

Effect of Pavement/Shoulder Drop-Offs on Highway Safety

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Drop-offs at the pavement/shoulder (or shoulder/roadside) edge have been recognized as a potential highway safety problem for many years. In the American Association of State Highway Officials' (AASHO) 1954 publication *A Policy on Geometric Design of Rural Highways*, the subject of drop-offs is covered as follows (1, p. 205):

Unstabilized shoulders frequently are hazardous because the elevation of the shoulder at the pavement edge may be several inches lower than the pavement.

This passage was expanded in the 1965 edition of the publication to add further caution as follows (2, p. 239):

Unstabilized shoulders frequently are hazardous because the elevation of the shoulder at the pavement edge tends to become one-half to several inches lower than the pavement.

These statements in the AASHO policies must have come from the general perceptions of the policy writers because no research on the differential effects of drop-off heights and shapes was available before about 1977. Research since 1977 has demonstrated that the probability of severe consequences from a pavement/shoulder drop-off traversal are a function of drop-off height and shape and vehicle speed and reentry angle.

CHARACTERIZATION OF THE PAVEMENT/SHOULDER DROP-OFF TRAVERSAL

A pavement/shoulder drop-off traversal occurs when the driver inadvertently leaves the travel lane and drops onto a lower shoulder. Depending on the severity of the vehicle departure angle and the driver's level of surprise and response, seven general outcomes are possible as shown in Figure 1.

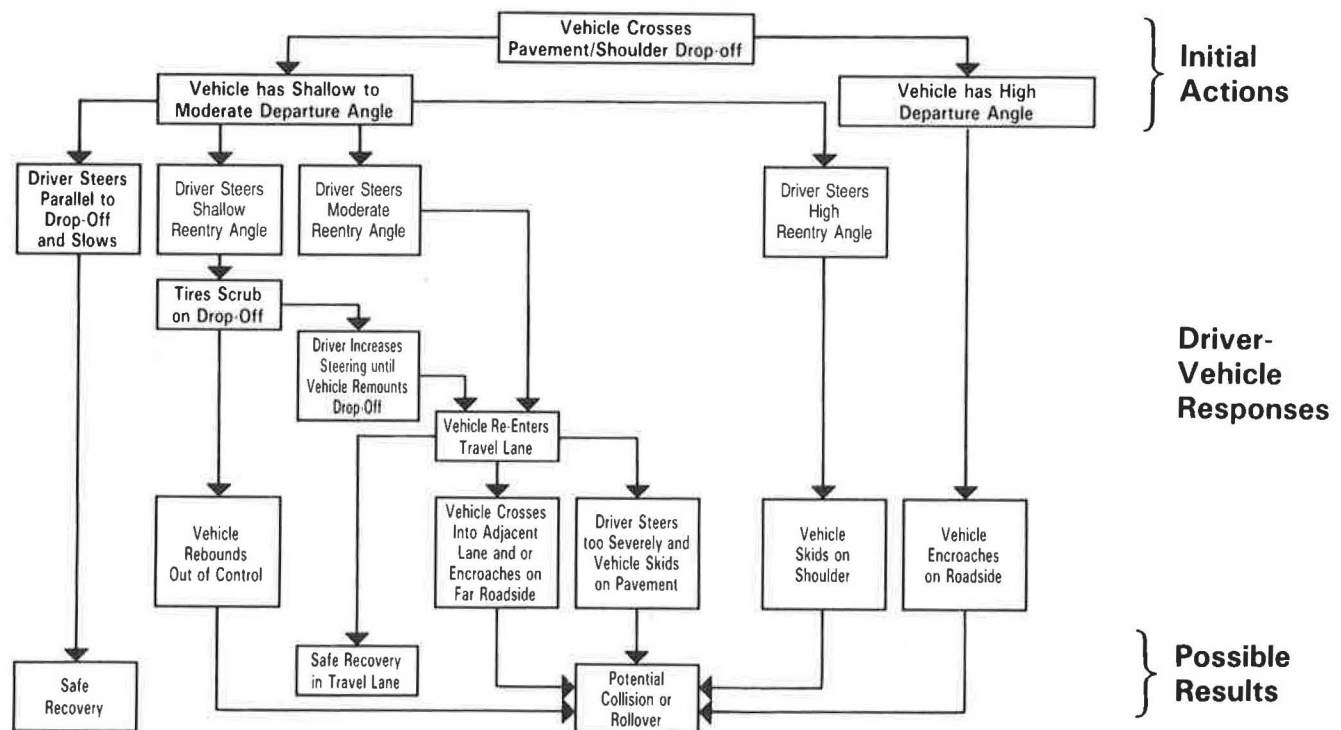
If the departure angle is high, recovery is quite unlikely, and a collision of some type on the roadside is probable (Outcome 7). If the departure angle is shallow to moderate, the driver has some potential to respond with a recovery attempt (Outcomes 1–6).

