CHAPTER 4 Pavement Edges

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The Phenomenon

An abrupt difference in elevation between two adjacent riding surfaces can occur at the joining of (a) a paved traveled way and an unpaved shoulder, (b) a paved traveled way and a paved shoulder, (c) a paved shoulder and an unpaved adjacent area, or (d) two traveled lanes. If this difference in elevation reaches certain levels for certain edge shapes, safety can be affected.

Pavement edge drops can be produced when the longitudinal edges of an asphalt concrete pavement lift are not tapered to become flush with the surface of the existing paved shoulders. Edge elevation differentials are a necessary temporary situation at the edge of a pavement overlay until the adjacent overlay can be placed. Another common pavement edge drop can result from the displacement of untreated shoulder material from the edge of the traveled way caused by vehicle tire contacts or erosion from wind, rain, or other environmental conditions.

The pavement edge elevation differentials considered here range in height from less than 1 in. to 6 in. The edge drop-offs created by trenching for the construction of pavement widening, edge subdrainage systems, and so forth are deeper and constitute more obvious traffic safety problems.

Pavement edges can affect vehicle control because of inappropriate action or inaction by a driver. The following scenario describes some of the elements of an edge drop.

1. A vehicle is under control in a traffic lane adjacent to a pavement edge where an unpaved shoulder is lower than the pavement.
2. Through inattention, distraction, or some other reason the vehicle is allowed to move into a position with the right wheels on the unpaved shoulder and just off the paved surface.
3. The driver then carefully tries to gently steer the vehicle to gradually bring the right wheels back up onto the paved surface without reducing speed significantly.
4. The right front wheel encounters the pavement edge at an extremely flat angle and is prevented from moving back onto the pavement. The driver further increases the steer angle to make the vehicle regain the pavement. However, the vehicle continues to scrub the pavement edge and does not respond. At this time there is equilibrium between the cornering force to the left and the edge force acting to the right, as shown in Figure 1a.
5. The driver continues to increase the steer input until the critical steer angle is reached and the right front wheel finally mounts the paved surface. Suddenly, in less than one wheel revolution, the pavement edge force has disappeared and the cornering force of the right front wheel may have doubled because of increases in the available friction on the pavement and the increases in the right front wheel load caused by cornering (see Figure 1b).
6. The vehicle yaws radically to the left, pivoting about the right rear tire, until that wheel can be dragged up onto the pavement surface. The excessive left turn and yaw continues, and it is too rapid in its development for the driver to prevent penetrating the oncoming traffic lane (Figure 1c).
7. A collision with oncoming vehicles or spin out and possible vehicle roll may then occur.

In many situations vehicle loss of control may not develop because the driver steers more aggressively. By moving back onto the pavement at a slightly sharper angle and increased lateral velocity, the scrubbing action on the face of the pavement drop-off can be avoided. In many cases, however, the same result--vehicle loss of control--may occur without the influence of a pavement edge drop. A loose, muddy, or low-friction shoulder can have the same effect if the driver oversteers when trying to return to the paved surface. Often it is this oversteering that is the cause of an accident when a pavement edge drop of modest height is blamed.

The qualitative effect of pavement edges, or the so-called lip drop-off, has been to some degree understood for many years. In Baker's Traffic Accident Investigator's Manual (1) published by Northwestern University, 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 Baker on September 22, 1982, it was determined that this conclusion was

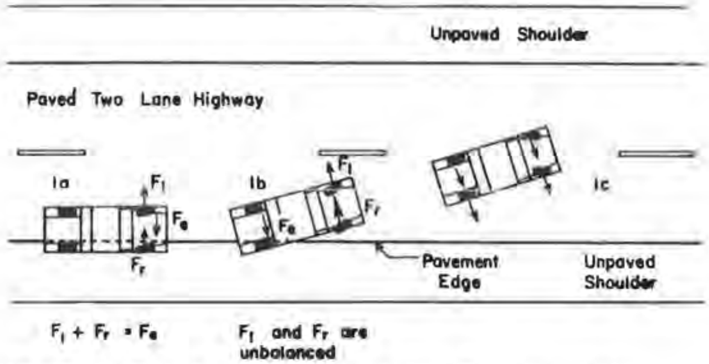

FIGURE 1 Illustration of the pavement edge influence on vehicle stability.

reached by informal testing at Northwestern as early as 1959.

