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PAVEMENT EDGE DROP

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FINAL REPORT
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16. Abstract

The purpose of this study was to evaluate the performance of naive drivers in negotiating pavement edge drops from a scrubbing condition. Two vertical heights were used (3.0 and 4.5 inches), two shapes (vertical and a 45-degree bevel), two vehicle sizes (large and small), both front- and rear-wheel drive, and hard and soft shoulders. Various speeds were used. The criterion for "failure" in the recovery maneuver was intrusion beyond the 12-foot lane adjacent to the edge drop.

The results indicate that a drop of the magnitude of 4.5 inches cannot be safely negotiated at speeds as low as 20 mph. The 3.0-inch drop could be generally safely negotiated at speeds of 30 mph, but only in the largest of the three test vehicles used. Performance was poorer in the two small vehicles, indicating that speed limits should be set at no more than 25 mph in areas where edge drops of this magnitude exist. Differences between the front- and rear-wheel drive vehicles were inconsistent, and will require further study. Soft shoulders increase the effective height of the edge to be climbed, but effects associated with drag, etc. appear to be minor. In repeated trials, subjects showed some improvement in performance but, at best, they fell far short of the performance of a professional driver.

Using the 45-degree bevel edge, subjects consistently negotiated it successfully at speeds up to 55 mph, the highest tested.

The results of this investigation, together with other available data, indicate that pavement edge drops pose a considerable hazard to drivers who attempt recovery from a scrubbing condition. Rounded or beveled pavement edges seem to greatly reduce the hazard. There are presently no definitive data on the maximum safe height for a vertical edge drop at freeway operating speeds.

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

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EXECUTIVE SUMMARY

Introduction

Edge drops are vertical discontinuities between adjacent road surfaces. If the edge drop is high enough, it can create a problem for drivers who attempt to steer over it. The problem is maximized if the wheels of the car hang up (scrub) along the vertical face of the drop. Such a situation can lead to an unexpectedly sudden change of direction on the part of the vehicle that may prove difficult for the driver to control.

Because of the problems edge drops sometimes present, there has been a great deal of interest in determining safe limits for them. A number of investigations have been reported, using both full-scale vehicle tests and simulation techniques. While questions have been raised about the available research, some inferences seem clear. For example, Ivey et al. (1984), based on their review of the literature, concluded that edge drops were reasonably safe if they were controlled to 3 inches or less, or the face of the drop had a 45-degree bevel. However, some questions remain that warrant further research.

The Current Study

The investigation reported here was primarily concerned with evaluating the performance of ordinary (naive) drivers on their first encounter with the edge drop. The following independent variables were included:

a. Edge drop height

b. Vertical face and 45-degree bevel

c. Hard and soft shoulder surfaces

d. Vehicle size and front- versus rear-wheel drive

The primary dependent variable was the extent to which the vehicle intruded beyond its own lane during the recovery process. Any intrusion counted as a "failure," but these failures ranged from going no more than a foot or two out of the proper lane to traveling two or more lanes over.

The subjects were trained in the task prior to making runs at test speed. During the test runs they were coached by an on-board observer to increase the likelihood that recoveries would be made from a scrub position. The process seemed to work well, and most runs with the vertical face were made from a full scrub, many on the first attempt by the subject. It was not possible to determine with any degree of confidence whether a scrub was achieved prior to recovery on runs made on the 45-degree bevel edge.

Results and Conclusions

Using the vertical face it was found that edge drops on the order of 4.5 inches could not be negotiated by the naive subjects without intruding beyond their own lane at any of the speeds used in the study (minimum of 20 mph). Edge drops on the order of 3 inches were generally negotiated adequately at speeds of about 30 mph, in a large passenger car. However, tests on the same edge drop with small cars, run by a professional driver, suggest that the safe speed would have to be lower, probably between 20 and 25 mph.

Using the 45-degree bevel edge, virtually all runs (at speeds up to 55 mph) by all subjects were made without intruding beyond the lane adjacent to the edge drop.

Tests run on soft shoulders by a professional driver indicate that it is the height of the edge to be climbed, not the nature of the material at the edge, that affects the ease with which the edge can be mounted.

The results of this investigation provide some additional evidence concerning the effect of edge drops on driver performance. When the edge drop has an essentially vertical face, these data indicate that naive drivers, attempting to recover from a scrubbing condition, may have significantly greater difficulty than suggested by earlier studies. It also appears that vehicle size is a significant factor, with small cars having more trouble with this maneuver than large cars. Because of these results, it is recommended that edge drops having a vertical face be controlled to a depth not to exceed three inches. At that depth, speeds should be posted at a maximum of 25 mph.

One solution to the potential control problems posed by edge drops is to provide a 45-degree bevel at the pavement edge. At a depth of 4.5 inches, and at speeds up to 55 mph, virtually no control problems were experienced with this configuration.

Further research is required to define the maximum safe vertical-face edge drop for speeds above 25 mph.

INTRODUCTION

Nature of the Problem

When a vehicle strays from the road surface onto the shoulder the normal reaction of a driver is to attempt to return it promptly to the road surface. The urgency the driver feels to accomplish the return may be increased if the shoulder surface is not smooth. If there is a vertical discontinuity (edge drop) between the shoulder and road surfaces, the probability of a successful recovery maneuver depends on factors such as the height of the edge drop, the shape of the pavement edge, and the lateral velocity of the vehicle at the time of contact with the edge. Klein, Johnson, and Szostak (1977) carried out a series of investigations to evaluate this problem. Their results are reproduced in Figure 1. Based on these data, there is a simple linear relationship between edge drop height and normal velocity required to climb until the edge drop height reaches about four inches. From that point on the velocity required to climb increases very rapidly.

The data in Figure 1 have implications for the likelihood that the maneuver can be accomplished without encroaching beyond the lane adjacent to the shoulder. This question was addressed analytically by Graham and Glennon (1984). Two examples of their results are shown in Figure 2. For each case there is a "safe recovery zone." Combinations of forward speed and re-entry angles outside the safe zone may result in encroachment or skidding or redirecting and scrubbing. The latter result, of course, still leaves the driver off the road, and further attempts at re-entry can be anticipated. Ultimately, re-entry will be accomplished and the key question is "what happens then?"

An answer to what might happen has been provided by Zimmer and Ivey (1983). The description applies to situations where the right front wheel is in light contact with the pavement edge and the vehicle is traveling more or less parallel to the road edge. According to Zimmer and Ivey, the following sequence of events may occur:

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 reducing speed significantly.

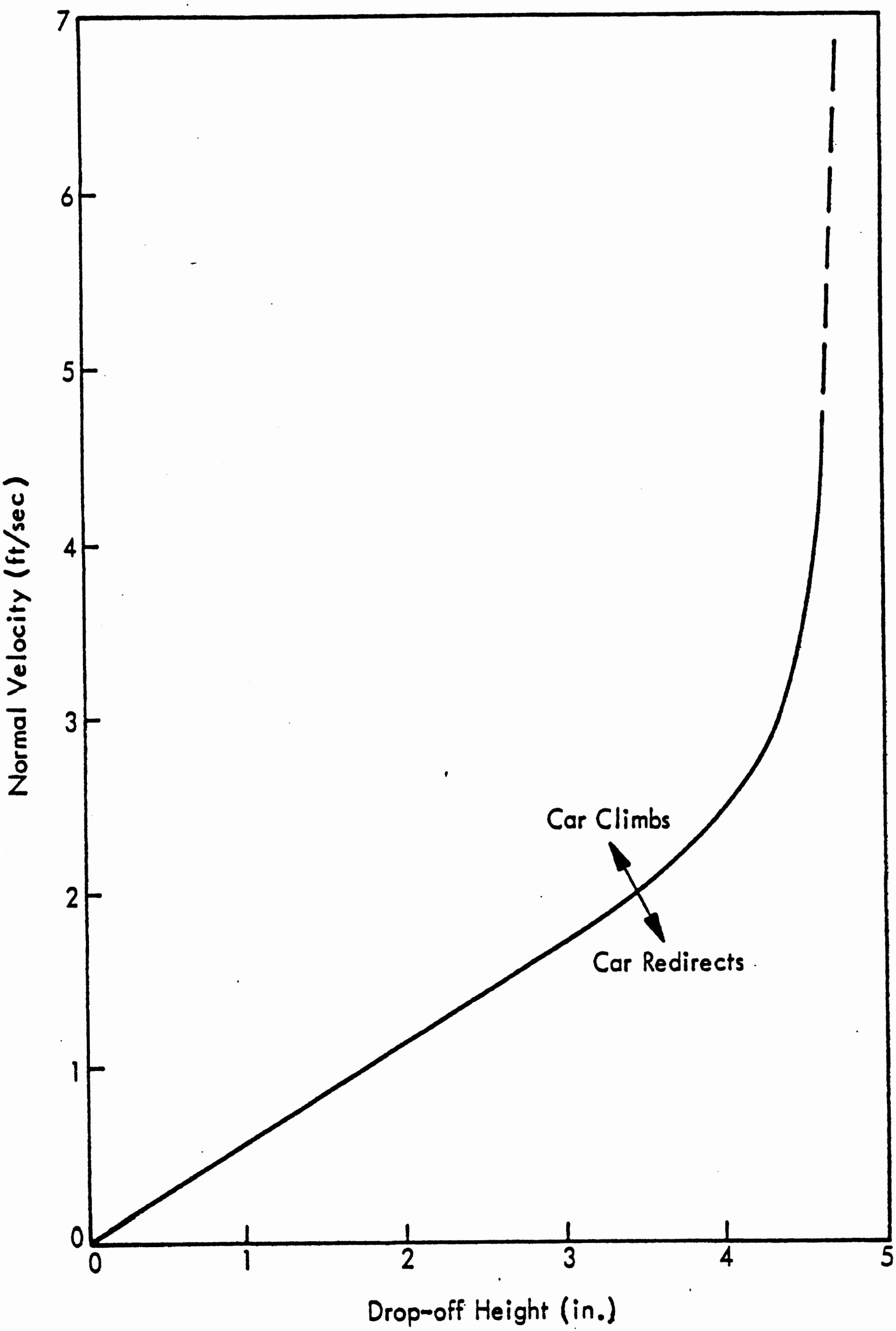
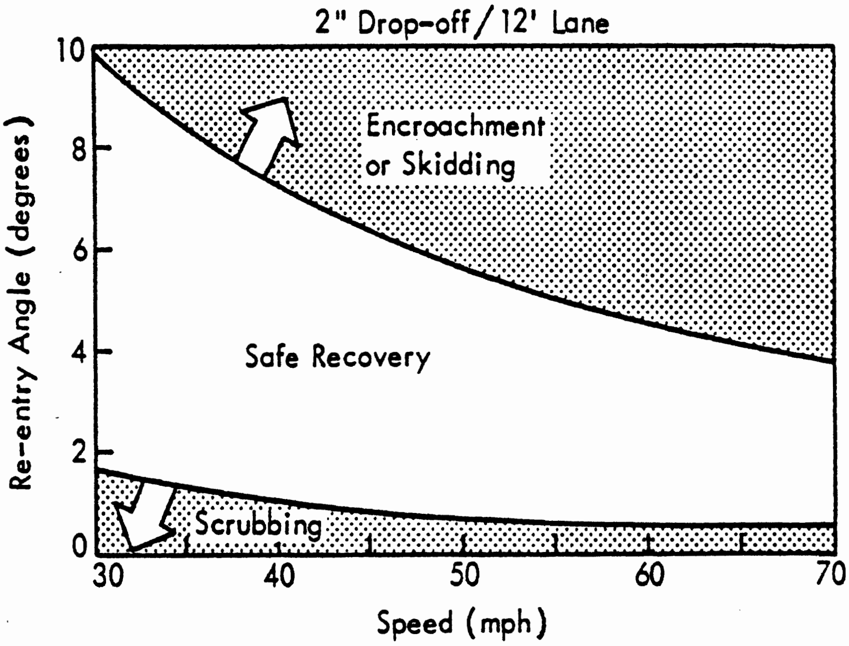


Figure 1. Normal velocity required to climb as a function of edge height (from Klein, Johnson & Szostak, 1977).



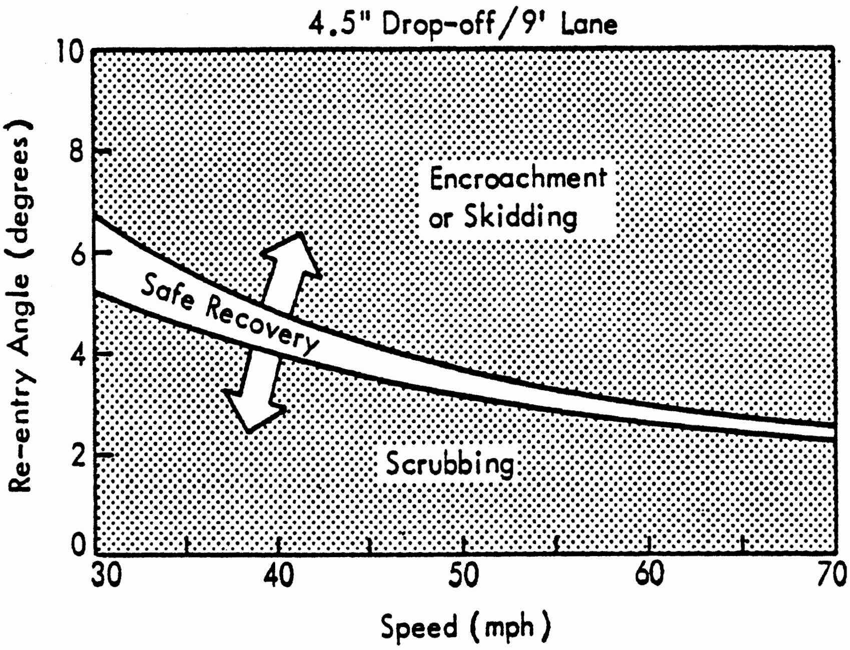


Figure 2. Example boundaries for safe re-entry angles for traversal of vertical face drop-offs (from Graham & Glennon, 1984).

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 (a) of Figure 3.

5. The critical steer angle is added by the driver, and the right front wheel mounts the paved surface [(b) of Figure 3]. 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.

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 [(c) of Figure 3].