If the driver steers a high reentry angle the vehicle will skid on the shoulder resulting in immediate loss of control (Outcome 6). If the driver is particularly alert and knowledgeable about the potentially hazardous effects of drop-offs, he may be able to steer parallel to the drop-off and slow the vehicle to a stop on the shoulder (Outcome 1).

If the driver steers a moderate reentry angle that is just high enough to remount the pavement/shoulder drop-off, he will usually recover within his travel lane (Outcome 3). For moderate reentry angles that are higher than the minimum necessary to remount, particularly at higher speeds, the vehicle will either encroach on adjacent travel lanes or skid out of control, depending on the severity of the driver's steering response (Outcomes 4 and 5).

If the driver steers a shallow reentry angle, the vehicle's tires will either scrub along the drop-off face and either subsequently remount the drop-off (Outcomes 3 to 5) or possibly rebound out of control (Outcome 2), depending on the driver's steering response.

A scrubbing reentry occurs when the wheel that contacts the drop-off edge has insufficient normal velocity to overcome the retarding force produced by the tire and edge contact. The term "scrubbing" describes the near-parallel traversal of the tire along the drop-off edge in which a relatively large contact area occurs between the tire



Note: Definition of shallow, moderate, and high angles are relative to speed, drop-off shape, and height.

FIGURE 1 General characterization of pavement/shoulder drop-off traversal. Definitions of shallow, moderate, and high angles are relative to speed, drop-off shape, and height.

sidewall and the drop-off edge. The wheel develops a high resistance to mounting the pavement/shoulder drop-off, and the driver continues to increase the steer angle in a further attempt to mount the drop-off. The contact of the tire and the drop-off edge continues until the front-wheel steer angle is sufficient to overcome the retarding force and to create a sufficient side force at the unobstructed (left) front wheel to lift the obstructed (right) tire over the drop-off. Once the obstructed front tire has mounted the drop-off, the large steer angle produces a large lateral acceleration and a large yaw velocity that combine to produce rapid lateral movement. This lateral movement will continue until the driver reverses the steer angle and the vehicle has time to respond to the steer reversal.

The responses produced by scrubbing reentries constitute the primary hazard associated with pavement/shoulder drop-offs. At higher speeds and drop-off heights, the results are either excessive lateral encroachments on adjacent lanes or opposite road-sides (Outcome 4) or loss of control because of excessive steering corrections (Outcome 5).

SCOPE AND OBJECTIVES

The purpose of this paper is to synthesize the state of the art on the safety of pavement-shoulder drop-offs so that practical guidelines can be developed for their treatment in the improvement of existing highways under the current resurfacing, rehabilitation, and restoration (RRR) process.

A pavement/shoulder drop-off may be an existing condition on a candidate RRR highway or it may be created by a RRR pavement overlay project. The existing drop-off may have been created by a previous pavement overlay or may have evolved from shoulder wear, settlement, or erosion. The two questions for considering existing drop-offs in the RRR process are

1. What combination of drop-off shape and height constitute an intolerable hazard?
2. What is the most cost-effective method for treating intolerable drop-offs?

An all too common practice in many areas is to leave a pavement/shoulder drop-off when overlaying an existing highway, particularly one with unpaved shoulders. The RRR questions to be addressed are

1. What are the drop-off heights and shapes that are tolerable for safety?
2. What are the design and construction methods that can be used to produce tolerable pavement/shoulder edge conditions?

A critical review is presented of available studies on pavement/shoulder drop-offs for the purpose of identifying the combinations of shape and height that are tolerable for various highway design speeds.

CRITICAL REVIEW AND ANALYSIS

Research on the safety of pavement/shoulder drop-offs is limited. A review of the literature produced only five recent references with any reasonable contribution to the state of the art.

These five studies are comparatively analyzed in an attempt to synthesize the body of knowledge. Various aspects of the subject are discussed in separate paragraphs.

Role of Pavement/Shoulder Drop-Offs in Highway Accidents

The literature on the relationship between highway accidents and pavement/shoulder drop-offs is limited. This relationship is discussed in only two studies.