Testing and Analysis

In 1974 the California Department of Transportation (Caltrans) studied several highway accident cases where pavement edge drops were cited as a contributing factor. There were contentions that a drop-off height as small as 1 to 2 in. would throw a vehicle out of control as it tried to climb back up the pavement edge, that the steering wheel would be wrenched out of the driver's hands, and that the vehicle would be forced into a path into the opposing lanes before it could be straightened out. As a result, Nordlin et al. (2,3) conducted a number of vehicle tests under various conditions to confirm or refute some of the claims that were being made and, in general, to observe the effects of pavement edge drops on vehicle stability and controllability.

Fifty tests were conducted by using a professional driver to compare the following test conditions:

1. Three drop-off heights--1.5, 3.5, and 4.5 in.;
2. Four test vehicles--small, medium, and large passenger automobiles and a pickup truck;
3. Two surface conditions--an asphalt concrete (AC) shoulder that dropped off to a compacted soil surface, and an AC shoulder that dropped off to another AC paved surface; the AC shoulder drop-off edges were nearly vertical and slightly irregular with minor cornering raveling; and
4. Two vehicle trajectories--with only the two right wheels dropping off and then coming back up onto the AC pavement, and next with all four wheels dropping off onto the shoulder and then returning back up onto the AC pavement.

The driver, a former race car driver, was a private consultant who conducted vehicular impact tests and other automotive research. In all of these tests the driver eased the test vehicle at about 60 mph out of the far right traveled-way pavement lane, across the 5-ft-wide AC shoulder, over the edge drop-off at angles of 1 to 7 degrees (generally 3 to 5 degrees), straightened the vehicle, climbed up the drop-off at angles of 1 to 8 degrees (generally 3 to 5 degrees), and eased across the AC shoulder back into the adjacent far right traveled-way lane. The path of the right tires during the two-wheel drop-off tests and the left tires during the four-wheel tests reached a distance of at least 1 ft and usually about 3 ft to the right of the drop-off edge.

The following observations were reported in regard to the formal tests in the Nordlin study.

1. The pavement edge drops did not throw the vehicles into an unstable condition or cause the driver to even come close to losing control during any of the tests.
2. For almost all of the steering maneuvers, the steering wheel was turned through an angle of 60 degrees or less. The driver handled the steering wheel with minimal effort at all times. In several of the tests he even held the wheel lightly with the thumb and forefinger of each hand. There was no difference in performance between vehicles with and without power steering.
3. It took less than one wheel revolution for the leading wheel to climb the drop-off once the pavement edge was contacted; thus tire scrubbing was negligible. Varying amounts of front wheel wobble occurred when the leading wheel mounted the 3.5- and 4.5-in. drop-offs. This was caused by the interaction of the tire sidewall and the irregular pavement edge. The driver felt a significant jolt and heard an accompanying loud front-end noise when the vehicles dropped off or remounted the 3.5- and 4.5-in. pavement drop-offs. A minimum roll angle of 10 degrees (generally 3 to 7 degrees) occurred when the vehicles went off and back up the drop-offs. However, none of these occurrences affected the trajectory of the vehicle in any of the tests. In all of the tests the vehicle traveled on a smooth path after climbing the drop-off without overshooting beyond the nearest traveled-way pavement lane.
4. During the formal test series two nonprofessional drivers (a male and a female) did not encounter any stability problems or have any steering difficulties while informally driving the medium and large passenger automobiles over and back up the three drop- off heights at speeds of 40 to 45 mph.

In 1978 Stoughton et al. (4) conducted several tests involving a broken, crumbling AC pavement edge and a 2-in. drop to the surface of an adjacent muddy soil shoulder. The same professional driver from the Nordlin study drove a pickup truck at 60 mph on a trajectory with only the two right wheels dropping off and coming back up onto the AC shoulder. Because the tires sank in the mud, the overall drop-off height was 2.75 in. where the truck returned to the pavement. No problems with vehicle stability or controllability occurred in driving the test course.

