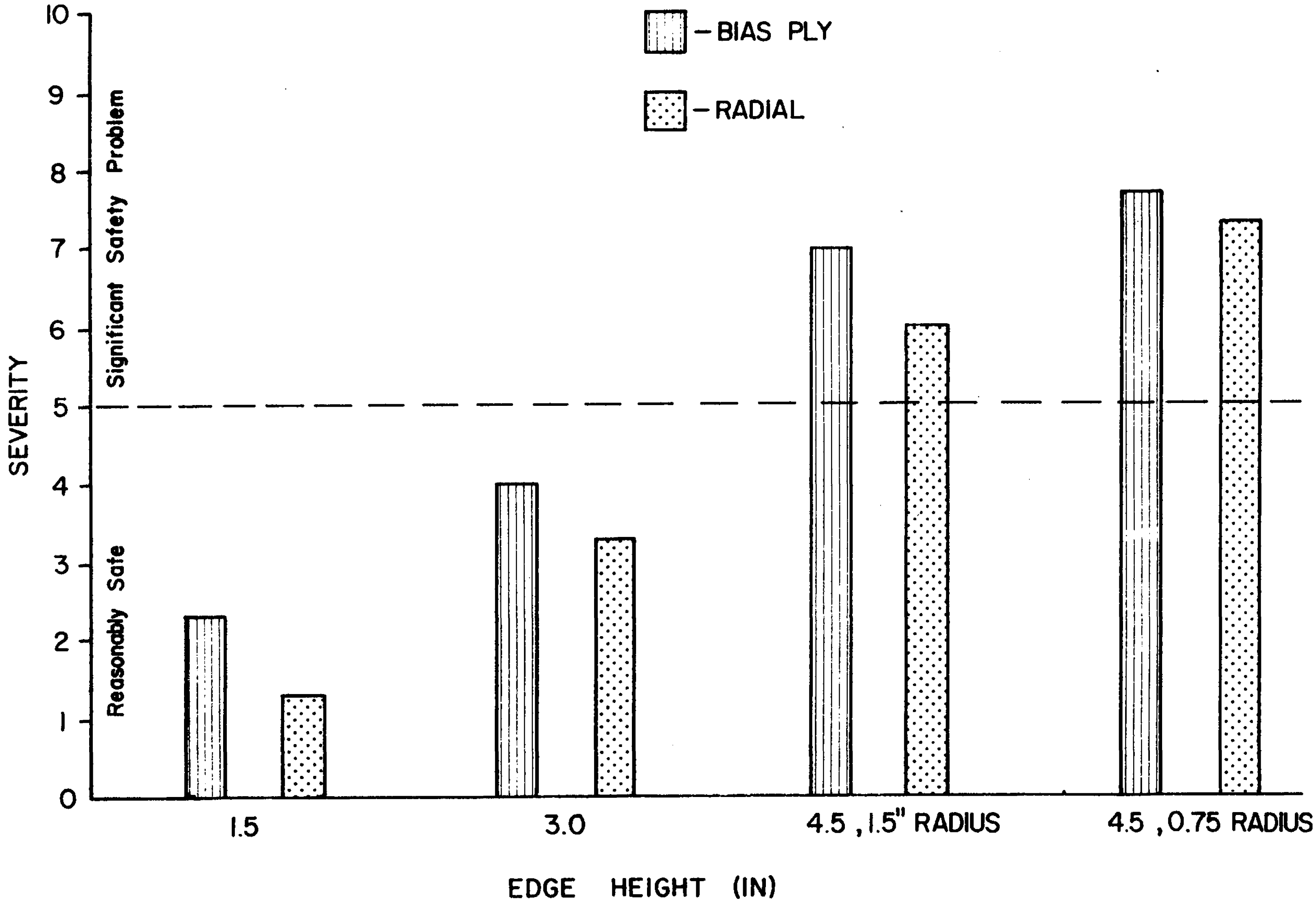


Figure 11. EFFECT OF TIRES
Scrubbing Condition - Intermediate Vehicle
Professional Driver at 35, 45 & 55 mph