7. A collision with oncoming vehicles or spin out and vehicle roll may then occur.

Research on the Problem

Pavement edge drops are hazards because of their potential for causing serious control problems. However, documenting that edge drops contribute significantly to the traffic toll has not proven to be easy. Perhaps the most promising approach as been taken by Ivey and Griffin (1976), who examined about 16,000 single-vehicle accidents. A total of 34 key words were passed against each of the accident narratives. A total of 19 key words were shown to be associated in varying degrees with roadway-disturbed accidents. The first five key words, in order of frequency, were: water, dropped, soft, curb, and edge. As the authors point out, the last four are related to lateral disturbances.

Ivey and Griffin then polled a number of researchers, engineers, designers, accident investigators, etc., to produce a listing of characteristic disturbances that play a role in accidents. The first four items on the resulting list were: pavement edge-shoulder drop-off, curbs and raised medians, hydrodynamic drag (standing water), and poor shoulder maintenance (which includes soft shoulders). The two techniques agree in ranking the same types of problems at the top of the list.

An attempt to assess the cost-effectiveness of various levels of shoulder maintenance was reported by Kulkarni, Golabi, Finn, and Johnson (1980). They estimated the

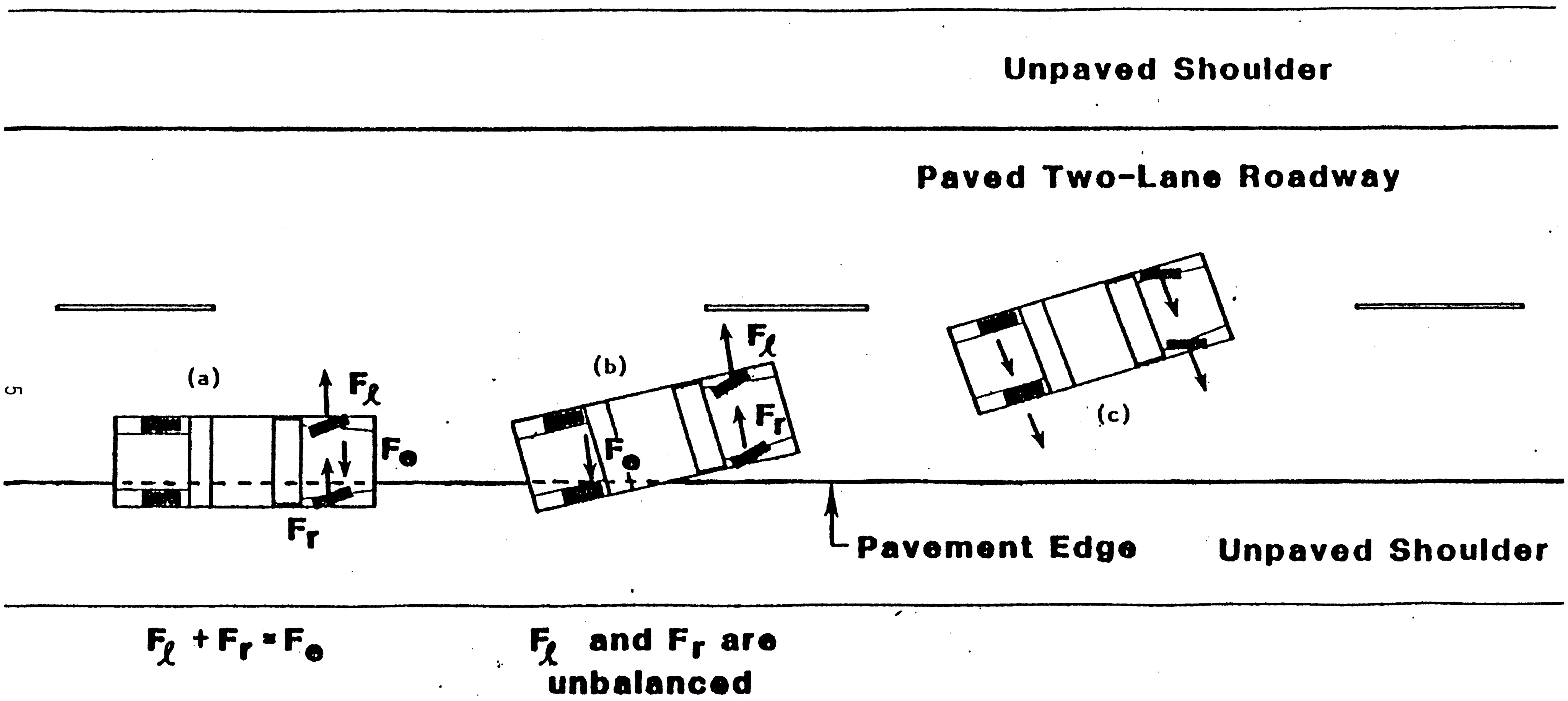


Figure 3. Loss of control phenomenon (from Zimmer & Ivey, 1983).

percentage of drivers who would be likely to run onto the shoulder for various edge-drop heights and combined that with the estimated percent who could not recover. For a 3-inch edge drop, they estimated that 15% of drivers could not recover. The percentages for 4 and 5-inch edge drops were 55 and 90 respectively.

One of the first systematic studies of the effect of various degrees of pavement edge drops on vehicle stability was reported by Nordlin, Parks, Stoughton, and Stoker (1976). Three drop-off heights were used (1-1/2, 3-1/2, and 4-1/2 inches), and four vehicle sizes, ranging from a compact sedan to a full-size station wagon and a pickup truck. All tests were made by one professional driver at a speed of 60 mph, although some tests were also run by two "nonprofessional" drivers at speeds of 40–45 mph. The criterion for "failure" was encroachment beyond the 12-foot lane. However, the drop was not at the edge of the 12-foot lane, but five feet further to the right, at the edge of the paved shoulder. Thus, the subjects had a total of 17 feet of maneuvering room before an encroachment would be recorded. Under these conditions, the investigators report that none of the parameters tested caused problems. The vehicles never encroached into the other lane, and control problems were minor for both types of drivers.

In a follow-up study (Nordlin, Stoker, Stoughton, and Parks, 1978) three additional tests were run using a pickup truck, a crumbling road edge with a two-inch edge drop, and a muddy shoulder. It was anticipated that the muddy shoulder would increase the effective depth of the edge drop by allowing the test vehicle's tires to sink in by about two inches. The post-test measurements indicated that the tire did not sink in as far as two inches in most cases. Once again, one professional driver was used. As before, no problems were experienced in recovering from the test conditions.

The tests conducted by Nordlin and his colleagues did not control for the position of the test vehicle's wheels relative to the edge drop. Situations where the wheels are scrubbing along the edge prior to the recovery attempt should prove more difficult for the driver than situations where the wheels are some distance away from the edge, In the latter case, the vehicle can develop significant yaw velocity before the edge drop is encountered by the wheel.

This difference was investigated by Klein and Johnson (1978). These investigators used one level of edge drop (4–1/2 inches) and three different vehicles (basically the same as used by Nordlin et al., except for the pickup truck). The subjects drove into the test area at gradually increasing speeds, starting at 25 mph. A total of 22 "naive" subjects were used. These were nonprofessional drivers, presumably having no more experience with edge drops than one would encounter in normal driving experience. Most of these people drove only the middle-size vehicle.

In this test, in all cases in which the tires were not scrubbing the edge prior to recovery, the vehicles returned to the road with little difficulty. No lane encroachments were recorded. However, in the cases in which scrubbing was occurring prior to recovery, over half resulted in lane encroachments. The probability of an encroachment was correlated with speed. That is, the higher the speed, the greater the probability of intruding beyond the first lane. Further, there were differences between the vehicles tested. The middle-sized of the three test vehicles had a "critical speed" (i.e., the speed above which most runs resulted in encroachments) of about 42 mph. The critical speeds of the other two vehicles were about 30 mph.

The tests reported by Zimmer and Ivey (1983) were similar to those of Klein and Johnson. However, Zimmer and Ivey felt that edge shape was a significant variable. They tested three edge-drop heights (1-1/2, 3, and 4-1/2 inches). All of the edges had relatively large radii, except for the 4-1/2 inch level, where a short-radius condition such as that used by Klein and Johnson was employed, as well as a 45-degree bevel. Four vehicles were used, ranging from a mini-compact to a full-size sedan and a pickup truck. Three speeds were used (35, 45, and 55 mph), as well as three starting positions (right wheels in contact with the edge drop, right wheels on the lower surface, but not in contact with the edge drop, and all four wheels on the lower surface with none of them in contact with the edge drop). The entire matrix of tests was run by one professional driver. Three other persons, varying in their presumed driving ability, ran portions of the test matrix.

The results of the tests indicated that there were few problems when the wheels of the test vehicles were not scrubbing the edge. However, when the wheels were in contact with the edge prior to the recovery attempt, severe control problems were experienced with the 4-1/2 inch edge drop. There were pronounced differences associated with the shape of the edge drop. The larger radius and bevel edges provided for much smoother entries than the short-radius edges. The results suggest that a 4 1/2 inch drop with a 45-degree beveled edge can be negotiated as readily as a sharp-edged drop only 1 1/2 inches high.

In a recent special report issued by the National Academy of Sciences, pavement edge problems were discussed in some detail (Ivey, Johnson, Nordlin, and Zimmer, 1984). The authors provide a good review of the literature. They conclude with the following statement:

> "Summarizing, the results of published studies on the influence of longitudinal pavement edges on vehicle safety are consistent and

> supplement each other. It is agreed that loss of vehicle control can develop at speeds greater than 30 mph under certain circumstances where inattentive or inexperienced drivers return to the traffic lane by oversteering to overcome the resistance from a continuous pavement edge/tire scrubbing condition. This safety problem is minimized where the pavement edge drop does not exceed three inches in height or the face has a 45 degree slope. A loose or muddy soil shoulder should not increase the edge climbing difficulty provided the overall height is the same. However, similar-looking losses of control can occur even without any edge drop when an errant vehicle is returned to the higher surface friction of the pavement by oversteering. Pavement edge heights of over five inches can interfere with the underneath clearance and thus create safety problems for small automobiles."

State Practices Concerning Edge Drops

In view of the lack of definitive research on the problem of edge drops it was thought that it might be instructive to see what policies various state departments of transportation have formulated to deal with them. One such survey was run in six states about ten years ago (Nordlin et al., 1976). As part of the current program a second survey was carried out, using the same six states and adding three others. The results of both of these efforts are described in the Appendix.

A comparison of the policies from the same states for the two surveys indicated that there were few changes, although some of the policies seem to have become less specific. It is apparent that all of the states surveyed expect that there will be no edge drops after construction. Only three of the states mention specific edge drop heights as allowable maximums. Two of these are 2.0 inches, and one is 1.8 inches. While it is not clear what basis there is for these values, it is interesting that they are in such close agreement.

FIELD TEST

Method

Introduction. As was noted in the introductory section of this report, there have been several field studies designed to provide information concerning the interaction of motor vehicles and pavement edge drops. However, there are three primary concerns with the available data that suggest the desirability of further research. These are:

1. Use of professional drivers
2. Scrubbing vs. non-scrubbing encounters
3. Subject learning

Most of the published studies have relied primarily on professional drivers. While the reasons for doing this are understandable, it does leave open the question of how well the performance of such individuals represents that of ordinary drivers. The only study that made extensive use of naive drivers (Klein and Johnson) used only a 4.5-inch drop, and collected data in a speed-ascending series, giving the subjects experience in the maneuver before they encountered difficult trials. This, of course, raises the subject of subject learning. It is not known how quickly experimental subjects will improve their performance on such a maneuver. It may not have been a problem, but it would be desirable to know.

Some of the published investigations apparently made no attempt to control for wheel position relative to the vertical edge prior to recovery. In those that did, it is apparent that the control problems are significantly greater if the wheels are scrubbing prior to recovery than if they are not. Because a scrubbing contact seems to pose the most potential danger, it seemed appropriate to use that as the basis for the current series of tests.

The problems with available research are significant, and limit their application to roadway maintenance policies. The research to be described used a somewhat different approach that would, it was hoped, avoid the problems mentioned.

Independent Variables

Edge drops. Two levels of edge drops were used, nominally 3 and 4.5 inches. As originally set up, the actual values varied by about plus or minus 0.5 inch. As the study progressed, the shoulder area adjacent to the pavement wore away, so that the edge heights increased significantly after some data had been collected. Efforts were then made to restore the original level and provide a relatively stable shoulder surface. Although this proved difficult, it was finally accomplished and the remainder of the trials were run using heights that were as close as practical to the target values. The tables presented in the Results section list the approximate range of edge drop heights experienced by each subject.

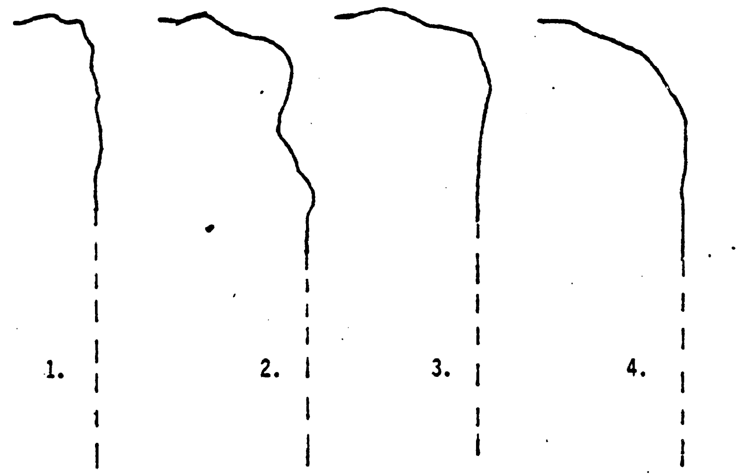
Edge shape. Two edge shapes were employed. Most of the runs were made using a vertical face with a short-radius transition to the horizontal surface. Figure 4 shows typical examples of these edges from the 3- and 4.5-inch drop zones used in the test. Runs were also made using a 45-degree bevel edge that was 4.5 inches high.

Speed. Using the vertical face, the naive subjects were run at two different speeds at each level of edge drop. Based on pilot data, these were set at 30 and 40 mph for the 4.5-inch drop, and 40 and 50 mph for the 3-inch drop. The intent was that these two speeds would bracket the "critical speed," i.e., a speed at and above which most trials resulted in the car intruding beyond the adjacent 12-foot lane. However, the initial speed selection proved optimistic, with all subjects moving beyond the adjacent lane during recovery on most trials even at the lower speed. Therefore, many subjects originally scheduled for the higher speed at each drop condition were run at speeds ten miles per hour less than the lowest speed originally scheduled (i.e., 20 mph at the 4.5 inch drop and 30 mph at the 3.0 inch drop). Using the 45-degree bevel edge, subjects made successive runs at increasing speeds, up to a maximum of 55 mph. Generally, one run was made at each speed, although some were repeated if the experimenter thought the first attempt was not right in some respect.