In 1976 Ivey and Griffin examined all of the 15,968 single-vehicle accidents that occurred in North Carolina during 1974 for the purpose of studying the contribution of surface discontinuities (bumps, dips, rocks, holes, drop-offs, etc.) (3). Computerized police officers' narratives for all of these accidents were examined for any one of 19 key words that denoted a surface discontinuity. Some 566 (3.5 percent) of these accidents were associated with surface discontinuities; of these, 154 (1.0 percent of total) appear to have been related to drop-offs.

Klein et al. reviewed accident data from three different sources to analyze the frequency with which surface discontinuities contribute to highway accidents (4). In this analysis, the authors concluded that the most significant discontinuity was the pavement/shoulder drop-off. Depending on the source of data, surface discontinuities contributed to 0.8 to 2.6 percent of all accidents, and accidents involving pavement/shoulder drop-offs ranged from 0.2 to 1.3 percent of all accidents.

Although these studies indicate a relatively small percentage of total accidents that involve pavement/shoulder drop-offs, they did not attempt to determine the relative exposure to drop-off conditions. If only highways with pavement/shoulder drop-offs were considered, the contribution of drop-offs to the accident experience might be substantial.

Probability of Severe Consequences

Klein et al. conducted several full-scale tests using "naive" drivers (4). They were interested in the statistical distribution of consequences when these drivers encountered a 4.5-in. vertical face drop-off and tried to recover. Of 73 tests, 53 percent produced tire scrubbing on the drop-off edge. Of those tests that produced scrubbing, 56 percent resulted in exceedance of the 12-ft lane boundary after mounting the drop-off. The likelihood of a lane boundary exceedance after scrubbing was strongly correlated with speed. Forty-seven percent of the tests resulted in a nonscrubbing reentry, none of which produced lane exceedance.

These results may be somewhat misleading because the report did not document the distribution of speeds used in the tests. Therefore, the probability of scrubbing in a particular test may be higher or lower than indicated earlier depending on the speed used. These studies also did not account for the element of surprise.

Shallow-Angle Approach

Klein et al. conducted several full-scale, shallow-angle reentry tests to evaluate the potential for mounting a vertical face drop-off when a vehicle is not initially scrubbing (4). Various drop-off heights were tested with various reentry angles and speeds to produce a relationship between drop-off height and the minimum normal speed necessary to mount the drop-off. Normal speed is that component of vehicle speed perpendicular to the pavement/shoulder edge.

This relationship between vertical face drop-off height and the minimum normal speed necessary to mount the drop-off is shown in Figure 2. This relationship indicates

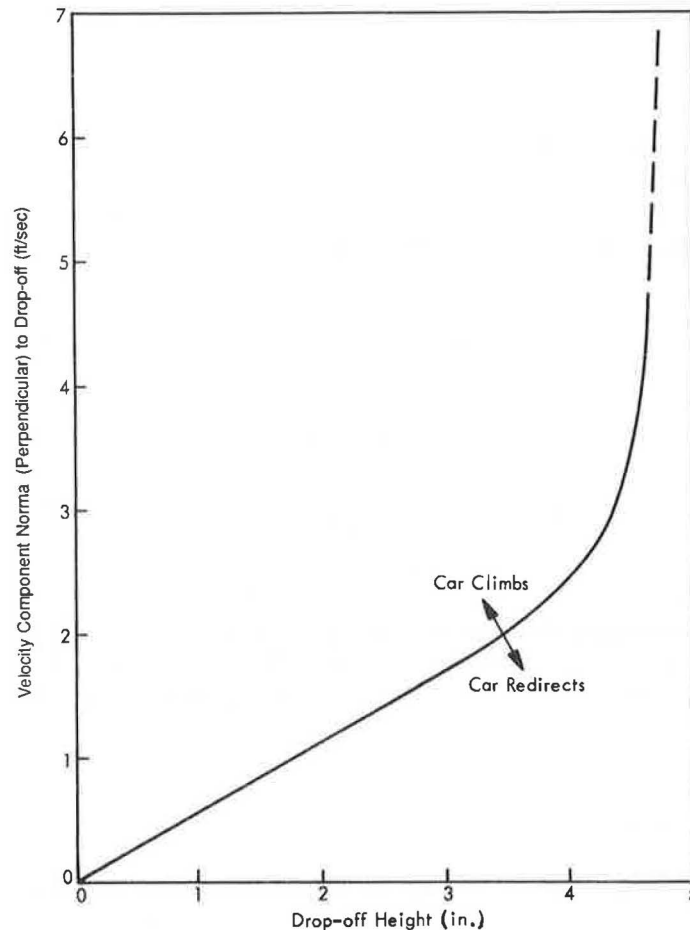


FIGURE 2 Normal velocity required to climb a vertical face drop-off as a function of edge height (4).

that if the reentry angle is too small for a given speed and drop-off height, the vehicle will not mount the drop-off but will be redirected into a scrubbing mode. It also indicates that higher drop-off heights require very high normal speeds for vehicles to remount without scrubbing. Therefore, the probability of scrubbing increases dramatically for drop-off heights above about 4.5 in.