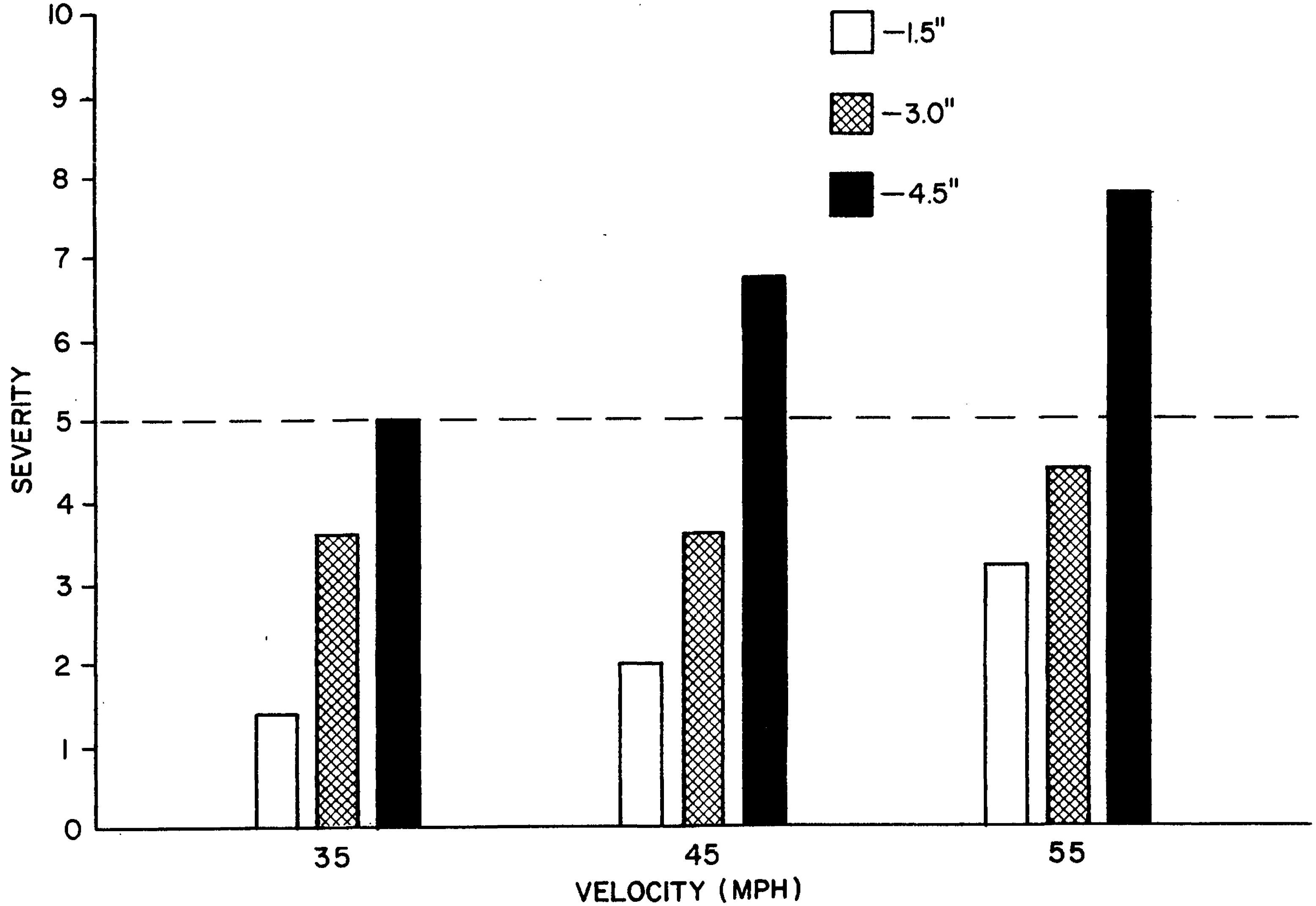


Figure 12. VEHICLE COMPARISON
Driver 1
All Vehicles, Scrubbing

ure of roadway cornering friction necessary to remain under control and out of the oncoming lane of traffic. Table 4 summarizes the maximum lateral accelerations produced by the driver returning to a straight path, after returning to the pavement and compensating for the steer input required to traverse the edge. It was shown by Kummer and Meyer (6) that the friction demand of the pavement is equal to the deceleration of the vehicle expressed as a percentage of the acceleration of gravity, g. Thus, the pavement should have an available cornering friction averaging at least 0.25 to provide stability at the 1.5 inch and 3.0 inch edge heights. This relatively low number is easily achievable on dry pavements and commonly available on wet pavements. On the other hand, the 4.5 inch edge height required up to a maximum of 0.88 g which is equal to or above the maximum value of cornering friction achievable on many dry pavements. In fact, the available friction of the dry asphalt pavement was exceeded in the runs marked with a (*) since side slip did occur.

Based on the same study (6), the average driver considers any lateral acceleration above 0.30 g to be excessive. This could lead to a situation where the average driver will hesitate in developing over 0.30 g and thus, as the only alternative, allow the vehicle to travel into the oncoming lane of traffic.