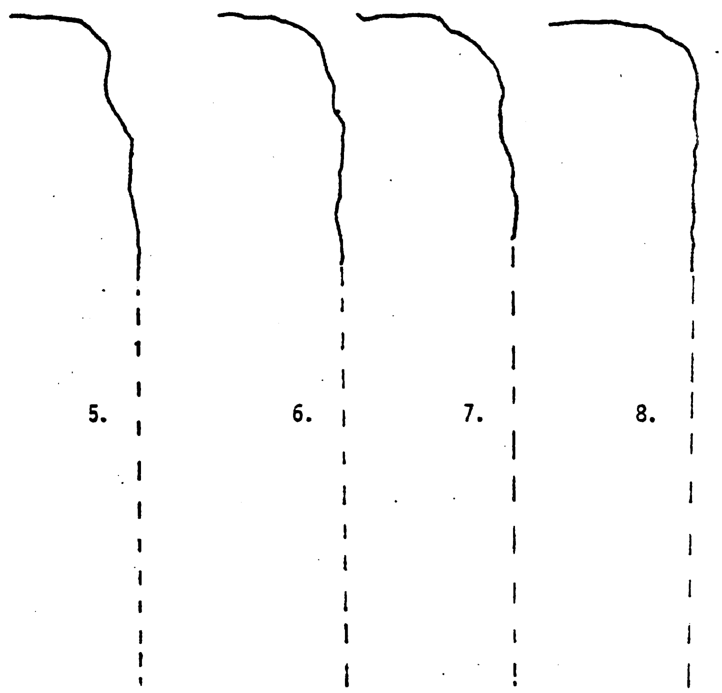
Vehicles. Three vehicles were used. One was a full-size sedan (1979 Chevrolet Impala), with rear-wheel drive. The second was a small, rear-wheel drive sedan (1977 Chevrolet Vega). The third was a small, front-wheel drive sedan (1980 Honda Civic). The naive drivers used only the large, rear-wheel drive car. The professional driver used all three.

Shoulder condition. Most of the data were collected on a dry, hard-packed dirt shoulder. To evaluate the effects of a soft shoulder, the deeper edge drop was partially filled with soft sand for a limited number of runs with the professional driver.

Subjects Fifty naive subjects were run in the test. These people were employees of the Texas Transportation Institute, most occupying clerical and technical positions. None were or ever had been professional drivers. Half the test subjects were male, half female. Their ages ranged from 20 to 48 years.



Edge profile samples from 3-inch-drop site



Edge profile samples from 4.5-inch-drop site

Figure 4. Sample pavement edge profiles.

The original intent was to run ten subjects in each of the five cells of the speed by edge-drop height by edge-shape matrix. However, some shifting was required because another (lower) level of speed was added to each vertical-face edge drop condition. The subjects were distributed as follows:

Condition A (40 mph, nominal 4.5-inch edge drop): 3 subjects

Condition B (50 mph, nominal 3.0-inch edge drop): 6 subjects

Condition C (30 mph, nominal 4.5-inch edge drop): 9 subjects

Condition D (40 mph, nominal 3.0-inch edge drop): 10 subjects

Condition E (30 mph, nominal 3.0-inch edge drop): 8 subjects

Condition F (various speeds, nominal 4.5-inch edge drop): 4 subjects

Condition G (various speeds, 45-degree bevel edge, nominal 4.5-inch drop): 10 subjects

Some subjects were run under more than one condition, after it became clear that learning effects were relatively small. Three of the subjects in Condition G had previously participated in one of the other conditions.

A professional driver was used as well. This individual was tested on both vertical-face edge drops, with all three cars. He was also tested on the sand-fill condition. These tests were run at a wide range of speeds.

Dependent Variables

Lane-keeping. The primary measure was the ability of the driver to keep the vehicle within the 12-foot lane adjacent to the drop. To measure this, all runs were recorded on videotape by a camera suspended about 20 feet above the lane used for the tests. Video recordings for the 45-degree bevel edge were made from ground level.

Driver-vehicle measures. The vehicle was instrumented to measure and record the following variables on the vertical-face tests:

a. Lateral acceleration
b. Yaw rate
c. Steer angle
d. Steer torque

These measures were selected as providing a good representation of the severity of the recovery maneuver and the amount of work the driver was doing. It was expected that they would be correlated with lane-keeping performance, which was the variable of primary concern. However, it was thought useful to collect these data for two reasons: first, they were deemed a useful supplement as an indication of the task difficulty from the subject's perspective; second, it was possible that they might provide a more sensitive indication of appropriate task limits.

The data were recorded on digital magnetic tape for later analysis.

Test Facility

The field test was conducted at the Texas Transportation Institute. It was set up along the edge of a former runway. The surface is concrete, 7,000 feet long and 160 feet wide. The vegetation and top soil were removed for a distance of 750 feet at three points along the runway for the 3-, 4–1/2 inch and 45-degree bevel edge drops. Figure 5 is a view of one of the test areas. This photograph was taken looking back toward the start point for each run. The joint in the pavement to the left of the white line is 12 feet 6 inches from the pavement edge. Although this was a bit generous, it was used as the lane edge for purposes of data analysis. The cones on the right of the picture are distance markers, set at 50-foot intervals. The five cones in the shoulder area on the left of the picture form a barrier intended to encourage the driver to remount the edge. Figure 6 is a close up of the 3-inch edge.

Safety Considerations

A number of steps were taken to ensure maximum safety for the subjects and the experimenter involved in the tests. First, the test was run on a facility that allowed a great deal of room for recovery if the subject experienced severe difficulty. Second, the tests were run at speeds intended to do no more than provide the subjects with problems staying in the adjacent lane. Third, the vehicle was equipped with a roll bar, outriggers to prevent roll over (see Figure 7) and a safety fuel tank. Fourth, the vehicle occupants wore full safety harnesses and helmets.

Method

The subjects reported individually to the test site. Each was given a brief explanation of the purpose of the study, a description of the potential risks, and an explanation of the safety features of the test vehicle. In describing the driving task to the subjects, special emphasis was placed on returning to the pavement from a scrubbing position and keeping the vehicle in the lane adjacent to the shoulder.

At this point the experimenter and subject entered the car, with the experimenter driving. They strapped themselves in, donned their helmets, and the experimenter

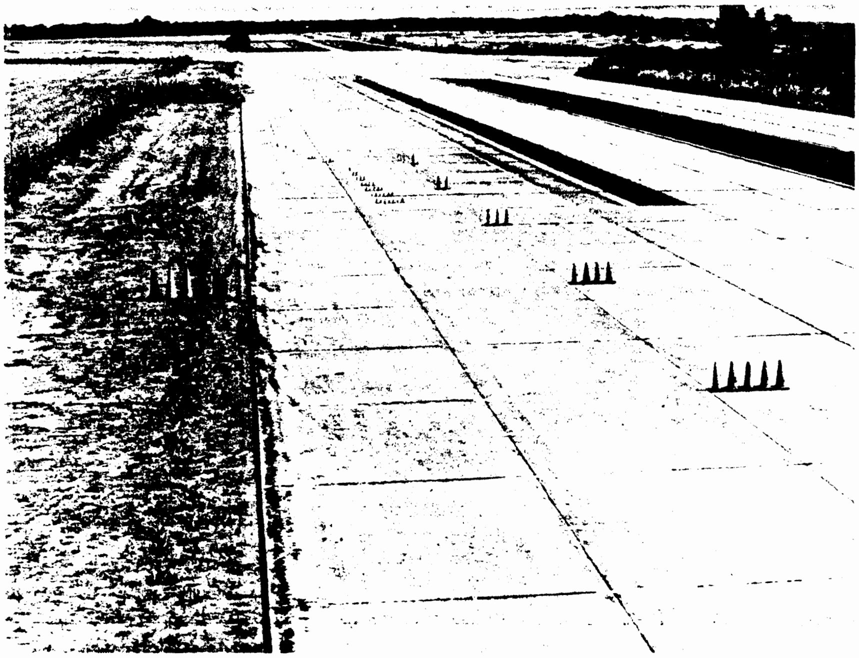


Figure 5. Overall view of one of the test areas, looking back toward the vehicle start point.

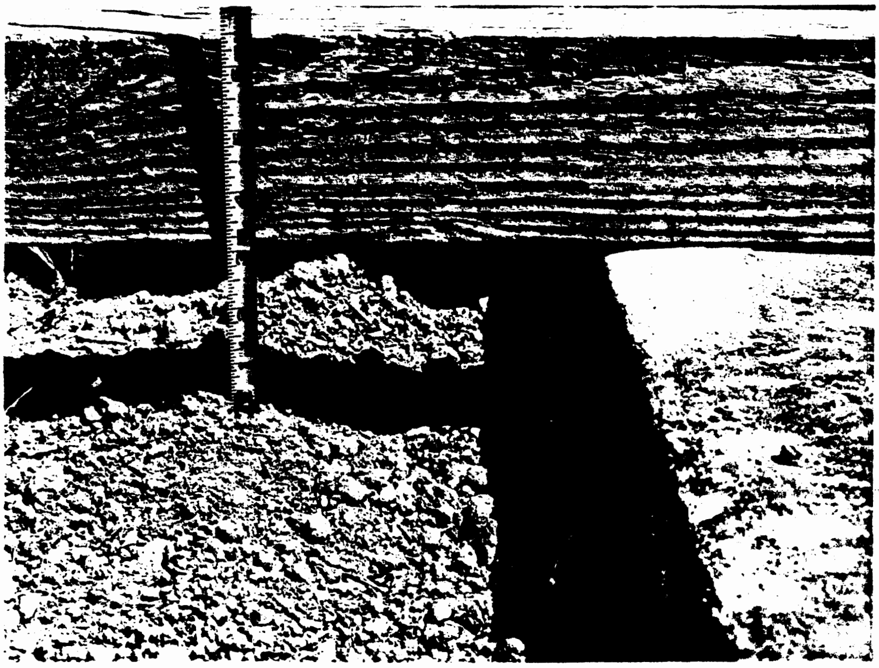


Figure 6. Close-up photograph of edge in the 3-inch drop area.

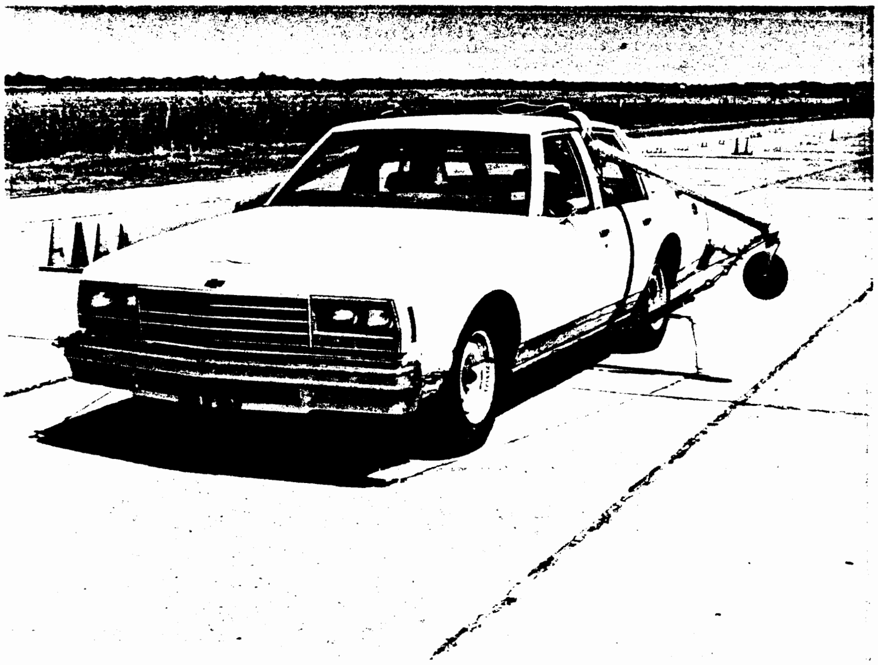


Figure 7. Photograph of large, rearwheel drive vehicle as set up for edge drop tests.

demonstrated, at low speed, how to start the test, enter the shoulder area, and achieve a scrubbing condition. He did not demonstrate recovery from the drop off. The experimenter and subject then swapped places and the subject drove the test vehicle for 5–10 minutes to become familiar with its handling characteristics and the operation of the cruise control. Following this, the subject practiced, at a speed substantially below the intended test speed, the entire test run sequence except for the recovery maneuver. The practice runs were repeated until both the subject and the experimenter were confident that the subject understood the task and would be likely to scrub on the first test run at the prescribed speed.

On each trial the sequence was as follows:

1. The experimenter, in the vehicle with the subject, received a "ready" signal via radio from the video operator.

2. The subject accelerated to the prescribed speed and activated the cruise control. The experimenter verified the speed setting.

3. As the vehicle approached the test area, the experimenter instructed the video operator to begin taping, announced subject and run number identification, initiated collection of the instrumentation data, and prompted the subject to begin the maneuver sequence. This prompting took the form of telling the subject to:

   "Move over" – gradually steer the vehicle to the right toward the pavement edge.

   "Drop off" – drop the right side tires off the pavement onto the soil shoulder.

   "Scrub" – gradually bring the vehicle back toward the pavement and maintain a position in which the right side tires are rubbing against the vertical edge of the pavement.

   "Get back up" – return the vehicle to the pavement from the scrubbing position.

The experimenter could not "feel" scrub with the 45-degree bevel edge the way he could with the vertical-face edges. Therefore, it was not possible to be sure the tires were in contact with the edge prior to recovery.

4. By instruction, the subject was not to use the brakes during the drop off, scrub and recovery portions of the run. The instructions also stated that immediately upon returning to the pavement the subject should continue driving as though on a two-lane highway. It was emphasized that the subject should stay in the

right lane. To reinforce this idea, the subject was told to imagine that an "18-wheeler" was approaching in the on-coming lane.

5. After having gained satisfactory control of the vehicle, the subject was instructed to slow down and return to the test start point, where the data collection system was reset and the tires were inspected for excessive sidewall wear. The next trial could then be started. Figures 8 through 12 illustrate the sequence of events. In Figure 8 the test vehicle is approaching the drop-off area. In Figure 9 the right-side wheels are on the shoulder and the subject is starting to move toward the edge. In Figure 10 the right-side wheels are in contact with the pavement edge and the subject is starting the recovery maneuver. In Figure 11 the front wheel has mounted the edge of the pavement. In Figure 12 the entire car is out of the shoulder area and is about to intrude beyond the adjacent lane. Figure 13 is a ground-level shot of the vehicle just prior to the front wheel mounting the pavement. Note the large steer angle on this 3-inch edge. Also note the "groove" worn in the adjacent shoulder area. The plowing action of the front wheels displaced the soil in this area, causing the changes in edge-drop height noted earlier.