This basic relationship of the pavement/shoulder drop-off maneuver shown in Figure 2 was at least partly validated by Graham and Glennon who used HVOSM computer simulation techniques to study vertical face drop-offs (5). Unfortunately, no such relationship has been established for any other drop-off shape.

Nonscrubbing Reentry

Four separate studies indicate that successful recovery from a pavement/shoulder drop-off maneuver is possible even at fairly high speeds. Tests conducted by Stoughton et al. (6) with various sizes of passenger cars and a standard pickup truck indicated that a professional driver had little difficulty recovering from a drop-off with a typical irregularly rounded edge of asphalt pour, even at speeds of 60 mph and drop-off

heights of 4.5 in. These tests appear to have been carefully controlled to avoid scrubbing.

The full-scale tests reported by Klein et al. indicated that the naive drivers who did not scrub on a 4.5-in. vertical face drop-off were able to successfully recover within the travel lane (4). Only 47 percent of the tests conducted resulted in a nonscrubbing reentry.

Zimmer and Ivey conducted full-scale nonscrubbing tests using a professional driver to test drop-offs of various heights with a 1.5-in. tapered corner (7, 8). The averaged subjective severity ratings made by the driver indicate that he was able to recover successfully with little difficulty at speeds up to 55 mph and drop-offs as high as 4.5 in. These tests indicated little sensitivity to type of vehicle for various sizes of passenger cars and a standard pickup truck.

Graham and Glennon used analytical methods to show the reentry angle boundaries of successful nonscrubbing recovery for vertical face drop-offs (5). From the relationship shown in Figure 2, the minimum reentry angle to avoid scrubbing was solved to form the lower boundary of successful recovery for any combination of vehicle speed and drop-off height. For the upper boundary, Graham and Glennon developed an analytical model that determined the maximum reentry angle that would allow the vehicle to still recover within the lane as a function of lane width. To exercise this model, constraints of 0.3g's lateral acceleration and 0.7-sec driver perception-reaction time were used. Figure 3 shows two example plots from those calculations.

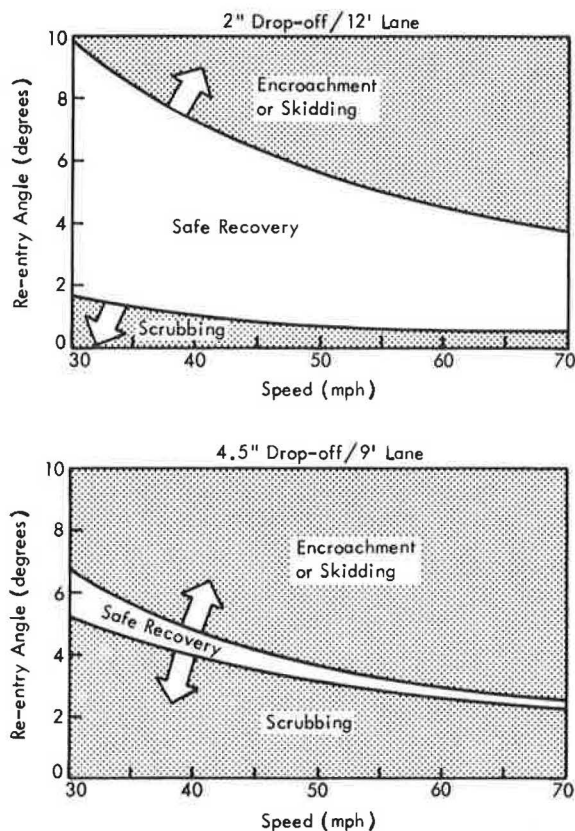


FIGURE 3 Example boundaries for safe reentry angles for traversal of vertical face drop-offs (5).

Although the exact form of the analytical model and the constraint values used might be debated, the analysis indicates that the reentry angle range available for successful nonscrubbing recovery decreases as speed and drop-off height increase and as lane width decreases.