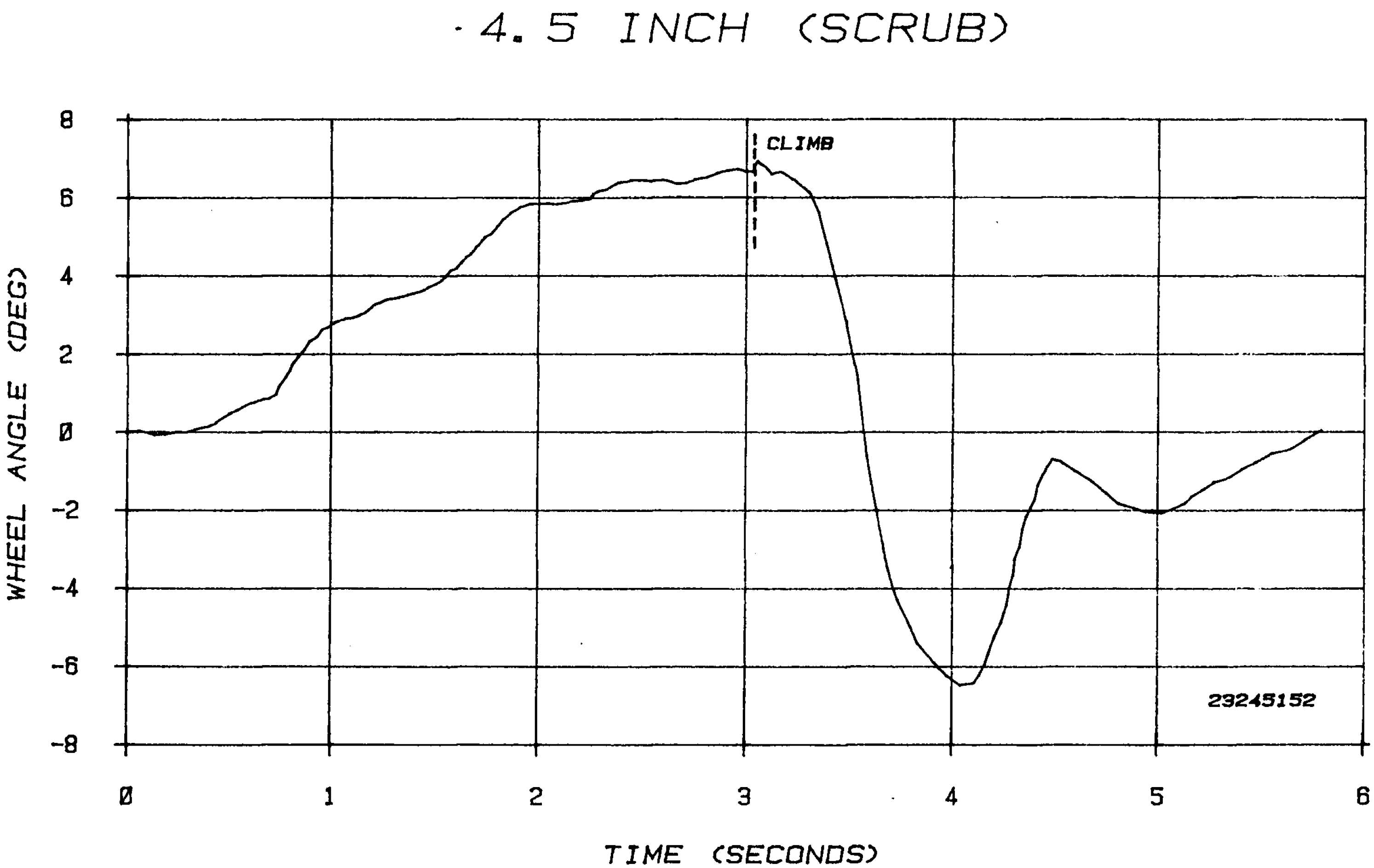
STEERING ANGLE

The angle of the front wheels was measured by means of a rotary potentiometer attached to the steering box output shaft. A typical output of this measurement during a 4.5 inch edge height, scrubbing condition test is shown by Figure 13. This figure illustrates the actions taken by the driver during the time required to mount the edge (between 0 and 3 seconds)

Edge Height	35 MPH		45 MPH		55 MPH	
	Scrubbing	Rapid	Scrubbing	Rapid	Scrubbing	Rapid
1.5"	0.07	0.09	0.18	0.1	0.26	0.13
3.0"	0.10	0.18	0.16	0.16	0.20	0.20
4.5" 1.5" radius	0.56	0.23	0.74	0.50	0.79*	0.53
4.5" 0.75" radius	0.65	0.29	0.71*	0.52	0.88*	0.55

* Lane Violation

Table 4. Maximum Recovery Lateral Acceleration g's.



4.5 INCH (SCRUB)
CLIMB
23245152
WHEEL ANGLE (DEG)
TIME (SECONDS)
8
6
4
2
Ø
-2
-4
-6
-8
Ø
1
2
3
4
5
6

Figure 13

with a constantly increasing steering input from time 0 to the rapid climb at 3.1 seconds, and the drivers reactions starting at 3.2 seconds to keep the vehicle from entering the oncoming lane of traffic.

The testing described has shown that the height of the pavement-shoulder edge and the method used to return are the most significant safety factors when considering vehicle, driver, tire and speed differences. Speed proved to be the next highest safety influence.

Up to and including the 3 inch edge height condition, the three skill levels of drivers rated each condition very closely, within about 5%. Only the professional driver conducted the 4.5 inch tests, due to the potential risk involved, so no driver comparison was possible at that condition. Also the effect of different tire construction was shown to be small with the bias ply tire having about a 10% higher severity level than the radial. This relatively minor tire influence was also found by Klein (5).

Small differences were also observed between the four vehicles used in the study. This was found to be somewhat unusual since a foregone conclusion was that the smallest vehicle would be more sensitive to edge mounting conditions. It is speculated, however, that the mini-compact possesses inherently better handling characteristics including a lower steering ratio. These characteristics are important once the vehicle has returned to the roadway, compensating sensitivity of the small vehicle, small tire combination to edge mounting.