The general approach for the tests run on the 45-degree bevel edge was the same. The difference was that, after training, these subjects made a series of runs at increasing speeds, starting at 40 mph and ending at 55 mph.

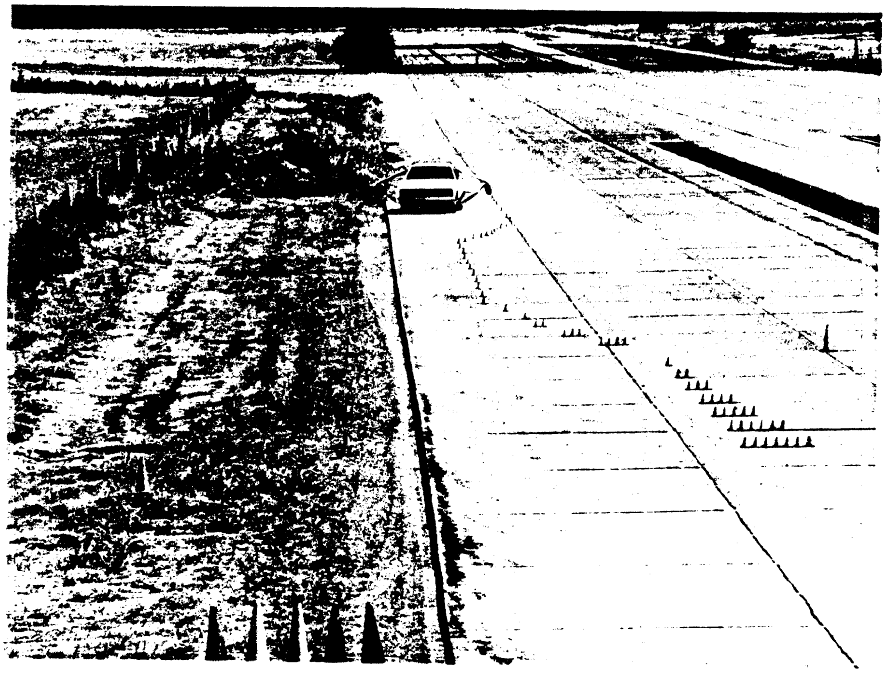


Figure 8. Photograph of test vehicle in approach to test area.

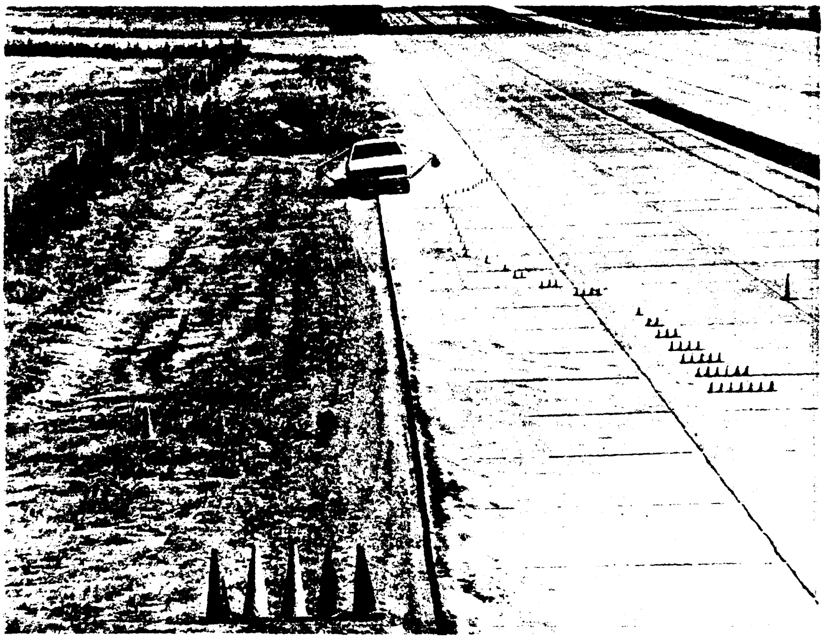


Figure 9. Photograph of test vehicle after right-side wheels have dropped onto shoulder.

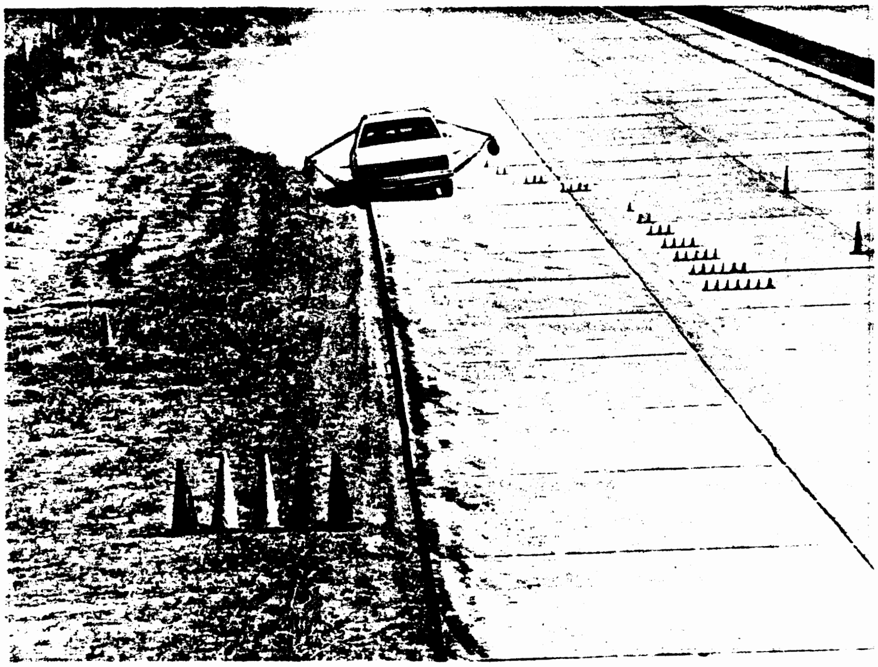


Figure 10. Photograph of test vehicle with right-side wheels in scrubbing contact with the pavement edge.

Figure 11. Photograph of test vehicle as front wheel mounts the edge.

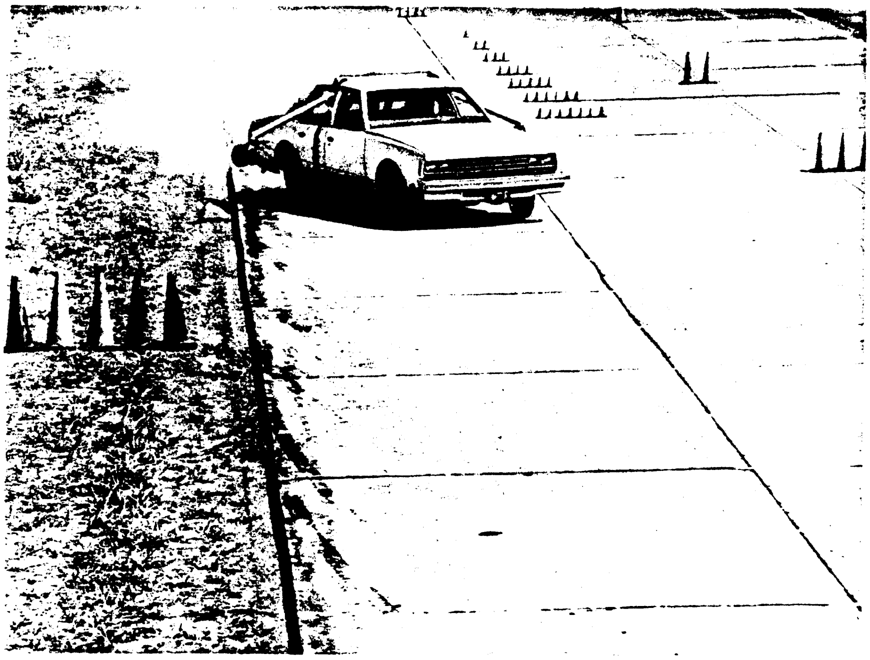


Figure 12. Photograph of test vehicle immediately after the rear wheel has mounted the edge drop.

Figure 13. Photograph of test vehicle taken just before front wheel mounted the edge.

Results

Lane Keeping

The maneuvers were viewed on video and scored on a 9-point scale as follows:

1 = Recovered to about the center of the adjacent lane (i.e., the lane next to the edge drop)

2 = Recovered to left of center of the adjacent lane

3 = Recovered just barely in the adjacent lane

4 = Intruded about 1-2 feet into the second lane (i.e., the lane to the left of the adjacent lane)

5 = Intruded about half the car width into the second lane

6 = Intruded about three-quarters of the car width into the second lane

7 = Intruded fully into the second lane

8 = Intruded into the third lane

9 = Intruded more than three lanes over from the edge drop

Clearly, scores of 4 or higher represent potentially dangerous situations in that the driver has gone beyond his/her lane, raising the possibility of a collision with parallel or oncoming vehicles. In addition, it should be recalled that these data are based on a 12.5-foot lane. On roads having narrower lanes, a minor incursion that would rate "4" under these conditions can be much more serious.

In the data tables that follow the number of trials shown for subjects differ. This is because they include only those trials on which an apparent good scrubbing condition was obtained prior to initiation of the recovery maneuver.

Vertical Edge – Naive Drivers. Table 1 gives the results for the naive drivers on the larger drop at 40 mph. Only three subjects were run under this condition because it quickly became apparent that it was too difficult. As evidence of this, it will be noted that on four of the ten trials the subject went at least fully into the second lane.

Table 2 shows the results on the larger edge drop at 30 mph. Unfortunately, many of these trials were run at depths up to 1.5 inches greater than intended. However, even when the depth was approximately correct, as it was for the earlier subjects and subjects F 1, F 2, and F 4, intrusions substantially into the second lane were common.

TABLE 1

RESULTS FOR NAIVE DRIVERS AT 40 MPH ON THE LARGER EDGE DROP (nominal 4.5 inches), VERTICAL EDGE

Subject Number	Performance Score by Trial					Estimated Actual Depth (inches)
	1	2	3	4	5	
A 1	7	6				4.5−5.0
A 2	5	4	4			4.25−4.75
A 3	4	3	7	8	8	3.75−4.50

TABLE 2

RESULTS FOR NAIVE DRIVERS AT 30 MPH ON THE LARGER EDGE DROP (nominal 4.5 inches), VERTICAL EDGE

Subject Number	Performance Score by Trial					Estimated Actual Depth (inches)
	1	2	3	4	5	
C 1	4	4	5	3	5	4.5−5.0
C 2	7	7	4	7		4.5−6.0
C 3	7	4	7			4.5−6.0
C 4	5	6	5			4.5−6.0
C 5	7	4	7	7		4.5−6.0
C 6	7	8	5	7		4.5−6.0
C 7	7	7	7			4.5−6.0
C 8	7	3	3	3	4	4.5−6.0
C 9	7	5	4	5		5.0−6.0
F 1*	7	7				3.75−5.0
F 2*	4	5				3.75−5.0
F 4*	5	7				4.0−5.0

*These three subjects were run on this combination after having run it at 20 mph.

Table 3 shows the results from four subjects run on the larger drop at speeds ranging from 20 to 32 mph. The drop heights were consistently about right during this series of trials. Even at the lowest speeds tested, the subjects usually intruded beyond the adjacent lane, especially on the first trial.

TABLE 3

RESULTS FOR THE NAIVE DRIVERS AT VARIOUS SPEEDS ON THE LARGER EDGE DROP (nominally 4.5 inches), VERTICAL EDGE

Subject Number	Speed (mph)	Performance Score by Trial					Estimated Actual Depth (inches)
		1	2	3	4	5	
F 1	20	3	3	3	3	2	3.75−5.0
F 1	30	7	7				3.75−5.0
F 2	20	5	4	3	3	4	3.75−5.0
F 2	30	4	5				3.75−5.0
F 3	22	5	3	2	2		3.75−5.0
F 3	27	4	3	3			3.75−5.0
F 3	32	4	4				3.75−5.0
F 4	20	5	2	2	3	3	4.0−5.0
F 4	25	3	2				4.0−5.0
F 4	30	5	7				4.0−5.0

Table 4 shows the results for the naive drivers on the smaller edge drop at 50 mph. Almost all of these data were collected on a drop deeper than intended, hence the relatively poor performance is not surprising.

TABLE 4

RESULTS FOR THE NAIVE DRIVERS AT 50 MPH ON THE SMALLER EDGE DROP (nominally 3.0 inches), VERTICAL EDGE

Subject Number	Performance Score by Trial						Estimated Actual Depth (inches)
	1	2	3	4	5	6	
B 1	5	5	4	5	4	5	3.0−4.0
B 2	4	4	4	5			3.5−4.5
B 3	4	9					3.5−4.5
B 4	4	4	4	4			3.5−4.5
B 5	7	7					3.5−4.5
B 6	9	9	4	4			3.5−4.5

Table 5 shows the results for the naive drivers on the smaller edge drop at 40 mph. For subjects D2 through D7, the edge drops were deeper than intended. However, for the others they were close and, even here, a consistent pattern of lane violations is seen.

TABLE 5

RESULTS FOR NAIVE DRIVERS AT 40 MPH ON THE SMALLER EDGE DROP (nominal 3.0 inches), VERTICAL EDGE

Subject Number	Performance Score by Trial					Estimated Actual Depth (inches)
	1	2	3	4	5	
D 1	5	4	4	3		3.0–3.5
D 2	7	5	4	3		3.5–4.5
D 3	4	6	5	5	7	3.5–4.5
D 4	7	9	9			3.5–4.5
D 5	7	7	5	4		3.5–4.5
D 6	5	4	5	4	4	3.5–4.5
D 7	5	5	4	4	7	3.5–4.5
D 8	7	6	7	6	4	3.0–4.0
D 9	4	5	3	3		3.0–3.75
D 10	5	4	5			3.0–3.75
E 8*	3					3.0–3.5

*This subject was run on this combination after having run it at 30 mph.