All of the studies indicate the possibility of successful nonscrubbing recoveries, even at high speeds and drop-off heights if reentry angles are maintained within a precise range. However, the probability that this type of maneuver can be performed by a nonprofessional driver, particularly one who is surprised when his right-front wheel suddenly drops, has not been addressed by the research but probably becomes smaller with increasing speed and drop-off height.

Scrubbing Reentry

For those studies that included tests of the scrubbing reentry, this maneuver was found to be the most hazardous type of reentry. The reason for this hazard is best explained by the results of Klein et al. shown in Figure 4. For a drop-off with only a 0.5-in. radius

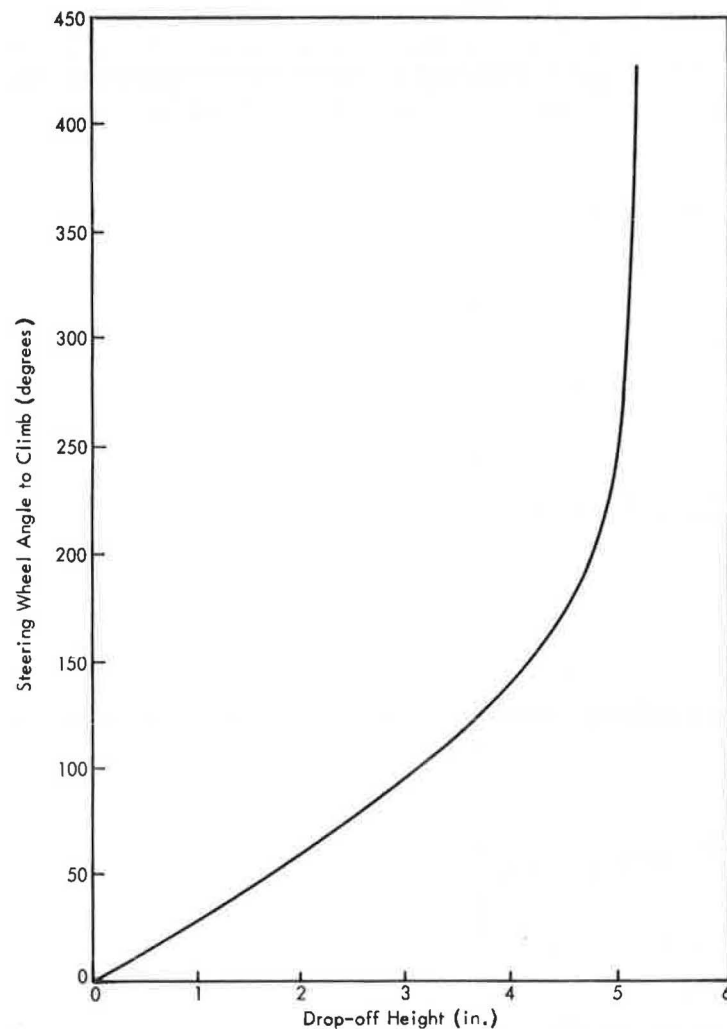


FIGURE 4 Steering wheel angle required to climb various edge heights from a scrubbing condition (4).