Figure 14 summarizes the subjective severity levels obtained by the professional driver, at 35, 45, and 55 mph, using all test vehicles. The 1.5 inch, 3 inch and 4.5 inch edge heights with a 1.5 inch radius edge are included. The dashed curve represents the return condition where the ve-

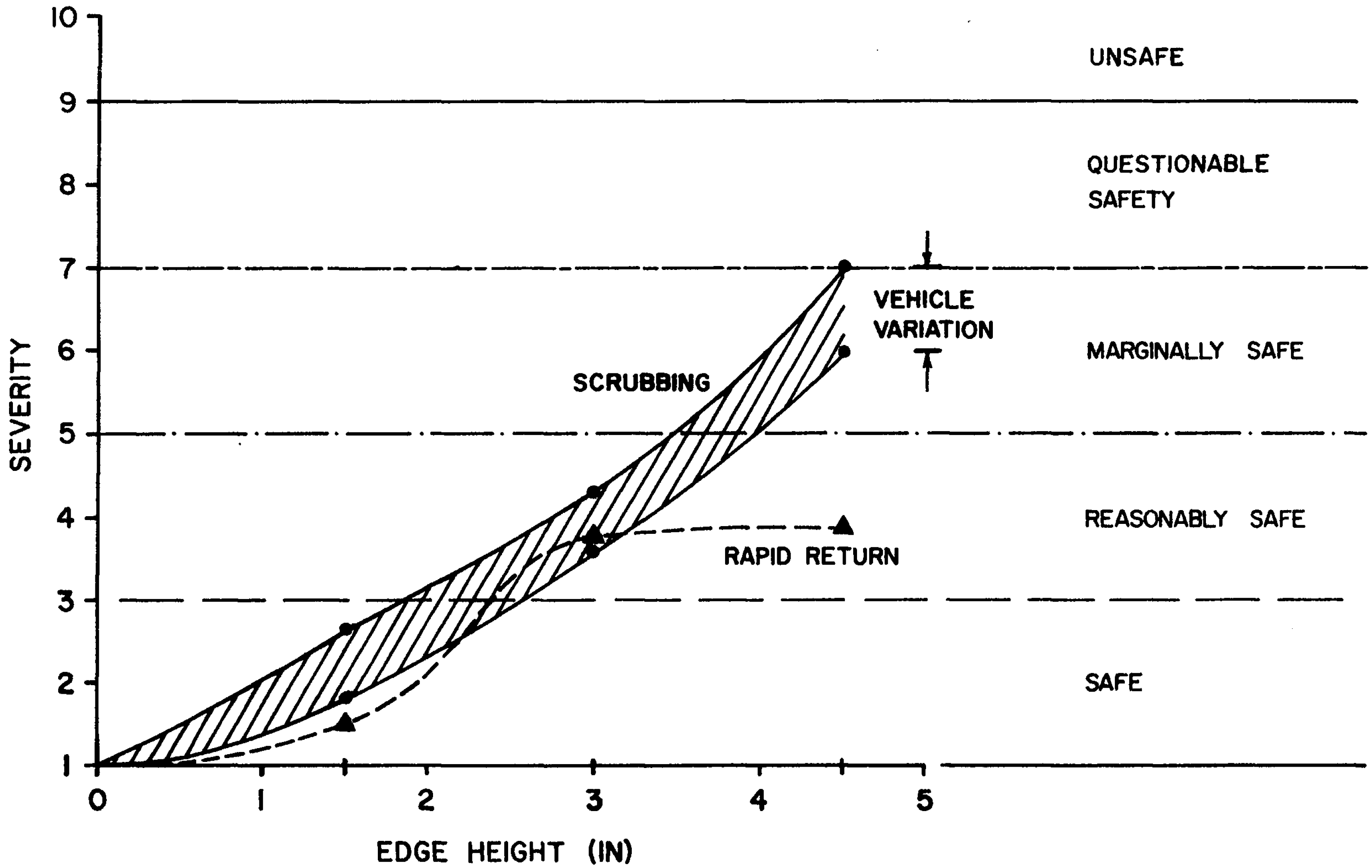


Figure 14. SUMMARY OF SEVERITY LEVELS

hicle is approximately half on the shoulder and half on the roadway and returns to the roadway without scrubbing at a comfortable rate. The solid curves represent the scrubbing condition. This is where the right wheels were in contact with the edge for some distance prior to returning.

In both cases, the 1.5 inch height produced levels that were considered mild by the driver. The 3 inch condition also produced similar results from both curves. It was considered to have a definite jerk or slight jolt, but it did not constitute a real safety problem. The 4.5 inch condition shows a definite divergence between the curves, with the rapid return remaining at the same level as the 3 inch but with the scrubbing condition producing high severities. Some runs produced lane violations and slip out. The difference between these two edge heights is illustrated in Figures 15 and 16. Figure 15 shows the results of a typical run made at 55 mph with the intermediate size vehicle and the professional driver returning to the pavement over a 3 inch drop height. Figure 16 shows the results of exactly the same conditions except at the 4.5 inch edge height condition. Notice the extreme arm movements of the driver at 4.67 and 5.75 seconds in Figure 16.