In 1976 Klein et al. (5) conducted a roadway surface study that included pavement edge drops. In the study accident data and public inquiries through questionnaires were analyzed, and a variety of both open- and closed-loop tests were conducted. Naive drivers were used in the closed-loop tests. In all of the pavement edge drop-off tests, a special effort was made to achieve the tire scrubbing condition before attempting to climb up the drop-off. In edge drop tests with drop-off up to 5 in. and the scrubbing condition, losses of vehicle control were encountered at higher speed levels, generally more than 30 mph. Klein et al. made a major contribution in defining a control difficulty parameter, T_{r_c}, and relating it to a critical speed for each test vehicle. They found that a value of about 0.6 sec for T_{r_c} accurately represented the limiting situation for not exceeding the lane boundary after a 4.5-in. climb. Referring to Klein's curve [Figure 2 (5)], speeds greater than 32 mph for the Pinto and the Caprice Wagon and greater than 44 mph for the Nova result in values of control difficulty that exceed 0.6 sec. These same speeds were found to be the

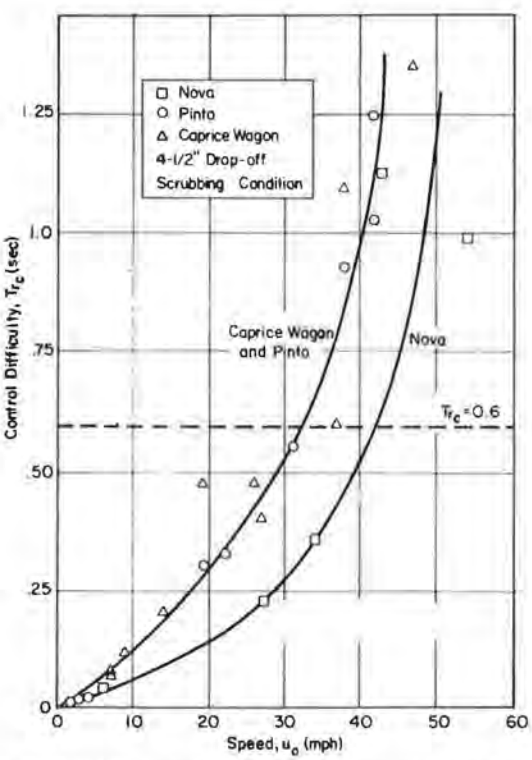

FIGURE 2 Control difficulty parameter versus vehicle speed *(5)*.

critical speed for the lane boundary not being exceeded during the closed-loop test with a 4.5-in. drop-off. The equation for T_{r_c} (control difficulty parameter) is

$$T_{r_c} = (M \cdot U_o)/(2 \cdot Y_{local}) \qquad (1)$$

where

M = vehicle mass,
U_o = forward speed, and
Y_{local} = local slope of cornering stiffness curve (i.e., the slope of the cornering force versus slip angle curve at the point the tire mounts the pavement edge).

Klein et al. found the time between edge mounting of the front and rear tires to also be less than 0.6 sec. As shown in Figures 3 (5) and 4 (5), they also developed curves for the relationships between steering wheel angle and the vehicle steer angle required to climb various vertical pavement edge

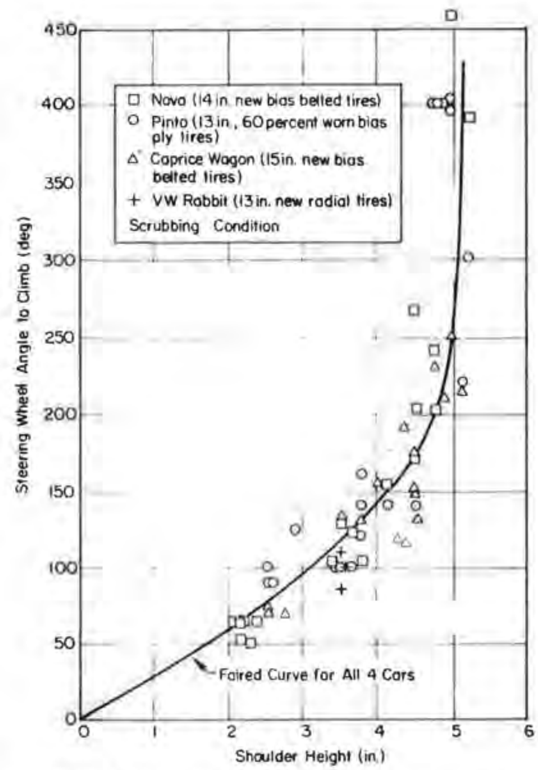

FIGURE 3 Steering wheel angle versus pavement edge height *(5)*.