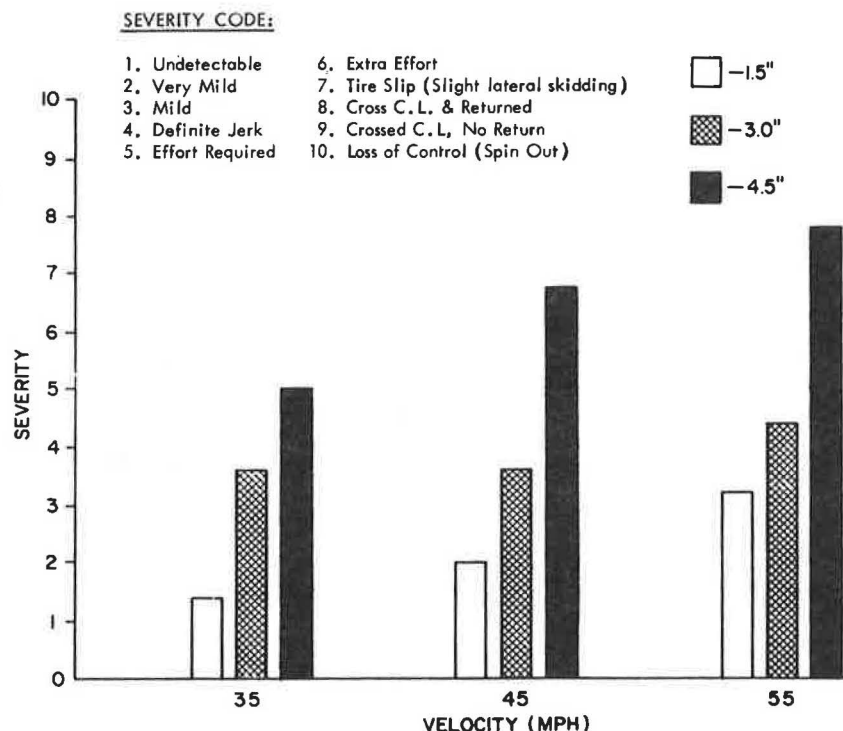


FIGURE 5 Severity ratings for traversals of tapered edge drop-offs (7-9).

corner rounding, this figure shows that as drop-off heights exceed about 3 in., large steering wheel inputs are required to mount the drop-off. Under these conditions, when the wheel mounts the drop-off, the large steer angle produces a large lateral acceleration and yaw velocity that combine to produce rapid lateral movement.

Zimmer and Ivey provide the most complete analysis on scrubbing reentry (7, 8). Figure 5 shows the severity ratings of a professional driver averaged over various vehicles and tires for a large matrix of full-scale scrubbing tests conducted on a drop-off with a 1.5-in. corner taper. These results must be interpreted as average (not critical), alerted (not surprised), professional (not nonprofessional) driver responses; as such they may indicate lower maneuver severities than can be expected on the highway. Nevertheless, these results do indicate undesirable consequences for 4.5-in. drop-offs at speeds of 45 mph and above.

Table 1 includes the limited data available from three of the studies showing more detailed results from selected scrubbing tests that exhibited lane exceedance or high lateral acceleration, or both. It can be seen from Table 1 that the scrubbing reentry maneuver becomes more severe as the drop-off approaches a full vertical face, as the drop-off height increases, and as the vehicle speed increases.

APPLICATION OF RESULTS TO RRR PRACTICE

When drivers experience a nominal encroachment onto a flush shoulder, their safe recovery within the travel lane depends on their ability to avoid steering a severe reentry angle that will either cause the vehicle to encroach on adjacent lanes or cause them to lose control within the lane when secondary steering correction is attempted.

One characterization of this upper boundary of reentry angles has been shown to be a function of vehicle speed and lane width as shown in Figure 6.

When a drop-off is introduced at the pavement/shoulder edge, the upper boundary shown in Figure 6 is joined by a lower boundary for safe reentry angles imposed by the

TABLE 1 Available Results of Scrubbing Tests

Source	Drop-Off Shape (in.)	Drop-Off Height (in.)	Vehicle Speed (mph)	Driver Type	Result
Zimmer and Ivey (1)	1.5 corner taper	4.5	45	Professional	Lateral acceleration of 0.74
Zimmer and Ivey (1)	1.5 corner taper	4.5	55	Professional	Lane exceedance and lateral acceleration of 0.79
Zimmer and Ivey (7)	0.75 corner radius	4.5	45	Professional	Lane exceedance and lateral acceleration of 0.71
Zimmer and Ivey (7)	0.75 corner radius	4.5	55	Professional	Lane exceedance and lateral acceleration of 0.88
Klein et al. (4)	0.5 corner radius	3.5	40	Unknown	Loss of control
Graham and Glennon (5)	Vertical face	2.0	30	Modeled	Minor lane exceedance and lateral acceleration of 0.30
Graham and Glennon (5)	Vertical face	2.0	45	Modeled	Major lane exceedance and lateral acceleration of 0.60
Graham and Glennon (5)	Vertical face	3.0	45	Modeled	Major lane exceedance and lateral acceleration of 0.80