In order to avoid entering the oncoming lane of traffic, the amount of lateral acceleration generated after returning to the roadway has a significant influence on safety. Figure 17 illustrates the average lateral acceleration developed over the three speed ranges and the four test vehicles at the various edge heights. The two conditions of pre-recovery position are considered. Driver opinion levels obtained from Kummer and Meyer (6) are indicated on the chart with a level greater than 0.3 g considered excessive. This would be a potential limitation imposed upon themselves by

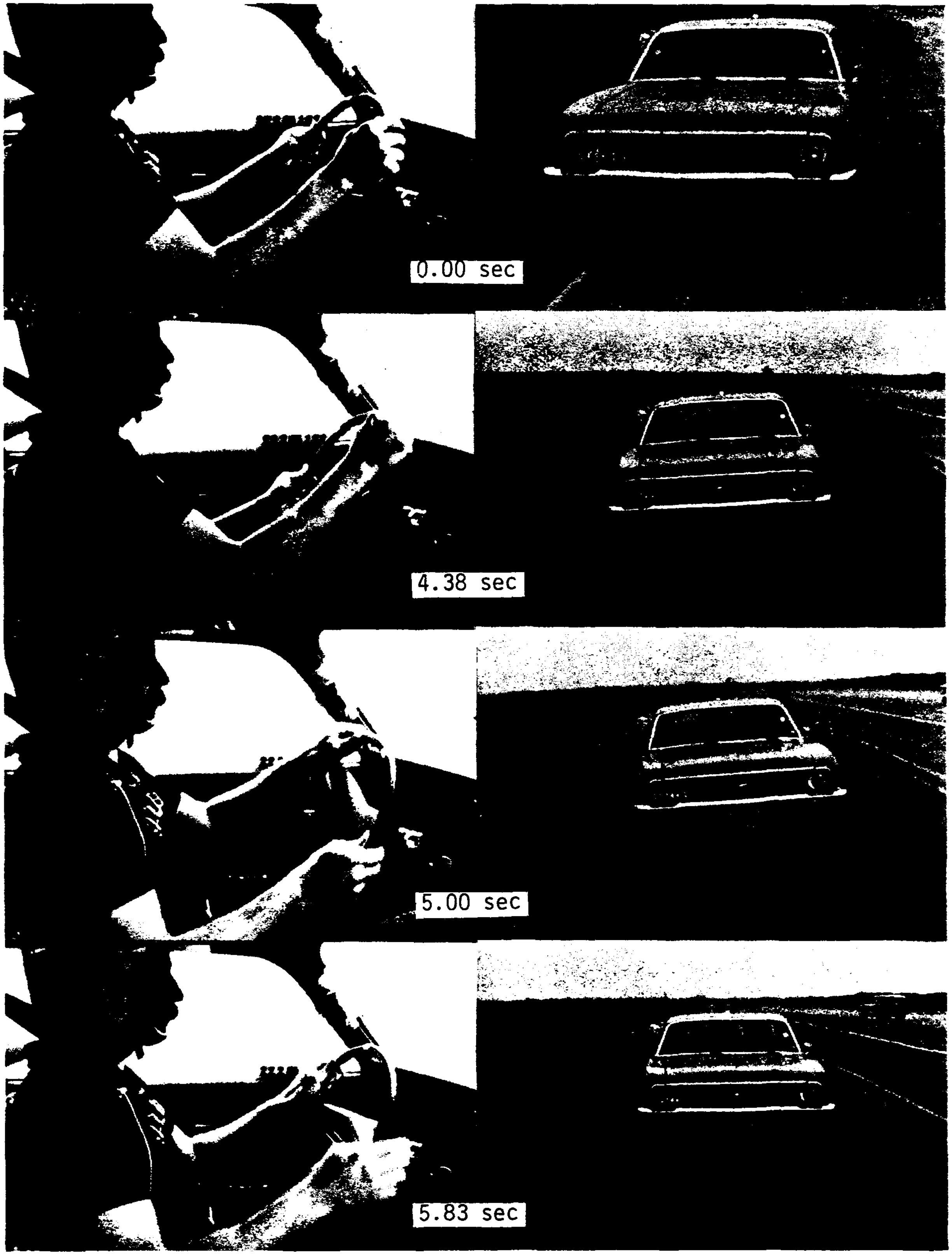


Figure 15
Scrubbing Condition - 3 Inch Edge Height
Professional Driver, Intermediate Vehicle at 55 mph