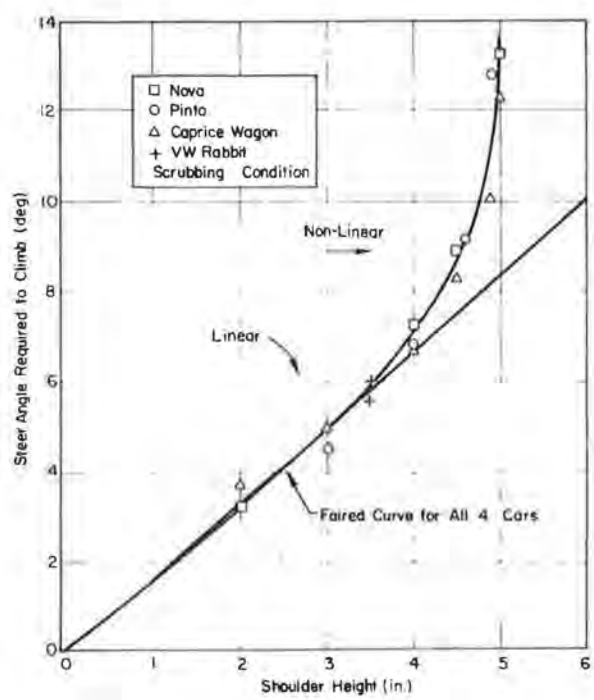

FIGURE 4 Steer angle required for different edge heights *(5)*.

heights from the scrubbing condition. For edge heights up to 3 in., both curves are relatively linear. In this range the edge-climbing maneuver appears relatively safe. As the curves become more curvilinear, the maneuver becomes significantly more difficult. As the curves start a precipitious rise, again approaching a straight line, the difficulty becomes extreme.

The Nordlin and Stoughton studies had not included the pavement edge-scrubbing condition, and the Klein study had concentrated almost entirely on the edge-scrubbing condition and one pavement edge geometry, that is, vertical with little edge rounding. Therefore, Zimmer and Ivey (6) in 1981 undertook a new study to extend the information already developed by Nordlin, Stoughton, and Klein.

The comprehensive test program developed by Zimmer and Ivey to evaluate the effects of pavement edge height situations included the following test conditions:

1. Three edge heights--1.5, 3, and 4.5 in.;
2. Four test vehicles--mini-compact, intermediate and full-sized passenger automobiles, and a pickup; weights varied from 1,668 to 4,713 lb, and wheel sizes varied from 12 to 15 in.;
3. Two tire constructions--the intermediate and full-sized automobiles were tested with both bias ply and radial tires; the other two vehicles were tested with only radial tires;
4. Three pavement edge drop geometry profiles--shape A = vertical with minimal corner rounding, shape B = fully rounded, and shape C = 45-degree slope;
5. Three test speeds--35, 45, and 55 mph;
6. Four drivers--a professional driver who teaches high-performance driving techniques, a semiprofessional driver who occasionally perform as a test driver, a typical male driver (a construction supervisor with no special driving skills), and a typical female driver (a technician with no special driving skills); and
7. Three vehicle trajectories--with only the two right wheels dropping off the pavement onto the earth shoulder and then moving back at an extremely flat angle to produce the edge-scrubbing condition before attempting to maneuver back up onto the pavement; with only the two right wheels dropping off but returning at a comfortable but sharp enough angle to preclude any continuous edge-scrubbing action; and with all four wheels dropping off onto the shoulder and returning at a sharp enough angle to minimize the edge-scrubbing action.

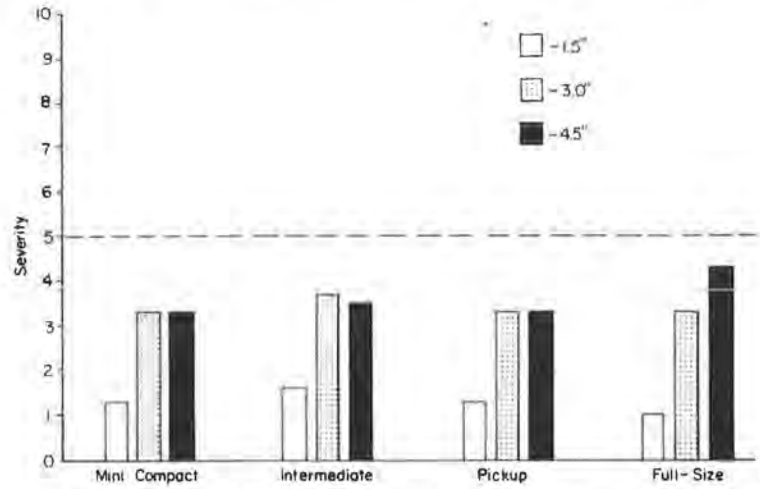

FIGURE 5 Severity rating situation for different edge heights (nonscrubbing condition, edge shape A) *(6)*.