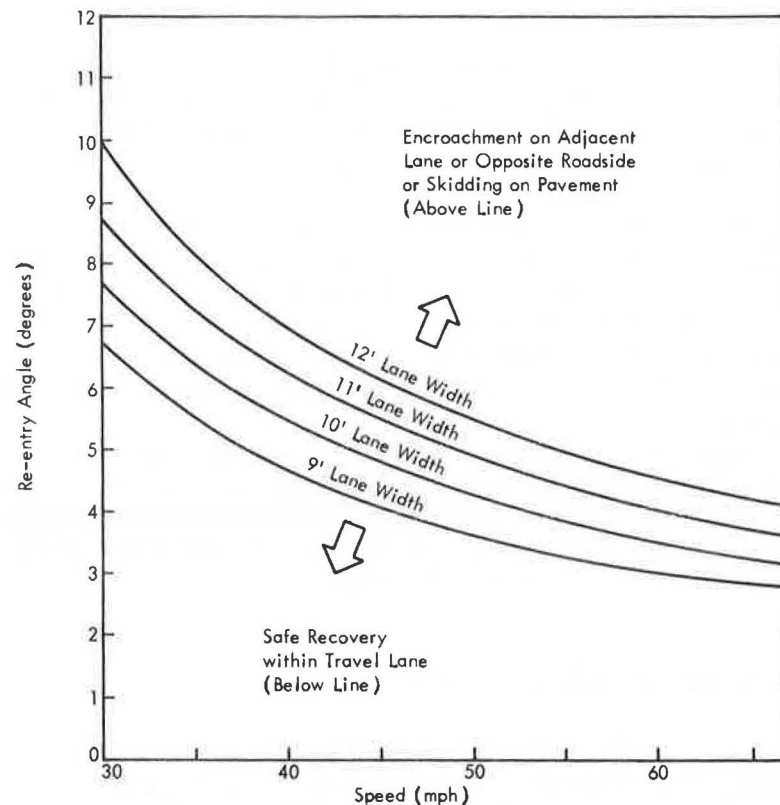


FIGURE 6 Maximum safe reentry angle for shoulder traversal as a function of speed and lane width (5).

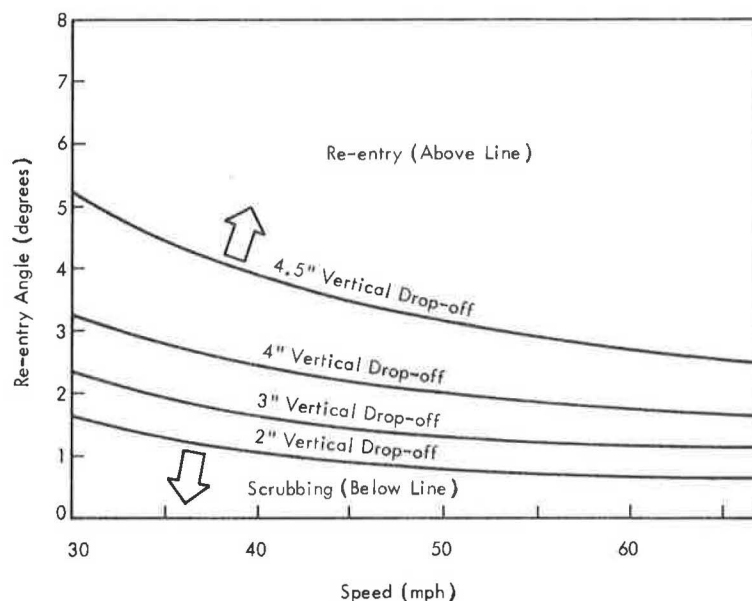


FIGURE 7 Minimum safe reentry angle for traversal of vertical face pavement/shoulder drop-off as a function of speed and drop-off height (4, 5).

potential for hazardous scrubbing reentry maneuvers, which are more likely as the drop-off height increases. Figure 7 shows this lower boundary relationship for vertical face drop-offs.

For any combination of vertical-face drop-off height and lane width, the upper and lower boundary conditions shown in Figures 6 and 7 can be combined to depict the range of safe reentry angles for any vehicle speed. Figure 3 shows a sample of these composite plots that indicates the high likelihood of a severe reentry maneuver, particularly for higher drop-off heights, higher speeds, and narrower lanes.

The available literature does not provide a refined set of data that can precisely predict the accident consequences of a pavement/shoulder drop-off maneuver. However, it does provide some useful insights into the safety of pavement/shoulder drop-offs as a function of vehicle speed, drop-off shape and height, and lane width. From the results reported in this paper, the following general conclusions can be drawn:

1. The most obvious hazard associated with pavement/shoulder drop-offs occurs when a driver tries to recover from a scrubbing condition.
2. The probability of a scrubbing reentry at a pavement/shoulder drop-off increases as (a) the drop-off face approaches a full vertical edge and (b) the drop-off height increases.
3. The probability of a successful recovery from a drop-off maneuver decreases as (a) the drop-off face approaches a full vertical edge, (b) the drop-off height increases, (c) the vehicle speed increases, and (d) the lane width decreases.
4. The severity (yaw velocity, lateral encroachment, etc.) of a scrubbing reentry maneuver increases as the drop-off shape approaches a full vertical edge and as the drop-off height and vehicle speed increase (see Table 1 and Figure 5).
5. A 5-in. drop-off height is a practical maximum to prevent hazardous undercarriage contact on most vehicles.