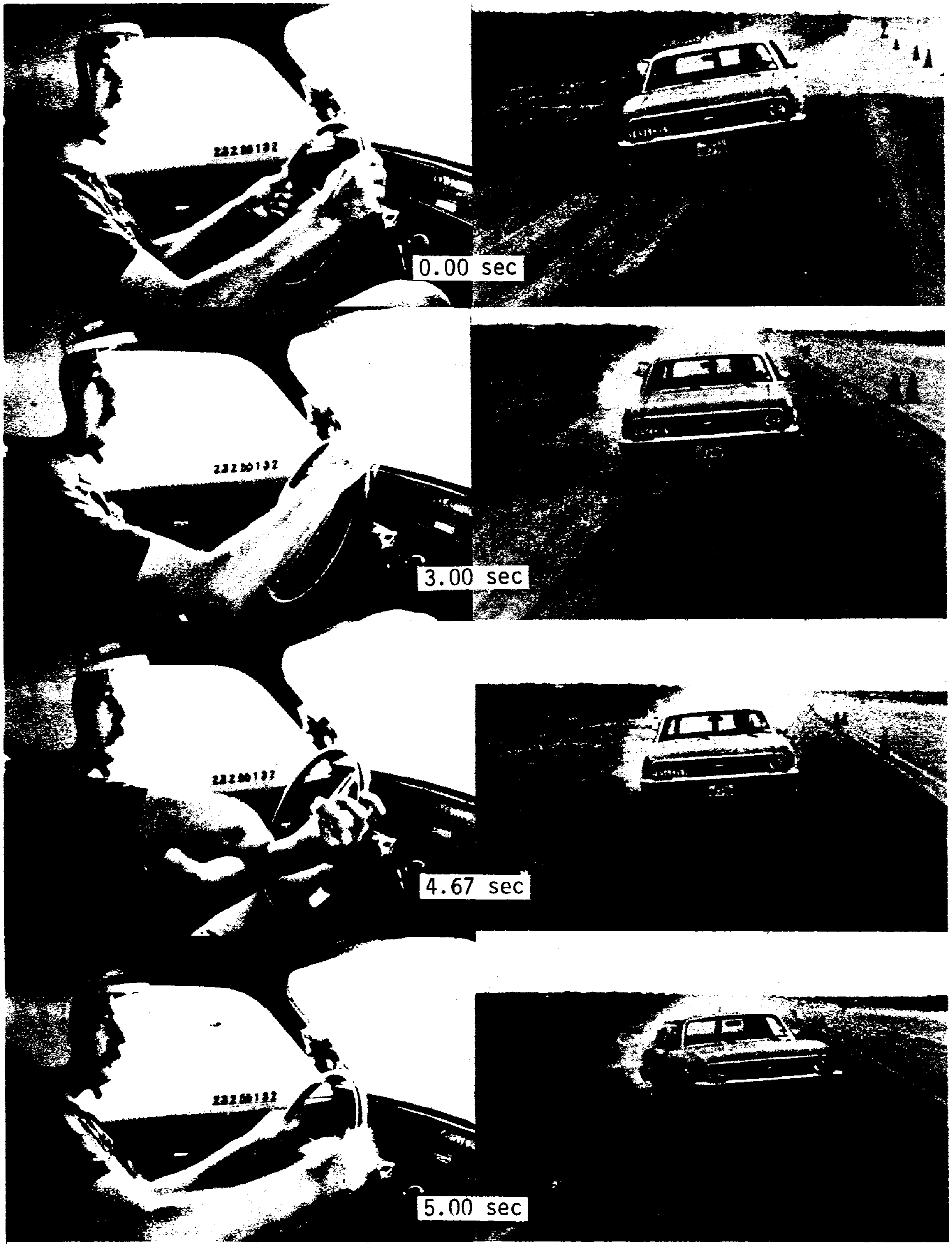


Figure 16
Scrubbing Condition - 4.5 Inch Edge Height
Professional Driver, Intermediate Vehicle at 55 mph