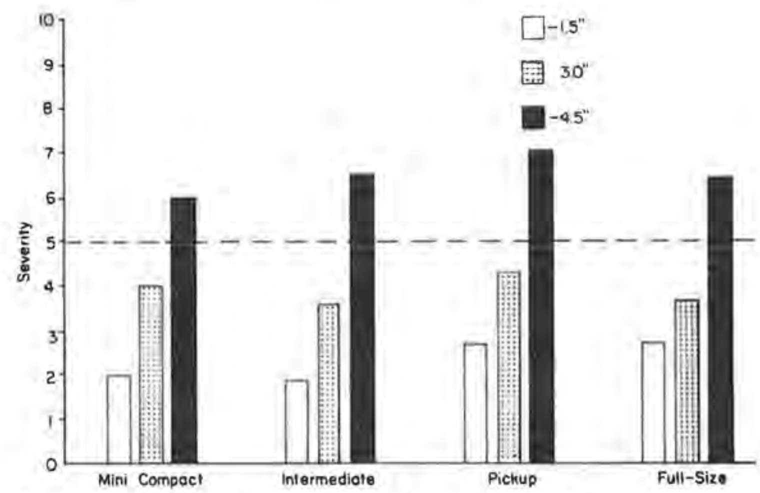

FIGURE 6 Severity rating situations for different edge heights (scrubbing condition, edge shape A) *(6)*.

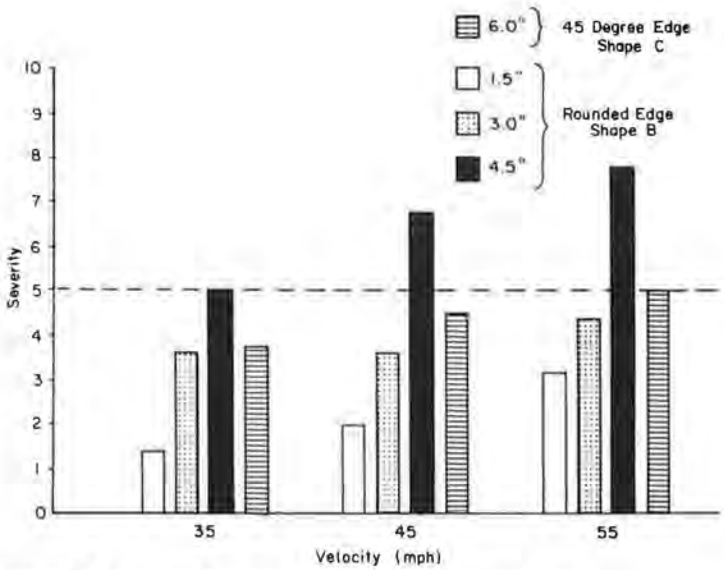

FIGURE 7 Effect of vehicle speed on maneuver severity *(6)*.

In addition to photographic and electronic data, the drivers expressed the severity of each test run immediately after completion by the following numerical ranking: 1 = undetectable, 2 = very mild, 3 = mild, 4 = definite jerk, 5 = effort required, 6 = extra effort, 7 = tire slip (slight lateral skidding), 8 = crossed centerline and returned, 9 = crossed centerline and no return, and 10 = loss of control (spin out).

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

Figures 5 (6) and 6 (6) show the average rating values for the tests involving the professional driver, the two-wheels-off trajectory, and the shape A pavement edge profile. However, Figure 5 presents the values for only the nonscrubbing tests. As can be seen, there is little difference either between vehicles or between the 3- and 4.5-in. heights. In comparison, Figure 6 shows the ratings for only the tests where the vehicle wheels were purposely put into intimate scrubbing contact with the edge before a return to the pavement was attempted. The difference between vehicles was small, but the effect of edge height was pronounced. For all vehicles, the maneuver-severity bars for the 4.5-in. heights extend into the upper half (critical range) of the chart.