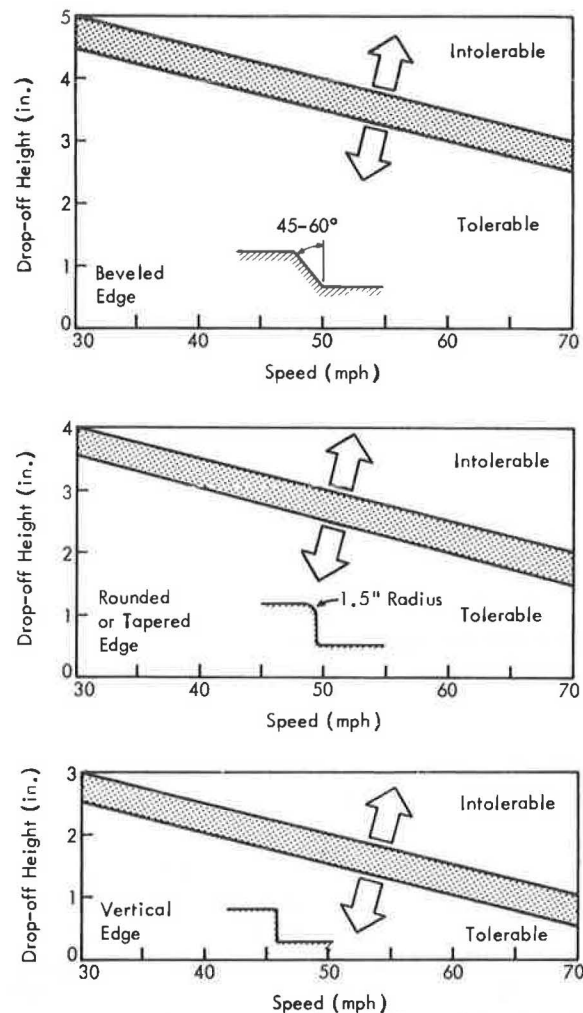


FIGURE 8 Suggested guidelines for determining tolerable pavement/shoulder drop-off heights.

Using these general conclusions and a safety-conservative interpretation of the fairly sparse results of the available studies, the data shown in Figure 8 suggest a provisional guideline for determining if existing drop-offs are tolerable on RRR candidate highways. As can be observed in Figure 8, the suggested tolerable drop-off height decreases with speed as the drop-off shape approaches a full vertical edge. The shaded band on each graph allows for (a) some discretion because of the uncertainty of available data, and (b) the slight variance of criticality associated with lane width whereby narrow lanes would have lower tolerable drop-off heights than wide lanes.

The suggested guidelines are based on the studied dynamic sensitivity of passenger cars and pickup trucks of various sizes. Lower tolerable drop-off heights may be appropriate on roadways that carry significant proportions of heavy trucks or motorcycles.

Using Figure 8 (or a similarly derived guideline), if an existing pavement/shoulder drop-off is found to be intolerable for prevailing highway speeds, then one of two alternatives would be reasonable to reduce the hazard. First, material (preferably

stabilized) can be added to raise the shoulder elevation to a tolerable level (preferably flush). Second, the edge shape can be changed to more closely approximate a 40 to 60 degree continuous taper by either adding an asphalt wedge or grinding the existing edge. Where tolerable pavement/shoulder drop-offs are allowed to remain, some consideration should also be given to the use of warning signs.

Figure 8 also provides guidance when placing a pavement overlay on RRR projects. It is desirable that such an overlay should be flush with the shoulder, but if project economics prohibit this condition, the created pavement/shoulder drop-off height should be as low as possible and the edge shape should be as close to the 45 to 60 degree taper as possible, all within tolerable limits. Where tolerable pavement/shoulder drop-offs are created, some consideration should be given to the use of warning signs.

Most of the conclusions in this study also apply to the drop-offs sometimes found at the shoulder/roadside edge. However, because of the lower probability of encroachment at the shoulder/roadside edge and a greater effective recovery width compared with the pavement/shoulder edge, the suggested guidelines for Figure 8 might be relaxed somewhat to allow higher tolerable drop-offs for this condition, particularly for the wider shoulder widths.

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