Figure 16a

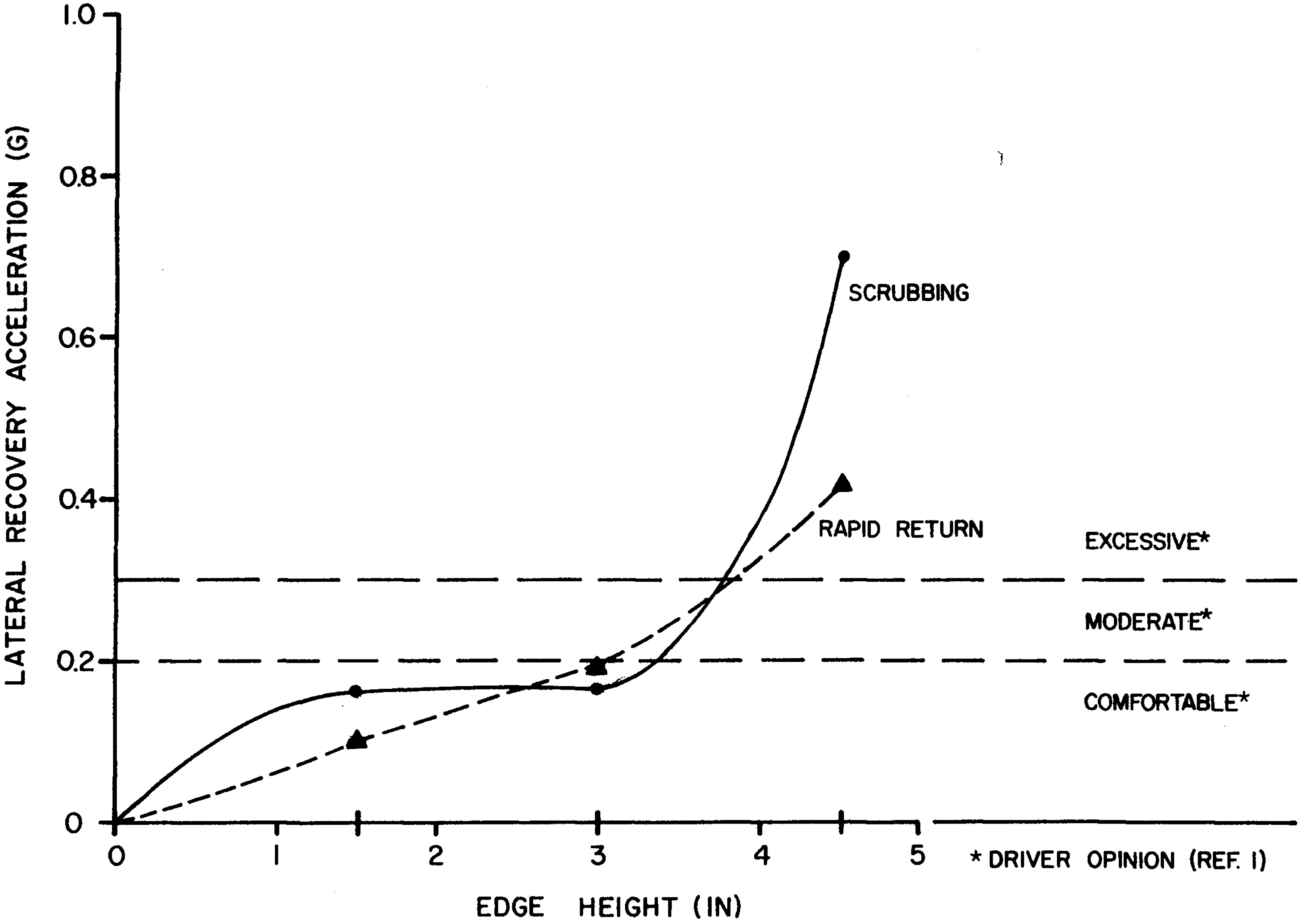


Figure 17. Maximum Lateral Acceleration and Edge Height

most drivers, who may not attempt to develop all of the available friction to remain in their lane of traffic. As in Figure 14, both return conditions show similar values at the 1.5 inch and 3.0 inch conditions and increase into the excessive region at the 4.5 inch condition. The scrubbing condition produced quite high values of 0.7 to 0.8 g which proved to be near the maximum available friction levels, since lane violations and slip outs did occur.

The non-scrubbing condition test runs compare favorably with the edge mounting work done by Nordlin (3). No loss of control of the test vehicle and no lane encroachment up to and including the 4.5 inch edge height occurred in Nordlin's study as was also the case here.

The influence of the edge shape is brought out by comparing the results of this study with the one done by Klein (5), who used a smooth, near vertical concrete surface for the edge that had a 0.5 inch radius at the top edge. This edge produced similar steering angles to return to the roadway from a scrubbing condition at the 4.5 inch height. Klein reported 9 degrees, compared to the 7 degrees observed in this study. The large difference shows up at the lower heights where 2.5 and 5 degrees were required on the sharp edge at the 1.5 and 3 inch heights compared to only 1.5 degrees needed on the more sloped asphalt edge used in this project.

CONCLUSION

The results of this work can be summarized by Figure 18. The "Relative Degree of Safety", in terms of the subjective severity levels defined previously, is plotted against the "Longitudinal Edge Elevation Change". Three curves are plotted, one for each pavement edge profile shape. Shape A is the sharp edge tested by Klein. Shape B is the rounded edge tested in this work. Shape C has been subjected to informal testing by the writers. The conclusion was reached in these informal tests that the Shape B was only a problem when the vehicle suspension or other underbody elements contact the pavement edge. Therefore, 5 inches would be reasonably safe for almost all manufactured automobiles. The curve for Shape C was placed accordingly, in a much less severe position than were Shapes A and B.

The terms describing relative degrees of safety are defined as follows.

SAFE - No matter how impaired the driver or defective the vehicle, the pavement edge will have nothing to do with a loss of control. (This includes the influence of alcohol and/or other drugs and any other infirmity or lack of physical capability.) (Includes the subjective severity levels 1 through 3.)

REASONABLY SAFE - A prudent driver of a reasonably maintained vehicle would experience no significant problem in traversing the pavement edge. (Includes subjective severity levels 3 through 5.)

MARGINALLY SAFE - A very high percentage of drivers could traverse the pavement edge without significant difficulty. A very small group of