Table 6 shows the results for the naive drivers on the smaller edge drop at 30 mph. For subjects E1 through E4 the drop heights are deeper than intended. However, for subjects E5 through E8 they are about right. Subject E5 had trouble staying within the adjacent 12-foot lane, but the other three subjects did so with a high degree of consistency.

TABLE 6

RESULTS FOR NAIVE DRIVERS AT 30 MPH ON THE SMALLER EDGE DROP (nominal 3.0 inches), VERTICAL EDGE

Subject Number	Performance Score by Trial						Estimated Actual Depth (inches)
	1	2	3	4	5	6	
E 1	5	4	3	5			3.5–4.0
E 2	6	5	7	5	5		3.75–4.5
E 3	7	4	4	4			3.75–4.75
E 4	7	7	7				3.75–4.75
E 5	4	5	4	4	5		3.0–3.5
E 6	3	3	2	3	4		3.0–3.5
E 7	3	2	2	2	3	2	3.0–3.5
E 8	2	2	2	2	2		3.0–3.5

To provide a summary of the performance of the naive subjects, means were calculated of the lane-keeping scores listed in Tables 1 through 6. Such a calculation assumes that the lane-keeping scale is at least equal-interval, which it clearly is not. However, as a simple and convenient basis for comparison, it was felt to be adequate. Table 7 lists means for all trials run by the naive subjects, including those at excessive depth. It is clear that the mean performance changed little at the higher speeds. Only at the lowest speeds used was there an improvement in mean performance.

Table 8 is identical to Table 7, except that only those trials run at correct edge drop heights are included. Except for the 30 mph, 3.0-inch edge drop, this correction had little effect.

A question of some concern was the degree to which the subjects learned how to improve their performance in this task. If their performance improved rapidly, then only the first trial scores would have much meaning. As a way of addressing this question, means of the subjects' performance scores were calculated on a trial by trial basis. The results of this analysis are shown in Table 9. An inspection of Table 9 suggests that there was some improvement with repeated exposure, although the differences are generally not large. In addition, as will be shown shortly, the performance of the naive subjects was, at best, much poorer than that of the professional driver.

Vertical Edge – Professional Driver. Table 10 summarizes the results for the professional driver using all three cars on the smaller edge drop. These runs were made with the height of the edge drop close to the target value. With the large, rear-wheel drive vehicle he rarely intruded beyond the adjacent lane at any of the speeds used (up to 55 mph). Compare this with the performance of the naive subjects (Tables 4, 5, and 6), who were rarely able to stay within the adjacent lane at speeds above 30 mph.

However, the performance of the professional driver seems to have deteriorated somewhat when operating the smaller vehicles, especially the front-wheel drive car. With the small rear-wheel drive car most recoveries were within the adjacent lane up to 45 mph. However, with the small front-wheel car, most attempts above 30 mph resulted in encroachments beyond the adjacent lane.

The results for the professional driver on the larger edge drop are summarized in Table 11. The first series of trials with the larger car were made with the drop deeper than planned, so these runs were repeated.

Comparing Table 11 with Tables 1, 2 and 3, it is clear that the professional driver did much better than the naive drivers with the larger edge drop. However, he was rarely

TABLE 7

MEAN LANE-KEEPING SCORES FOR NAIVE SUBJECTS AT VARIOUS SPEEDS AND EDGE DROP HEIGHTS. ALL RECORDED TRIALS

Speed (mph)	Edge Drop Height (inches)	
	4.5	3.0
50		5.2
40	5.6	5.1
30	5.6	3.9
20	3.2	

TABLE 8

MEAN LANE-KEEPING SCORES FOR NAIVE SUBJECTS AT VARIOUS SPEEDS AND EDGE DROP HEIGHTS. INCLUDES ONLY THOSE TRIALS RUN AT CORRECT DROP HEIGHTS

Speed (mph)	Edge Drop Height (inches)	
	4.5	3.0
50		4.7
40	5.6	4.6
30	5.2	2.4
20	3.2	

able to stay within the adjacent 12-foot lane, although most of the intrusions were minor. Performance appears to be somewhat poorer with the two small cars, although the number of trials is small.

Table 12 is a listing of the mean lane-keeping scores for the professional driver at various speeds in the three vehicles, and at the two edge drop heights. These means are based on very few trials. Hence they must be interpreted with caution. However, they do

TABLE 9

ANALYSIS OF LEARNING EFFECTS FOR THE NAIVE SUBJECTS

Condition	Mean Performance Score by Trial				
	1	2	3	4	5
3 inch edge drop 30 mph	4.0	3.4	3.9	3.6	3.8
3 inch edge drop 40 mph	5.6	5.5	5.1	3.6	
3 inch edge drop 50 mph	5.5	6.3	4.0	4.5	
4.5 inch edge drop 30 mph	6.4	5.3	5.2	5.3	
4.5 inch edge drop 40 mph	5.3	4.3	5.5		

summarize the between-vehicle differences rather well, making it clear that the large, rear-wheel drive vehicle was much more controllable in this task.

Soft Shoulders. Table 13 presents the results of the professional driver, using the large car, on the soft-shoulder test. Comparing these results with those obtained in the smaller drop without sand fill (Table 10) indicates that the soft shoulder had a negative effect on recovery capability. A comparison of the data in Table 10 with that in Table 11 (larger drop without sand fill) indicates comparable performance, suggesting that the principal effect of a soft shoulder is simply to increase the height to be climbed.

45-Degree Bevel Edge. This test was run only with naive subjects. The results are summarized in Table 14. An inspection of this table shows that at all speeds up to 55 mph the subjects had little trouble negotiating the drop. Only twice did the vehicle encroach beyond the adjacent lane. Both of these were recorded at speeds below 55 mph, and in each case another run was made at the same speed resulting in a score of "1."

In-Vehicle Measures.

As noted earlier, recordings were made of lateral acceleration, yaw rate, steering wheel angle, and steer torque. These recordings were made in the large, rear-wheel drive vehicle only, with both naive drivers and the professional.

TABLE 10

RESULTS FOR THE PROFESSIONAL DRIVER AT VARIOUS SPEEDS ON THE SMALLER EDGE DROP (nominally 3.0 inches), VERTICAL EDGE

Car	Speed (mph)	Performance Score by Trial					Estimated Actual Depth (inches)
		1	2	3	4	5	
Large RW Drive	30	3	2	2			3.0−3.5
	35	2	2	2	2	4	3.0−3.5
	40	2	2	2			3.0−3.5
	45	2	2	4			3.0−3.5
	50	2	3	2	2	3	3.0−3.5
	55	2	4	3			3.0−3.5
Small RW Drive	30	3	4	3			3.0−3.5
	35	4	2	2	3		3.0−3.5
	40	3	4	2			3.0−3.5
	45	5	4	5			3.0−3.5
Small FW Drive	39	6					3.0−3.5
	31	5					3.0−3.5
	33	3					3.0−3.5
	27	2					3.0−3.5
	28	3	4				3.0−3.5
	23	2					3.0−3.5
	33	5	3				3.0−3.5
	35	4	4				3.0−3.5

TABLE 11

RESULTS FOR THE PROFESSIONAL DRIVER AT VARIOUS SPEEDS ON THE LARGER EDGE DROP (nominally 4.5 mph), VERTICAL EDGE

Car	Speed (mph)	Performance Score by Trial			Estimated Actual Depth (inches)
		1	2	3	
Large RW Drive	30	4	2	2	5.0−6.0
	40	4	2	2	5.0−6.0
	50	4	6	4	5.0−6.0
	55	7	7		5.0−6.0
	30	4	4	3	4.0−4.5
	35	4	4	2	4.0−4.5
	40	4	4		4.0−4.75
	45	4	7		4.0−4.75
Small RW Drive	22	5	5		4.5−5.0
	25	7			4.5−5.0
	15	4	5	4	4.5−5.0
Small FW Drive	20	4	3	2	4.5−5.0
	30	4	4	4	4.5−5.0
	35	5			4.5−5.0

TABLE 12

MEAN LANE-KEEPING SCORES FOR THE PROFESSIONAL DRIVER AT VARIOUS SPEEDS AND EDGE DROP HEIGHTS> INCLUDES ONLY THOSE TRIALS RUN AT CORRECT DROP HEIGHTS

Edge Drop (inches)	Speed (mph)	Vehicle		
		Large RW Drive	Small RW Drive	Small FW Drive
3.0	25	–	–	2.0
	30	2.3	3.3	4.0
	35	2.4	2.8	4.0
	40	2.0	3.0	6.0
	45	2.7	4.7	–
	50	2.4	–	–
	55	3.0	–	–
4.5	15	–	4.3	–
	20	–	5.0	3.0
	25	–	7.0	–
	30	3.7	–	4.0
	35	3.3	–	5.0
	40	4.0	–	–
	45	5.5	–	–

TABLE 13

RESULTS FOR THE PROFESSIONAL DRIVER AT VARIOUS SPEEDS IN THE SAND FILL USING THE LARGE, REAR-WHEEL DRIVE CAR

Speed (mph)	Performance Score by Trial	
	1	2
35	4	
40	4	1
45	2	
50	4	4
55	4	
52	4	

Note: The nominal 4.5 inch edge drop site was filled with sugar sand to within 3.0 inches of the pavement to simulate a soft or muddy shoulder. The condition was restored after each run.

TABLE 14

RESULTS FOR THE NAIVE DRIVERS AT VARIOUS SPEEDS ON THE 4.5 inch, 45° BEVEL EDGE

Subject Number	Performance Score by Speed (mph)			
	40	45	50	55
1	2	3	4 1*	1
2	1	2	1 1	1
3	1	1	1	1
4	1	1	1	1 1
5	1	1	1	1 1
6	1	1	1	1 1
7	1 4	2	1 1	1
8	2		3 1	1
9	3	1	1 1	3
10	1 1	1	2	1 1

*In some cases more than one run was made at a given speed.

On each run the subjects first had to pull the car to their left, out of the edge drop. Once that had been accomplished, it was necessary to initiate a corrective action in the opposite direction in an effort to retain or recover the initial lane position. This process could continue through a number of iterations until the vehicle was stable. However, typically, the first two maneuvers were the most severe. As an indication of the difficulty level of the task and the work the subjects were doing, it was decided to read the peaks of each of the measures for the first two maneuvers.

The detailed results of this analysis are given in Appendix B. Table 15 is a summary, comparing the means of the obtained data for the various speed and edge-drop conditions, for both naive and professional drivers. An inspection of Table 15 reveals a remarkable level of uniformity in the results. That is, regardless of the condition being tested, lateral acceleration peaks averaged close to 0.5 g, yaw rates averaged generally between 20 and 30 degrees/sec., and first peak steer torque averaged close to 25 foot-pounds. Second peak steer torque averaged higher and was more variable, although there was no obvious relationship with the independent variables. Steer angle was the only measure that seemed to have a clear relationship with edge drop height. As would be expected, the higher drop was associated with greater average steer angles.

TABLE 15

MEANS OBTAINED FOR IN-VEHICLE MEASURES UNDER VARIOUS CONDITIONS OF SPEED AND EDGE DROP HEIGHT FOR BOTH NAIVE AND PROFESSIONAL DRIVERS

Driver	Speed (mph)	Edge Height (inches)	Peak Reading	Measures			
				Lateral Acceleration (g)	Yaw Rate (Degrees/Sec)	Steer Angle (degrees)	Steer Torque (Foot-Pounds)
Naive	40	4.5	1	0.52	23.7	174	21.9
			2	0.53	50.7	176	40.8
	30	4.5	1	0.59	29.7	236	28.1
			2	0.51	31.9	204	48.3
	Various	4.5	1	0.49	29.1	254	27.8
	≤ 30		2	0.43	25.8	215	68.8
	50	3.0	1	0.51	15.9	104	22.3
			2	0.40	20.2	98	31.2
	40	3.0	1	0.54	21.9	145	25.6
			2	0.44	26.0	134	38.6
	30	3.0	1	0.53	23.2	168	23.5
			2	0.41	25.1	144	41.7
Professional	Various	4.5	1	0.49	26.0	190	25.3
	≤ 55		2	0.56	41.0	236	77.1
	Various	3.0	1	0.46	22.4	155	23.8
	≤ 55		2	0.50	29.4	157	61.9

SUMMARY AND CONCLUSIONS

Introduction

Pavement edge drops are recognized as potentially serious hazards. Because of this there has been considerable interest in better defining safe limits for edge drops as a guide to maintenance. A number of investigators have worked on the problem, utilizing both field studies and analytical techniques. Their work is reviewed in the introductory section of this report.

While progress has been made in addressing the issue of edge drops, significant questions remain. One problem arises from the fact that most field investigations of edge drops have used professional drivers. The degree to which one can extrapolate from the performance of professional drivers to that of typical drivers has not been addressed. The one study that used a large number of "naive" subjects employed only one size of edge drop (4.5 inches). In addition, in some studies the lateral position of the vehicle relative to the edge drop has not been controlled. Not knowing whether the tires were scrubbing prior to the recovery attempt makes it difficult to evaluate the results.

Still, it appears from the available data that edge drops on the order of 4.5 inches are a severe hazard at medium and higher speeds, that soft shoulders do not pose special problems (the difficulty of recovery being determined by the vertical height to be negotiated), and that the shape of the pavement edge can have a significant effect on the ability of drivers to successfully remount the primary surface.

The present study was designed to add to the store of useful information about the effect of edge drops in several ways, i.e.:

a. Through the extensive use of naive subjects.

b. By a process that obtained useful data on the subjects' first exposure to the edge drop and permitted an assessment of the ability of participants to improve their performance on successive trials.

c. By evaluating different edge-drop heights and shapes.

d. By using different size vehicles, and vehicles with both front- and rear-wheel drive.

e. By comparing hard-packed with soft shoulders.

Conclusions

It is very important that the reader bear in mind that the specific situation investigated was recovery from a situation in which the right-side tires were in contact with the pavement edge (scrubbing). Scrubbing is clearly the worst case. Because of this, it would be a serious error to infer that the results of this investigation apply to all encounters with edge drops. Initiating the recovery maneuver while the tires are even a short distance from the pavement edge makes the task much easier, and greatly reduces the probability that the vehicle will intrude beyond the adjacent lane. Actually, scrubbing is a state that is somewhat difficult to achieve. In all probability, the proportion of motorists who "experience" an edge drop and actually scrub prior to recovery is very small.

The naive subjects in this study experienced much greater difficulty with the recovery task than anticipated. This is instructive in that it indicates that data taken in earlier studies using professional drivers significantly overestimate the performance to be expected from ordinary drivers. However, it creates a problem in that the safe limits suggested by the results of this investigation for edge drops having a vertical face are far below normal highway speeds. Thus the question of what is a safe height for such a configuration at higher speeds remains to be resolved.