Figure 7 (6) shows the effect of vehicle speed on the severity of the maneuver by the professional driver over shape A in the two-wheels-off trajectory with scrubbing action. All vehicles were averaged because vehicle differences were shown to be small. The maneuver-severity increase is almost linear as the speed increases for each drop-off height. As before, the 4.5-in. height is a potentially unsafe condition even at a speed as low as 35 mph.

Summary of Findings

The results of the work by Zimmer and Ivey under the edge-scrubbing condition are summarized in Figure 8

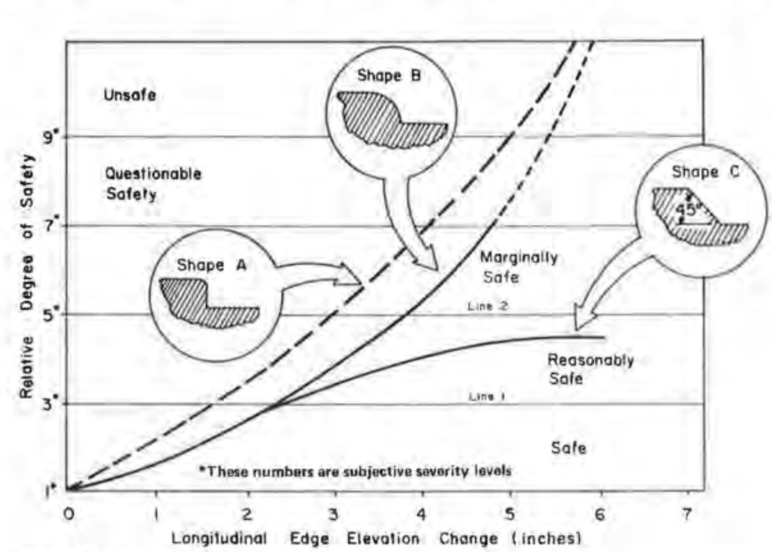

FIGURE 8 Relative degrees of safety for various edge conditions *(6)*.

(6), where the relative degree of safety, in terms of the subjective severity levels defined previously, is plotted against the longitudinal edge elevation change (drop-off). The terms describing the 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 or other drugs and any other infirmity or lack of physical capability. (Includes subjective severity rating values 1 through 3.)
- Reasonably safe: A prudent driver of a reasonably maintained vehicle would experience no significant problem in traversing the pavement edge. (Includes severity values 3 through 5.)
- Marginally safe: A high percentage of drivers could traverse the pavement edge without significant difficulty. A small group of drivers may experience some difficulty in performing the scrubbing maneuver and remaining within the adjacent traffic lane. (Includes severity values 5 through 7.)
- Questionable safety: A high percentage of drivers would experience significant difficulty in performing the scrubbing maneuver and remaining in the adjacent traffic lane. Full loss of control could occur under some circumstances. (Includes severity rating values 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 values 9 and 10.)

Figure 8 includes curves for the three pavement edge profiles. The data in the figure indicate that the shape A profile is safe or reasonably safe under the scrubbing action for drop-off heights up to and including 3 in. Under the same conditions, shape B is safe or reasonably safe for drop-off heights up to 3.75 in. Zimmer and Ivey (6) conclude that shape C would only be a problem when the vehicle suspension or other underbody elements contacted the pavement edge. For this shape, an edge drop height of 5 in. might be reasonably safe for even the smallest current automobile.

Figure 8 could also be used to develop recommendations for maintenance. For example, the shape B curve crosses line 1 at about the 2.5-in. drop-off height. This might be the signal that it is time to schedule maintenance activities to prevent the height from increasing beyond 3.75 in. (the crossing of line 2), where the drop-off becomes marginally safe for the edge-scrubbing condition. The advantage of avoiding shape A is also apparent from Figure 8. If shape C can be constructed, either during original construction or as a maintenance activity, the need for edge maintenance could be significantly reduced. Shape C may also have significant advantage in resisting pavement edge deterioration.

In summary, 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 and tire-scrubbing condition. This safety problem is minimized where the pavement edge drop does not exceed 3 in. in height or the face has a 45-degree slope. A loose or muddy soil shoulder should not increase the edge-climbing difficulty, provided that 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 more than 5 in. in height can interfere with the underneath clearance and thus create safety problems for small automobiles.

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