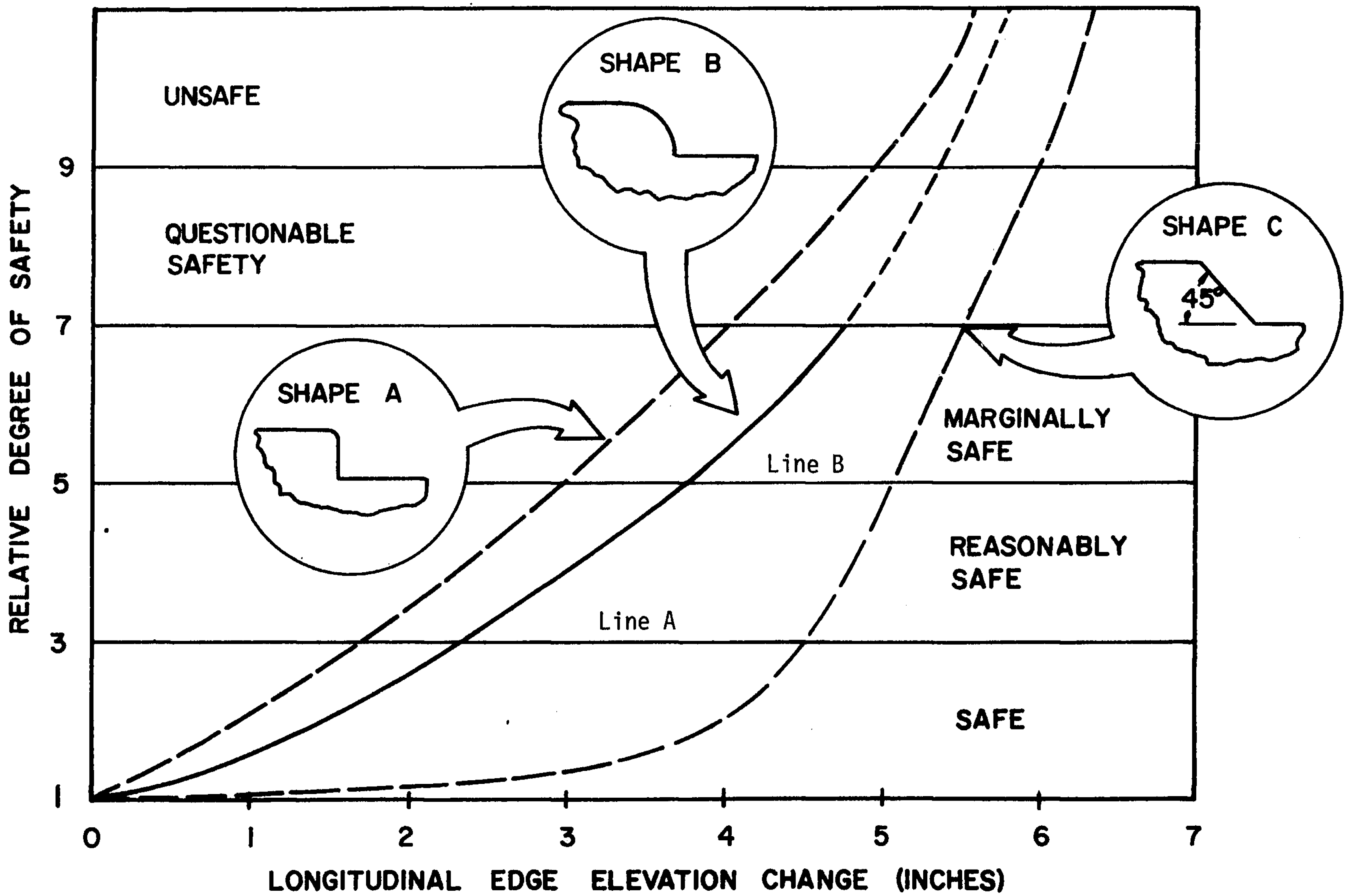


Figure 18. RELATIONSHIP BETWEEN EDGE GEOMETRY AND SAFETY
Scrubbing Condition

drivers may experience some difficulty in performing the scrubbing maneuver and remaining within the adjacent traffic lane. (Includes subjective severity levels 5 through 7.)

QUESTIONABLE SAFETY - A high percentage of drivers would experience significant difficulty in performing the scrubbing manuever and remaining withing the adjacent traffic lane. Full loss of control could occur under some circumstances. (Includes subjective severity levels 7 through 9.)

UNSAFE - Almost all drivers would experience great difficulty in returning from a pavement edge scrubbing condition. Loss of control would be likely. (Includes subjective severity levels 9 through 10.)

Figure 18 could have direct applicability to recommendations for maintenance. As an example, consider the Shape B curve where the curve crosses Line A (2.5 inches). This height might indicate a need to prepare for maintenance before the edge level increases to the point the curve crosses Line B (3.5 inches). For Shape A edges the maintenance would be somewhat more critical, with maintenance activities indicated between 2.0 inches and 3.0 inches, roughly corresponding to the crossing of Lines A and B.

The advantage of avoiding Shape A is also apparent from Figure 18. If Shape C can be constructed, either during the original construction or as a maintenance activity, the need for edge maintenance could be significantly reduced.

Although the curve for Shape C is based on limited testing, the curves for Shape A and B edge profiles are soundly established. The writers are satisfied these curves can be used as a guide for the maintenance of pavement edges and to indicate the desirability, if cost effectiveness can be shown, of gradually moving toward profile Shape C. The profile (Shape C) may also have significant advantages in reducing edge deterioration.

Pavement edges have been shown by Klein (5) using data from Michigan's Highway Safety Research Institute and Indiana, and Klein's own survey questionaire to be the most significant safety related roadway disturbance. It was the second most significant from California data, and was among the top two in importance in earlier studies by Texas Transportation Institute. Appropriate use by highway engineers of the information contained here can, in time, make a major impact in reducing accidents influenced by pavement edges.

By establishing maintenance guidelines based on the findings illustration by Figure 18, unnecessary maintenance of shoulders can be reduced while available maintenance funds can be concentrated on areas having real safety significance.

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