For edge drops having a vertical face and short-radius transition at the top, the results of this investigation indicate that heights on the order of 4.5 inches present severe hazards. Naive drivers can hardly drive slowly enough to be able to remount such a drop from a scrubbing position without intruding beyond the adjacent lane. Clearly, edge drops of this magnitude should be avoided if at all possible. This is in disagreement with the results of Klein and Johnson (1978), the only other study in the published literature that relied largely on naive subjects. Klein and Johnson report a "critical speed" (a speed above which most trials resulted in encroachments beyond the adjacent lane) of about 42 mph in the test vehicle used by most subjects. The critical speeds of the other two vehicles were about 30 mph. Neither the professional nor naive drivers in the current investigation could recover within the adjacent lane at 30 mph on the 4.5-inch drop with any of the vehicles used. The reason(s) for the substantial differences between these two investigations is not known.

The results for edge drops on the order of 3 inches are somewhat mixed. On the one hand, it appears that naive drivers can generally negotiate such drops without intruding beyond the adjacent lane at speeds up to 30 mph. However, these tests were run in a relatively large car. The professional driver experienced frequent intrusions beyond the adjacent lane on the 3-inch drop in the small front-wheel drive car at speeds near 30 mph. Given that: (1) the professional driver's performance in this study was generally much better than the naive drivers', and (2) small cars are very common on the nation's highways today, it appears that the maximum safe speed for a 3-inch drop would be something less than 30 mph. How much less can be roughly approximated, by comparing the performance of the professional and naive drivers. On this basis, it appears that it would be between 20 and 25 mph.

The shape of the edge drop can have a very great effect on the problems drivers many experience in attempting to negotiate it. To the extent it is possible to do, it is recommended that in the future pavement edges be shaped approximately like the 45-degree bevel edge used in this study. Such a configuration should greatly reduce, if not eliminate, control problems attributable to edge drops.

Soft shoulders present a special hazard. Soft material allows the vehicle's wheels to sink in to some degree, effectively increasing the height to be negotiated. It is the actual height that the wheel must climb during the remounting effort, and not the undisturbed pavement surface to shoulder surface distance that determines the difficulty that the driver will experience during the maneuver. On the other hand, soft material in the shoulder area does not appear to exert an appreciable effect through drag or other dynamic phenomena.

The comparison of front- and rear-wheel drive vehicles did not yield consistent data. Both small cars seemed to have greater difficulty in negotiating the edge drops than did the larger car. However, the front-wheel drive car did somewhat better than the rear-wheel drive car on the 4.5-inch drop, while the opposite is true on the 3-inch drop. Further study on this issue would be desirable.

The analysis of learning effects in this investigation indicates that ordinarily drivers do not rapidly increase their skill in negotiating pavement edge drops. This means that future investigators can make repeated use of their subjects without undue concern about increases in basic capability.

Based on the results of this investigation, and assuming that protection against a worst-case scenario (i.e., recovery from a scrubbing condition) is viewed as desirable, it appears that edge drop having a vertical face should be controlled to no more than 3 inches, and then should be posted for speeds no greater than 25 mph. To maximize safety, particularly on high-speed roads, edge drops should either be controlled to depths less than 3 inches (although, there are at present no objective data to indicate what a safe height would be) or the pavement edge should be shaped in a way that facilitates recovery (e.g., by providing a 45-degree bevel).

A key remaining practical concern is the maximum permissible edge drop height for highways posted at 55 mph. Assuming that recovery from a scrubbing condition is the determining factor, the results of this study suggest that the recommendations of other researchers (e.g., Ivey et al., 1984) are not adequate. This discrepancy may be due to use of the scrubbing condition criterion. Thus, the primary remaining issue may not be pinning down the edge height at which drivers can safely recover form a scrubbing condition, but rather a policy matter, i.e., deciding the reasonableness of using recovery from the scrubbing condition as a determining factor for setting edge drop height.

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APPENDIX – A

A SURVEY OF STATE PRACTICES

Background

An issue of interest is the attitudes various states have toward maintenance of edge drops. Confronted as they are with the necessity of maintaining vast networks of various types of roads, and dealing with various operating and climate conditions, it was felt that their operating policies may provide useful insights into the issue of pavement edge drops. One such survey was conducted by Nordlin et al. (1976), who summarized policies from their own state (California) and five others. The data were apparently collected in 1974. The results are summarized below:

California had four categories, depending on the type of shoulder construction. These are as follows:

1. Paved shoulder: repair edge drops greater than 3/4 inch.
2. Unpaved shoulder: repair edge drops greater than 1-1/2 inch, or when edge failure becomes apparent.
3. Asphaltic concrete shoulders less than 8 feet wide, with unpaved area beyond that (drop from shoulder to unpaved area): repair edge drops greater than 1-1/2 inch or when edge failure becomes apparent.
4. Asphaltic concrete shoulders 8 feet wide or more, with unpaved area beyond that (drop from shoulder to unpaved area): repair edge drops greater than 3 inches or when edge failure becomes apparent.

Illinois had no published standards, but attempted to keep shoulders flush with the pavement. They posted warning signs to alert traffic to shoulder construction.

New York had three categories of standards as follows:

1. A 2 inch maximum edge drop on state highways with a one-way design hourly volume less than 200 vph.
2. A 1-1/2 inch maximum edge drop for state highways with one-way design hourly volumes of 200–500 vph.
3. A 1 inch maximum edge drop on expressways with volumes over 500 vph.

Oregon required shoulders to be flush with the traveled way. They were also considering a change in their standards to permit a 2-inch maximum edge drop between the traveled-way pavement and a gravel shoulder. They also posted warning signs to alert traffic to shoulder construction.

Texas had no published standards, but they generally tried to limit edge drops to no more than 2 to 3 inches. They also provided a minimum 12:1 taper on new overlays between the traveled way pavement and the paved shoulder. It was also their practice to post warning signs to alert traffic to shoulder construction.

Washington required shoulders to be flush with the traveled way. They posted warning signs indicating "abrupt lane edge" during repaving operations and "shoulder drop off" at locations where the removal of a shoulder presented a dangerous hazard to traffic. They also required ruts or potholes over 3 inches deep in gravel or crushed stone shoulders to be filled with stabilized material.

Current Survey

As part of the background effort for the current program, a survey was taken of edge-drop attitudes and practices in nine states. Those contacted included the six reported on by Nordlin et al., plus Michigan, Pennsylvania, and Virginia. Individuals associated with new construction and maintenance in each state were contacted by telephone. Each person was asked what their state's policies were regarding edge drops. They were also asked if there were written policies. If there were, a copy was requested.

There were some differences in the results of the two surveys in the same states. In some cases the policies seem to have become less specific. In part this may be due to the persons talked to in each state and the questions asked by the interviewer. However, litigation was mentioned repeatedly as a concern when formulating guidelines. It may be that, lacking hard evidence on which to base objective criteria, some states have elected to produce very general guidelines as a means of sheltering themselves in case of litigation.

The results are summarized as follows:

California

New construction: It is intended that there be no edge drops. California did have a policy that allowed a 0.10 foot (1.2 inches) drop at lane lines. This has now been increased to 0.15 foot (1.8 inches).

Maintenance: There is a written policy concerning shoulder maintenance. It says that for asphaltic shoulders greater than two feet in width, loss of lateral support at the outside edge should be scheduled for repair when the loss in vertical depth of the adjacent material approximates the outside edge thickness of the surfaced shoulder, or when edge failure is apparent. For surfaced shoulders less than two feet in width (or where no surfaced shoulders exist) adjacent areas should be scheduled for maintenance on an as-needed basis to prevent loss of lateral support.

Illinois

New construction: It is intended that there be no edge drops. Illinois has various practices concerning shoulder treatments. For example, they will pave one-half of the shoulder with asphalt and use aggregate for the other half on new construction. However, there is to be no drop at either interface. A drop of 0.5 inch is allowed between paved and turf shoulders, to allow for drainage.

Maintenance: The state has written maintenance policies. These are very general, describing the condition of interest and the approved repair procedure. For example, it describes the placing of a bituminous concrete wedge adjacent to the shoulder to eliminate the potential hazard of a wheel dropping off. This is to be done when the shoulder surface is sufficiently lower than the edge of the pavement for an extended length so that driving onto the shoulder or back onto the pavement causes steering problems. Priority is to be given to locations where the edge drop is such that a wheel running off the edge would most severely affect vehicle control. However, no specific edge drop heights are given.

Michigan

New construction: All shoulders are paved with the same material as the road surface. It is intended that there be no edge drops. Shoulders are paved 8 or 9 feet on the right side and 3 or 5 feet on the left side. The same policies are followed on 3R projects.

Maintenance: There is no written policy on edge drops maintenance. Their practice is as follows:

For gravel shoulders, if the drop is one inch or less they regrade. If the drop is more than one inch and if the outside edge of the shoulder is 3–1/2 inches or more lower than normal, they cut a trench next to the paved lane, place new gravel in the trench, moving the old gravel to the outside, and regrade.

For asphalt shoulders, if the drop is in excess of one inch they use a slurry seal filler. If the shoulder has deteriorated too much they schedule a new three-foot wide asphalt ribbon.

New York

New construction: New York does not have guidelines at the present time, but they are in the process of developing them. They do pave virtually all shoulders, and the intent is that there be no edge drop. They consider the edge drop eliminated when the area has been backfilled to provide a slope of not less than 1:4.

Maintenance: For purposes of maintenance New York recognizes four classifications of roads. These are:

A1. Expressways with low average running speeds, Interurban and intercity state routes with a one-way design volume of 500 to 1,000 VPH or more and approaching capacity. Edge drops should be repaired when they exceed 1 inch.

A2. Expressways with high average running speeds. Edge drops should be repaired when they exceed 1 inch.

B. Minor state highways with a one-way design volume of 200 to 500 VPH. Edge drops should be repaired when they exceed 1-1/2 inches.

C. Minor state highways with a one-way design volume of less than 200 VPH. Edge drops should be repaired when they exceed 2 inches.

Oregon

New construction: For all new and 3R projects Oregon paves the shoulder. It is intended that there be no edge drops.

Maintenance: The state has general written guidelines. For shoulders composed of earth or sod, and gravel or crushed rock, corrective action should be taken when an edge drop of 2 inches or more is generally present or when roughness or rutting constitutes a safety hazard. For oiled, paved or curbed shoulders the guidelines say that they should be maintained in a manner consistent with the adjacent traveled roadway.

Pennsylvania

New construction: Pennsylvania paves all shoulders in various materials, depending on the nature of the road and traffic volume. It is intended that there be no edge drops.

Maintenance: The state's maintenance policy encourages level shoulders. There are no fixed guidelines to suggest when an edge drop should be repaired. The state is developing a roadway management system. As part of this process it is trying to help engineers select jobs for betterment. Among the problems being examined are edge drops.

Texas

New construction: The intent is that there be no edge drops.

Maintenance: The state has no written guidelines for maintenance. They make an effort to keep all problems, including edge drops, under control to the point that there is no hazard. This is especially true on horizontal curves. They also maintain stricter control in rural areas (because of higher speeds) than in urban areas.

Virginia

New construction: The state has written guidelines. Edge drops are not specifically mentioned in them. The intent is that there will be no edge drops.

Maintenance: There are no separate written policies for maintenance. The same standards apply here as in new construction, that is, it is intended that there be no edge drops.

Washington

New construction: The state has written guidelines. While not specifically addressed, the intention is that there will be no edge drops.

Maintenance: There are no separate written policies for maintenance. The same standards apply here as in new construction, that is, it is intended that there be no edge drops.

The survey makes it clear that the states are struggling with the issue of edge drops, but have arrived at no consensus concerning acceptable limits.

APPENDIX B

IN-VEHICLE MEASUREMENTS RESULTS

The results of the in-vehicle measurements are shown in Tables B-1 through B-8. The order and

general arrangement of these tables is the same as for the lane-keeping data. For each subject results of all four measures are shown for each trial. The first and second numbers for each measure are the peak values obtained for the first maneuver (i.e., pulling out of the edge drop to the left) and second maneuver (i.e., recovery to the right) respectively. Lane-keeping performance scores are shown for each trial as well. These tables do not match perfectly with earlier tables because data were lost on some trials.

Table B-1 gives the results for the naive subjects at 40 mph on the larger edge drop. It is interesting to examine the individual trial values and compare them with the lane-keeping measure. For example, subject 3, on trials 4 and 5, intruded into the third lane (score of 8). On those trials he experienced g forces ranging from about 0.6 to nearly 0.8, yaw rates ranging from about 30 to 40 degrees/sec, turned the steering wheel as much as 295 degrees in each direction, and exerted torque on the wheel ranging from 24 to more than 50 foot-pounds. On the other hand, in trial 2, the same subject stayed within the lane adjacent to the edge drop (score of 3). While he was exposed to g levels of about 0.5, the other measures, especially steering angle, were much lower than in the case of trials 4 and 5. Such differences may be attributable, at least in part, to the degree of scrub in each case. As far as the experimenter riding with the subject and the individual viewing the TV data could determine, a good scrub was achieved on all trials presented in the tables. However, if the tires broke contact with the edge just prior to the recovery maneuver for example, the task would be made easier without the observer being aware of the change.

Table B-2 gives the results for naive drivers at 30 mph on the larger edge drop. Although the speed is 10 mph less, a comparison of the means for the 30 and 40 mph conditions as given in Table 15 does not suggest it was conspicuously easier.

Table B-3 completes the summary of work on the larger edge drop. Again, a comparison of the means for these conditions as presented in Table 15 indicates little, if any, difference.

Tables B-4 through B-6 summarize the results with the naive drivers obtained on the smaller edge drop. In Table B-6, it is instructive to compare subjects E 1 through E 4 (where the edge drops were deeper than intended) with subjects E 5 through E 8. Clearly, the level of difficulty for the last four subjects was much less than for the first four, and lane-keeping performance improved accordingly.

TABLE B-1

RESULTS FOR NAIVE DRIVERS AT 40 MPH ON THE LARGER EDGE DROP (nominally 4.5 inches), VERTICAL EDGE

Subject Number	Measure	Trials 1	2	3	4	5	Estimated Actual Depth (inches)
A 1	Performance	7	6				4.5 − 5.0
	Lateral Accel.	0.61	0.49				
		0.68	0.34				
	Yaw Rate	25.4	27.1				
		39.3	23.7				
	Steer Angle	239	234				
		218	247				
	Steer Torque	38.5	—				
		61.4	—				
A 2	Performance	5	4	4			4.25 − 4.75
	Lateral Accel.	0.57	0.53	0.54			
		0.40	0.50	0.56			
	Yaw Rate	19.7	22.0	23.5			
		26.1	33.3	36.8			
	Steer Angle	114	118	156			
		109	139	159			
	Steer Torque	21.3	16.4	17.4			
		27.7	27.3	43.5			
A 3	Performance	4	3	7	8	8	3.75 − 4.5
	Lateral Accel.	0.41	0.53	0.65	0.69	0.63	
		0.35	0.41	0.67	0.78	0.62	
	Yaw Rate	8.3	11.9	29.7	33.5	36.3	
		20.5	25.5	—	—	41.0	
	Steer Angle	98	33	216	295	238	
		84	96	202	290	221	
	Steer Torque	21.4	9.9	22.9	24.0	25.3	
		32.9	31.5	48.6	52.5	39.3	

<u>Units:</u>
Lateral Accel. g
Yaw Rate Degrees/Sec
Steer Angle Degrees
Steer Torque Foot-Pounds

TABLE B-2

RESULTS FOR NAIVE DRIVERS AT 30 MPH ON THE LARGER EDGE DROP (nominally 4.5 inches), VERTICAL EDGE

Subject Number	Measure	Trials					Estimated Actual Depth (inches)
		1	2	3	4	5	
C-1	Performance	4			3		4.5–5.0
	Lateral Accel.	0.32			0.56		
		0.12			0.58		
	Yaw Rate	9.9			26.5		
		8.4			34.1		
	Steer Angle	77			286		
		68			236		
	Steer Torque	20.2			32.3		
		27.5			43.3		
C 2	Performance	7	7	4	7		4.5–6.0
	Lateral Accel.	0.61	0.60	0.54	0.59		
		0.37	0.66	0.59	0.61		
	Yaw Rate	24.9	30.8	25.5	32.9		
		17.8	38.8	35.1	38.7		
	Steer Angle	122	241	153	284		
		111	239	215	230		
	Steer Torque	27.5	26.8	28.9	30.8		
		30.4	43.8	35.2	40.4		
C 3	Performance	7	4	7			4.5–6.0
	Lateral Accel.	0.60	0.54	0.54			
		0.50	0.49	0.50			
	Yaw Rate	28.5	25.9	29.0			
		32.5	31.7	34.8			
	Steer Angle	293	289	–			
		213	200	271			
	Steer Torque	30.5	27.6	–			
		46.5	54.8	87.9			
C 4	Performance	5	6	5			4.5–6.0
	Lateral Accel.	0.53	0.52	0.51			
		0.53	0.67	0.48			
	Yaw Rate	33.2	34.1	29.9			
		36.2	–	31.8			
	Steer Angle	210	232	208			
		206	233	168			
	Steer Torque	27.1	27.2	26.8			
		52.7	37.2	37.8			
C 5	Performance	7	4	7	7		4.5–6.0
	Lateral Accel.	0.64	0.50	0.64	0.60		
		0.39	0.29	0.64	0.65		

TABLE B-2 (continued)

Subject Number	Measure	Trials 1	2	3	4	5	Estimated Actual Depth (inches)
C 5 (cont.)	Yaw Rate	32.2	20.2	34.0	34.2		
		27.9	26.3	41.3	–		
	Steer Angle	267	93	437	288		
		141	138	255	295		
	Steer Torque	23.5	23.4	29.9	28.1		
		28.5	28.1	74.6	56.8		
C 6	Performance	7	8	5	7		4.5–6.0
	Lateral Accel.	0.58	0.65	0.58	0.65		
		0.61	0.60	0.58	0.62		
	Yaw Rate	33.9	31.2	27.2	30.9		
		–	35.6	37.3	41.2		
	Steer Angle	221	383	191	426		
		276	200	222	242		
	Steer Torque	28.6	32.4	26.3	31.8		
		45.4	33.5	46.5	63.2		
C 7	Performance	7	7	7			4.5–6.0
	Lateral Accel.	0.63	0.64	0.61			
		0.45	0.36	0.43			
	Yaw Rate	31.2	32.6	31.7			
		32.6	29.5	30.8			
	Steer Angle	265	432	368			
		193	227	213			
	Steer Torque	25.7	24.2	24.3			
		42.1	52.6	69.5			
C 8	Performance	7	3	3	3	4	4.5–6.0
	Lateral Accel.	0.59	0.42	0.44	0.46	0.50	
		0.39	0.42	0.51	0.43	0.68	
	Yaw Rate	35.1	27.9	29.1	29.4	31.0	
		28.8	32.1	35.0	30.3	–	
	Steer Angle	204	137	182	170	190	
		172	186	221	173	227	
	Steer Torque	29.4	26.8	26.3	26.9	21.7	
		53.0	60.9	68.4	68.6	70.2	
C 9	Performance	7	5	4	5		5.0–6.0
	Lateral Accel.	0.64	0.59	0.54	0.57		
		0.56	0.57	0.56	0.54		
	Yaw Rate	32.8	32.6	30.9	30.5		
		29.3	34.2	31.6	29.2		
	Steer Angle	129	205	162	175		
		187	215	195	164		

TABLE B-2 (continued)

Subject Number	Measure	Trials					Estimated Actual Depth (inches)
		1	2	3	4	5	
C 9 (cont.)	Steer Torque	28.1 30.2	27.8 33.6	27.6 32.9	31.6 27.0		

Units:
Lateral Accel. g
Yaw Rate Degrees/Sec
Steer Angle Degrees
Steer Torque Foot-Pounds

TABLE B-3

RESULTS FOR NAIVE DRIVERS AT VARIOUS SPEEDS ON THE LARGER EDGE DROP (nominally 4.5 inches), VERTICAL EDGE

Subject Number	Speed (mph)	Measure	Trials 1	2	3	4	5	Estimated Actual Depth (inches)
F 1	20	Performance	3	3	3	3	2	3.75 − 5.0
		Lateral Accel.	0.51	0.44	0.45	0.46	0.42	
			0.38	0.31	0.39	0.33	0.34	
		Yaw Rate	25.3	24.2	24.5	25.3	24.0	
			29.5	24.0	29.2	25.2	25.9	
		Steer Angle	209	242	229	238	223	
			234	186	225	192	196	
		Steer Torque	22.9	19.3	26.9	29.4	24.6	
			66.6	76.3	74.7	76.3	76.1	
F 1	30	Performance	7	7				3.75 − 5.0
		Lateral Accel.	0.66	0.62				
			0.71	0.69				
		Yaw Rate	34.7	34.2				
			—	—				
		Steer Angle	354	362				
			296	273				
		Steer Torque	29.8	28.8				
			94.7	58.5				
F 2	20	Performance	5	4	3		4	3.75 − 5.0
		Lateral Accel.	0.52	0.47	0.44		0.49	
			0.27	0.34	0.26		0.34	

TABLE B-3 (continued)

Subject Number	Speed (mph)	Measure	Trials 1	2	3	4	5	Estimated Actual Depth (inches)
F 2 (cont.)		Yaw Rate	32.6	30.1	28.9		29.6	
			15.6	18.4	15.1		18.9	
		Steer Angle	241	243	229		239	
			130	167	152		170	
		Steer Torque	29.4	25.3	28.6		29.4	
			28.2	48.7	43.6		63.6	
F 2	30	Performance	4	5				3.75 – 5.0
		Lateral Accel.	0.55	0.61				
			0.56	0.48				
		Yaw Rate	32.1	34.3				
			29.2	23.6				
		Steer Angle	229	250				
			187	157				
		Steer Torque	29.2	30.4				
			55.1	36.9				
F 3	22	Performance	5	3	2	2		3.75 – 5.0
		Lateral Accel.	0.53	0.45	0.42	0.34		
			0.39	0.40	0.39	0.38		
		Yaw Rate	34.7	32.4	29.2	25.5		
			23.1	26.1	24.9	23.5		
		Steer Angle	376	321	234	204		
			202	244	234	202		
		Steer Torque	32.3	29.9	27.1	27.4		
			89.9	93.5	61.9	73.7		
F 3	27	Performance	4	3	3			3.75 – 5.0

TABLE B-3 (continued)

Subject Number	Speed (mph)	Measure	Trials 1	Trials 2	Trials 3	Trials 4	Trials 5	Estimated Actual Depth (inches)
F 3 (cont.)		Lateral Accel.	0.50	0.52	0.47			
			0.57	0.53	0.53			
		Yaw Rate	34.0	31.2	29.2			
			33.4	33.3	29.7			
		Steer Angle	327	227	313			
			266	241	243			
		Steer Torque	30.8	28.7	30.4			
			96.8	88.3	61.6			
F 3	32	Performance	4	4				3.75 – 5.0
		Lateral Accel.	0.53	0.53				
			0.60	0.64				
		Yaw Rate	29.0	35.0				
			35.4	—				
		Steer Angle	301	270				
			262	291				
		Steer Torque	30.7	30.0				
			100.6	101.5				
F 4	20	Performance	5	2	2	3	3	4.0 – 5.0
		Lateral Accel.	0.53	0.35	0.28	0.41	0.41	
			0.36	0.36	0.26	0.43	0.37	
		Yaw Rate	33.9	23.3	19.5	28.3	26.5	
			24.3	25.4	20.5	30.2	24.9	
F 4 (cont.)		Steer Angle	309	165	144	336	212	
			210	212	152	284	216	

TABLE B-3 (continued)

Subject Number	Speed (mph)	Measure	Trials 1	Trials 2	Trials 3	Trials 4	Trials 5	Estimated Actual Depth (inches)
F 4 (cont.)		Steer Torque	25.9	25.0	25.1	31.9	27.7	
			43.6	58.0	48.1	80.5	70.7	
F 4	25	Performance	3	2				4.0−5.0
		Lateral Accel.	0.47	0.40				
			0.43	0.43				
		Yaw Rate	27.9	22.7				
			25.4	27.8				
		Steer Angle	200	181				
			209	209				
		Steer Torque	27.1	26.5				
			59.7	67.2				
F 4	30	Performance	5					4.0−5.0
		Lateral Accel.	0.57					
			0.54					
		Yaw Rate	29.4					
			34.2					
		Steer Angle	224					
			226					
		Steer Torque	24.1					
			70.3					

Units:
Lateral Accel. g
Yaw Rate Degrees/Sec
Steer Angle Degrees
Steer Torque Foot-Pounds

TABLE B-4

RESULTS FOR NAIVE DRIVERS AT 50 MPH ON THE SMALLER EDGE DROP (nominally 3.0 inches), VERTICAL EDGE

Subject Number	Measure	Trials					Estimated Actual Depth (inches)
		1	2	3	4	5	
B 1	Performance	5	5	4	5	4	3.0 − 4.0
	Lateral Accel.	0.45	0.49	0.46	0.64	0.45	
		0.13	0.25	0.31	0.47	0.38	
	Yaw Rate	13.3	10.3	9.0	21.9	9.9	
		7.1	12.7	13.4	22.0	15.6	
	Steer Angle	77	83	77	102	72	
		57	55	74	98	92	
	Steer Torque	22.1	24.5	21.4	24.9	24.0	
		26.0	25.6	27.4	23.5	26.1	
B 2	Performance		4	4	5		3.5 − 4.5
	Lateral Accel.		0.55	0.60	0.64		
			0.57	0.71	0.62		
	Yaw Rate		21.9	26.4	34.1		
			30.1	40.5	37.2		
	Steer Angle		140	181	177		
			163	237	197		
	Steer Torque		19.9	28.1	29.7		
			56.3	78.2	42.0		
B 3	Performance	4					3.5 − 4.5
	Lateral Accel.	0.39					
		0.27					
	Yaw Rate	4.4					
		14.7					
	Steer Angle	86					
		72					
	Steer Torque	17.6					
		26.6					
B 4 (no data)							3.5 − 4.5
B 5	Performance	7	7				3.5 − 4.5
	Lateral Accel.	0.68	0.48				
		0.54	0.50				
	Yaw Rate	27.4	10.7				
		32.6	9.6				
	Steer Angle	157	91				
		109	16				
	Steer Torque	9.2	19.3				
		34.1	5.7				

TABLE B-4 (continued)

Subject Number	Measure	Trials					Estimated Actual Depth (inches)
		1	2	3	4	5	
B 6	Performance	9	9	4	4		3.5−4.5
	Lateral Accel.	0.25	0.72	0.26	0.52		
		0.41	0.29	0.08	0.54		
	Yaw Rate	9.0	23.8	3.2	13.2		
		15.9	20.8	7.7	23.3		
	Steer Angle	58	203	14	106		
		90	70	22	118		
	Steer Torque	20.4	30.1	14.2	29.6		
		26.9	28.2	11.2	29.8		

Units:
Lateral Accel. g
Yaw Rate Degrees/Sec
Steer Angle Degrees
Steer Torque Foot-Pounds

TABLE B-5

RESULTS FOR NAIVE DRIVERS AT 40 MPH ON THE SMALLER EDGE DROP (nominally 3.0 inches), VERTICAL EDGE

Subject Number	Measure	Trials					Estimated Actual Depth (inches)
		1	2	3	4	5	
D 1	Performance	5		4	3		3.0 – 3–5
	Lateral Accel.	0.52		0.54	0.50		
		0.25		0.48	0.45		
	Yaw Rate	22.3		24.8	18.7		
		17.0		26.9	22.9		
	Steer Angle	175		172	114		
		97		138	132		
	Steer Torque	19.4		24.7	29.8		
		19.4		27.1	30.4		
D 2	Performance	7	5	4	3		3.5 – 4.5
	Lateral Accel.	0.57	0.51	0.36	0.36		
		0.31	0.38	0.11	0.35		
	Yaw Rate	23.0	23.9	8.5	15.1		
		23.2	21.6	7.3	22.0		
	Steer Angle	167	178	40	166		
		112	121	50	141		
	Steer Torque	22.7	27.9	22.5	34.3		
		21.2	33.9	24.4	46.7		
D 3	Performance	4	6	5	5	7	3.5 – 4.5
	Lateral Accel.	0.52	0.52	0.56	0.60	0.63	
		0.44	0.36	0.46	0.55	0.61	
	Yaw Rate	19.1	19.1	24.2	25.6	27.4	
		23.5	19.0	31.0	33.0	39.2	
	Steer Angle	166	163	194	158	219	
		137	107	162	180	223	
	Steer Torque	38.6	18.4	24.3	19.7	22.8	
		41.3	29.9	35.9	47.2	48.2	
D 4 (no data)							3.5 – 4.5
D 5	Performance		7	5	4		3.5 – 4.5
	Lateral Accel.		0.63	0.56	0.50		
			0.43	0.43	0.42		
	Yaw Rate		23.4	21.1	14.4		
			25.5	23.7	21.1		
	Steer Angle		194	139	90		
			95	107	102		
	Steer Torque		25.7	22.7	22.3		
			23.6	32.7	30.1		

TABLE B-5 (continued)

Subject Number	Measure	Trials 1	2	3	4	5	Estimated Actual Depth (inches)
D 6	Performance	5	4	5	4	4	3.5−4.5
	Lateral Accel.	0.60	0.51	0.60	0.58	0.54	
		0.54	0.57	0.63	0.67	0.64	
	Yaw Rate	29.1	26.5	28.0	27.3	25.7	
		30.0	33.2	34.5	39.0	37.7	
	Steer Angle	161	207	227	150	–	
		144	213	197	230	224	
	Steer Torque	29.9	32.7	36.9	33.6	–	
		21.8	88.5	76.8	83.4	63.6	
D 7	Performance	5	5	4	4	7	3.5−4.5
	Lateral Accel.	0.58	0.57	0.53	0.52	0.60	
		0.47	0.52	0.55	0.51	0.48	
	Yaw Rate	23.7	27.4	27.5	23.6	32.6	
		28.8	31.8	37.2	28.4	31.8	
	Steer Angle	163	198	167	170	235	
		141	166	182	157	177	
	Steer Torque	28.2	25.8	38.6	22.7	24.5	
		34.7	52.4	33.5	66.3	58.1	
D 8	Performance	7	6	7	6	4	3.0−4.0
	Lateral Accel.	0.55	0.55	0.64	0.62	0.55	
		0.18	0.44	0.35	0.68	0.54	
	Yaw Rate	17.5	15.4	23.2	27.5	22.5	
		13.8	29.8	23.4	39.0	38.1	
	Steer Angle	135	43	124	162	185	
		45	138	91	167	173	
	Steer Torque	24.8	20.4	21.5	24.0	25.1	
		28.8	21.1	34.3	30.0	35.9	
D 9	Performance	4	5	3	3		3.0−3.75
	Lateral Accel.	0.49	0.57	0.45	0.39		
		0.30	0.39	0.40	0.25		
	Yaw Rate	17.4	26.7	15.8	10.1		
		16.4	22.9	17.9	10.6		
	Steer Angle	69	119	74	56		
		77	91	97	65		
	Steer Torque	26.5	26.6	21.8	22.1		
		25.2	26.8	25.6	25.6		
D 10	Performance	5	4	5			3.0−3.75
	Lateral Accel.	0.54	0.56	0.54			
		0.34	0.54	0.35			
	Yaw Rate	16.3	23.0	20.4			
		16.1	34.5	21.3			

TABLE B-5 (continued)

Subject Number	Measure	Trials					Estimated Actual Depth (inches)
		1	2	3	4	5	
D 10 (cont.)	Steer Angle	111	116	152			
		55	146	81			
	Steer Torque	23.1	24.9	21.4			
		33.2	29.2	33.1			
E 8	Performance	3					3.0−3.5
	Lateral Accel.	0.50					
		0.38					
	Yaw Rate	16.3					
		26.0					
	Steer Angle	145					
		107					
	Steer Torque	17.9					
		46.1					

Units:
Lateral Accel. g
Yaw Rate Degrees/Sec
Steer Angle Degrees
Steer Torque Foot-Pounds

TABLE B-6

RESULTS FOR NAIVE DRIVERS AT 30 MPH ON THE SMALLER EDGE DROP (nominally 3.0 inches), VERTICAL EDGE

Subject Number	Measure	Trials						Estimated Actual Depth (inches)
		1	2	3	4	5	6	
E 1	Performance	5	4	3	5			3.5 − 4.0
	Lateral Accel.	0.61	0.60	0.49	0.62			
		0.59	0.57	0.43	0.66			
	Yaw Rate	28.6	26.9	21.0	29.7			
		39.0	38.8	26.8	40.7			
	Steer Angle	186	147	137	196			
		244	242	153	267			
	Steer Torque	26.2	20.6	17.3	21.5			
		44.9	53.5	41.6	81.3			
E 2	Performance	6	5	7	5	5		3.75 − 4.5
	Lateral Accel.	0.60	0.59	0.62	0.62	0.60		
		0.27	0.57	0.37	0.57	0.45		
	Yaw Rate	28.6	34.0	31.1	33.8	33.0		
		17.1	36.9	22.7	34.1	25.9		
	Steer Angle	160	220	131	228	225		
		85	205	108	206	141		
	Steer Torque	24.3	27.6	24.8	27.9	26.0		
		27.8	54.0	20.8	55.2	44.7		
E 3	Performance		4		4			3.75 − 4.75
	Lateral Accel.		0.54		0.56			
			0.48		0.53			
	Yaw Rate		28.5		29.5			
			32.8		36.6			
	Steer Angle		276		300			
			185		211			
	Steer Torque		40.8		29.7			
			85.3		86.2			
E 4	Performance	7	7	7				3.75 − 4.75
	Lateral Accel.	0.69	0.60	0.62				
		0.60	0.59	0.38				
	Yaw Rate	36.5	37.2	36.3				
		38.2	30.6	21.2				
	Steer Angle	292	267	302				
		214	187	132				
	Steer Torque	24.1	30.4	30.7				
		56.6	31.4	35.9				

TABLE B-6 (continued)

Subject Number	Measure	Trials 1	2	3	4	5	6	Estimated Actual Depth (inches)
E 5	Performance	4	5	4	4	5		3.0−3.5
	Lateral Accel.	0.58	0.66	0.61	0.58	0.65		
		0.35	0.53	0.37	0.32	0.45		
	Yaw Rate	24.7	26.8	21.6	22.2	27.0		
		17.0	24.6	17.0	14.9	21.3		
	Steer Angle	166	130	111	133	163		
		104	150	110	93	128		
	Steer Torque	26.1	26.7	24.1	24.8	26.0		
		27.1	30.4	28.7	29.1	29.2		
E 6	Performance	3	3	2	3	4		3.0−3.5
	Lateral Accel.	0.47	0.51	0.51	0.56	0.55		
		0.19	0.31	0.46	0.50	0.43		
	Yaw Rate	18.7	20.1	21.5	24.8	24.9		
		14.2	15.8	24.9	27.7	21.6		
	Steer Angle	115	139	161	173	173		
		63	94	151	160	122		
	Steer Torque	24.7	23.8	21.7	23.9	25.1		
		12.4	30.0	36.3	44.4	31.4		
E 7	Performance	3	2	2	2	3	2	3.0−3.5
	Lateral Accel.	0.41	0.48	0.49	0.46	0.54	0.40	
		0.17	0.37	0.45	0.36	0.44	0.28	
	Yaw Rate	9.9	15.8	18.6	15.9	20.0	12.6	
		13.3	23.1	29.1	23.0	21.4	19.2	
	Steer Angle	90	132	153	126	177	112	
		72	125	170	118	153	99	
	Steer Torque	16.7	17.6	18.7	16.9	19.0	17.4	
		33.2	40.9	46.1	36.1	61.2	34.4	
E 8	Performance	2	2	2	2	2		3.0−3.5
	Lateral Accel.	0.36	0.38	0.34	0.35	0.31		
		0.26	0.29	0.27	0.31	0.25		
	Yaw Rate	12.5	13.3	8.7	10.7	7.6		
		21.9	22.6	21.0	23.5	20.0		
	Steer Angle	140	118	103	114	93		
		111	115	107	121	92		
	Steer Torque	20.5	20.6	19.5	19.5	18.9		
		40.8	42.8	35.2	38.8	32.7		

Units:
Lateral Accel. g
Yaw Rate Degrees/Sec
Steer Angle Degrees
Steer Torque Foot-Pounds

Tables B-7 and B-8 summarize the results obtained with the professional driver at various speeds on the two edge drops. A comparison between the naive drivers and the professional at the same speeds indicates that the professional experienced lower g levels and yaw rates, didn't turn the steering wheel as far or apply as much torque as did most of the naive drivers on most of their runs.

TABLE B-7

RESULTS FOR THE PROFESSIONAL DRIVER AT VARIOUS SPEEDS ON THE SMALLER EDGE DROP (nominally 3.0 inches), VERTICAL EDGE, LARGE, REAR-WHEEL DRIVE CAR

Speed	Measure	Trials 1	Trials 2	Trials 3	Trials 4	Trials 5	Estimated Actual Depth (inches)
30	Performance		2	2			3.0−3.5
	Lateral Accel.		0.44	0.48			
			0.47	0.49			
	Yaw Rate		23.6	25.0			
			27.9	28.2			
	Steer Angle		178	177			
			176	172			
	Steer Torque		27.6	25.6			
			73.3	74.9			
35	Performance	2	2	2	2	4	3.0−3.5
	Lateral Accel.	0.38	0.41	0.40	0.47	0.56	
		0.42	0.46	0.48	0.47	0.61	
	Yaw Rate	16.9	18.2	20.0	19.2	25.5	
		23.7	24.1	27.7	25.3	35.9	
	Steer Angle	148	145	182	142	140	
		147	147	160	151	207	
	Steer Torque	26.7	23.7	32.4	25.0	24.3	
		63.4	58.1	63.3	65.6	70.9	
40	Performance	2	2	2			3.0−3.5
	Lateral Accel.	0.36	0.42	0.44			
		0.40	0.45	0.48			
	Yaw Rate	14.8	17.6	15.0			
		21.8	25.8	27.5			
	Steer Angle	152	177	142			
		111	133	147			
	Steer Torque	27.6	27.6	17.5			
		30.7	37.3	66.5			
45	Performance	2	2	4			3.0−3.5
	Lateral Accel.	0.45	0.47	0.54			
		0.54	0.53	0.63			
	Yaw Rate	16.0	17.4	24.4			
		32.0	32.0	40.1			
	Steer Angle	144	152	144			
		165	154	209			
	Steer Torque	24.4	28.2	22.3			
		47.0	54.0	71.4			

TABLE B-7 (continued)

Speed	Measure	Trials 1	2	3	4	5	Estimated Actual Depth (inches)
50	Performance	2	3	2	2	3	3.0−3.5
	Lateral Accel.	0.45	0.52	0.44	0.42	0.49	
		0.49	0.52	0.47	0.47	0.56	
	Yaw Rate	15.5	17.4	9.4	11.5	15.9	
		31.3	31.5	25.3	23.7	31.9	
	Steer Angle	134	138	98	114	161	
		153	156	136	123	160	
	Steer Torque	14.4	22.1	25.6	18.9	21.9	
		58.9	63.9	64.3	59.8	70.5	
55	Performance	2	4	3			3.0−3.5
	Lateral Accel.	0.47	0.52	0.51			
		0.53	0.59	0.53			
	Yaw Rate	13.2	18.6	15.8			
		30.2	39.1	32.7			
	Steer Angle	130	156	126			
		147	194	158			
	Steer Torque	22.2	21.7	19.2			
		67.2	74.4	64.2			

Units:
Lateral Accel. g
Yaw Rate Degrees/Sec
Steer Angle Degrees
Steer Torque Foot-Pounds

TABLE B-8

RESULTS FOR THE PROFESSIONAL DRIVER AT VARIOUS SPEEDS ON THE LARGER EDGE DROP (nominally 4.5 inches), VERTICAL EDGE, LARGE, REAR-WHEEL DRIVE CAR

Speed	Measure	Trials 1	Trials 2	Trials 3	Estimated Actual Depth (inches)
30	Performance		2	2	5.0–6.0
	Lateral Accel.		0.42	0.46	
			0.42	0.50	
	Yaw Rate		22.5	28.1	
			32.1	40.6	
	Steer Angle		125	141	
			186	251	
	Steer Torque		24.3	24.8	
			68.9	75.8	
40	Performance	4	2	2	5.0–6.0
	Lateral Accel.	0.48	0.43	0.38	
		0.51	0.48	0.46	
	Yaw Rate	25.9	21.9	18.6	
		39.2	38.9	36.1	
	Steer Angle	158	144	139	
		197	211	196	
	Steer Torque	22.9	30.8	26.0	
		68.9	74.5	68.9	
50	Performance	4		4	5.0–6.0
	Lateral Accel.	0.45		0.48	
		0.53		0.52	
	Yaw Rate	15.7		22.1	
		38.6		36.2	
	Steer Angle	154		193	
		198		200	
	Steer Torque	15.9		29.9	
		76.0		77.1	
55	Performance	7	7		5.0–6.0
	Lateral Accel.	0.61	0.58		
		0.64	0.64		
	Yaw Rate	38.9	33.2		
		—	—		
	Steer Angle	233	275		
		259	280		
	Steer Torque	35.7	35.6		
		50.8	93.2		

TABLE B-8 (continued)

Speed	Measure	Trials			Estimated Actual Depth (inches)
		1	2	3	
30	Performance	4	4	3	4.0–4.5
	Lateral Accel.	0.51	0.50	0.46	
		0.57	0.61	0.53	
	Yaw Rate	29.5	28.1	25.1	
		40.1	–	38.6	
	Steer Angle	195	285	226	
		253	292	230	
	Steer Torque	20.0	23.7	22.0	
		87.3	100.8	94.7	
35	Performance	4	4	2	4.0–4.75
	Lateral Accel.	0.49	0.56	0.39	
		0.61	0.59	0.52	
	Yaw Rate	27.9	29.3	19.4	
		–	–	39.0	
	Steer Angle	270	219	177	
		254	238	221	
	Steer Torque	24.6	24.8	22.5	
		94.1	91.8	76.3	
40	Performance	4	4		4.0–4.75
	Lateral Accel.	0.50	0.51		
		0.61	0.62		
	Yaw Rate	26.7	26.3		
		40.0	40.0		
	Steer Angle	217	208		
		250	238		
	Steer Torque	26.0	19.9		
		91.7	88.2		
45	Performance	4	7		4.0–4.75
	Lateral Accel.	0.51	0.59		
		0.62	0.69		
	Yaw Rate	26.9	28.4		
		–	–		
	Steer Angle	174	288		
		249	273		
	Steer Torque	20.1	30.7		
		86.0	49.4		

Units:
Lateral Accel. g
Yaw Rate Degrees/Sec
Steer Angle Degrees
Steer Torque Foot-Pounds