Safety in Construction Zones Where Pavement Edges and Dropoffs Exist

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In this paper, the development of "Guidelines for Warning and Protective Devices for Pavement Dropoffs" are described. Included in this development are summaries of pertinent information from the literature, new analyses of vehicle stability, and the results of accident probability studies and benefit-cost studies. Four different safety-related vehicle-pavement dropoff interactions were analyzed and evaluated: nibbling, scrubbing, dragging, and rolling. These interactions are described in detail in the paper. A wide range of vehicle sizes was considered in developing the guidelines, from small automobiles to large tractor semi-trailers. Pavement edges and dropoffs can pose a significant hazard under some construction conditions and need to be carefully considered and dealt with appropriately. The guidelines presented here are now in use by the State Department of Highways and Public Transportation in Texas.

This paper is based on the senior author's published work in this area (*1–4*), on a review of other significant literature, on direct experience with the analysis of construction zone and pavement edge-related accidents, and on an understanding of vehicle dynamics for both automobiles and trucks. Bicycles and motorcycles were not considered in this work. Four levels of vehicle interaction with pavement edges were identified (Figure 1):

Level 1: Nibbling;
Level 2: Scrubbing;
Level 3: Drag; and
Level 4: Roll.

Nibbling is associated with pavement longitudinal edges not more than 1 in. in height. This interaction was not considered to have significance for safety but was included for analysis to ensure that understanding was accurate. When tires are traversing a nibbling edge, a force is imparted to them that may move the vehicle laterally a small distance. Although this is not a control problem for automobiles or stable truck configurations, it could initiate some degree of oscillation in double or triple bottoms at critical speeds.

Scrubbing is the classic edge phenomenon that has been recognized as a safety problem. It is a resistance to edge traversal that can result in loss of vehicle control once the vehicle has mounted the pavement edge. Scrubbing was considered to occur at edge height levels of 1 to 5 in. This interaction does not usually affect safety at 1-in. edge height, but such an effect is possible. Scrubbing loses safety significance for automobiles as edges exceed 5 in. because automobiles are rarely able to mount edges this high. For trucks, however, scrubbing will be important at larger edge heights.

Drag occurs when the edge height exceeds the clearance of the vehicle crossing the edge. As a safety problem, it was considered of lesser significance than scrubbing because in most cases the only problem is damage to vehicle undercarriage elements and possibly the hazard posed for other vehicles by the vehicle that is stopped by dragging. Because most vehicles have their fuel lines routed along the frame or lower monocoque structure, dragging could also result in rupture of these lines, as well as in damage to the brake lines. It was considered possible, under some drag conditions, that the eccentric, friction-type drag force could cause a vehicle spin-out. A spin-out at significant speed may roll the vehicle. It was determined that this possible phenomenon would be investigated.

Roll is a very significant safety consideration. If the edge drop is very high (initially considered to be more than 1 ft), the possibility of a vehicle roll was the final, or Level 4, consideration. Preliminary computations related to vehicle center of gravity (cg) height, track width, and ground clearance indicated that static rollover would not be likely if the edge height were less than half the track width of automobiles. This was true for automobiles but not for trucks because the ratio of truck cg height to track width is much smaller than the same ratio for automobiles. High-cg trucks may roll when the edge drop is no more than 1 ft. A dynamic analysis could give quite different results, however, including the problem of a vehicle digging into a soft shoulder surface when it runs off the edge. This consideration dictated that the edge drop distance to produce vehicle rolling should be assessed by using vehicle simulation models. This analysis will be described in the section of this paper that examines roll.

NIBBLING

"Nibbling" is a term that comes from the tire-manufacturing industry. It probably comes from the idea that a tire rolling immediately adjacent to a longitudinal pavement edge or "seam" of low height nibbles at the edge until it gets a good bite, and then the tire-edge interaction forces pull the tire up onto the higher-level pavement.

Marshal et al. (*5*) defines nibbling as "the process which occurs when a tire encounters a road seam of moderate height at an angle of attack of five degrees or less." The literature

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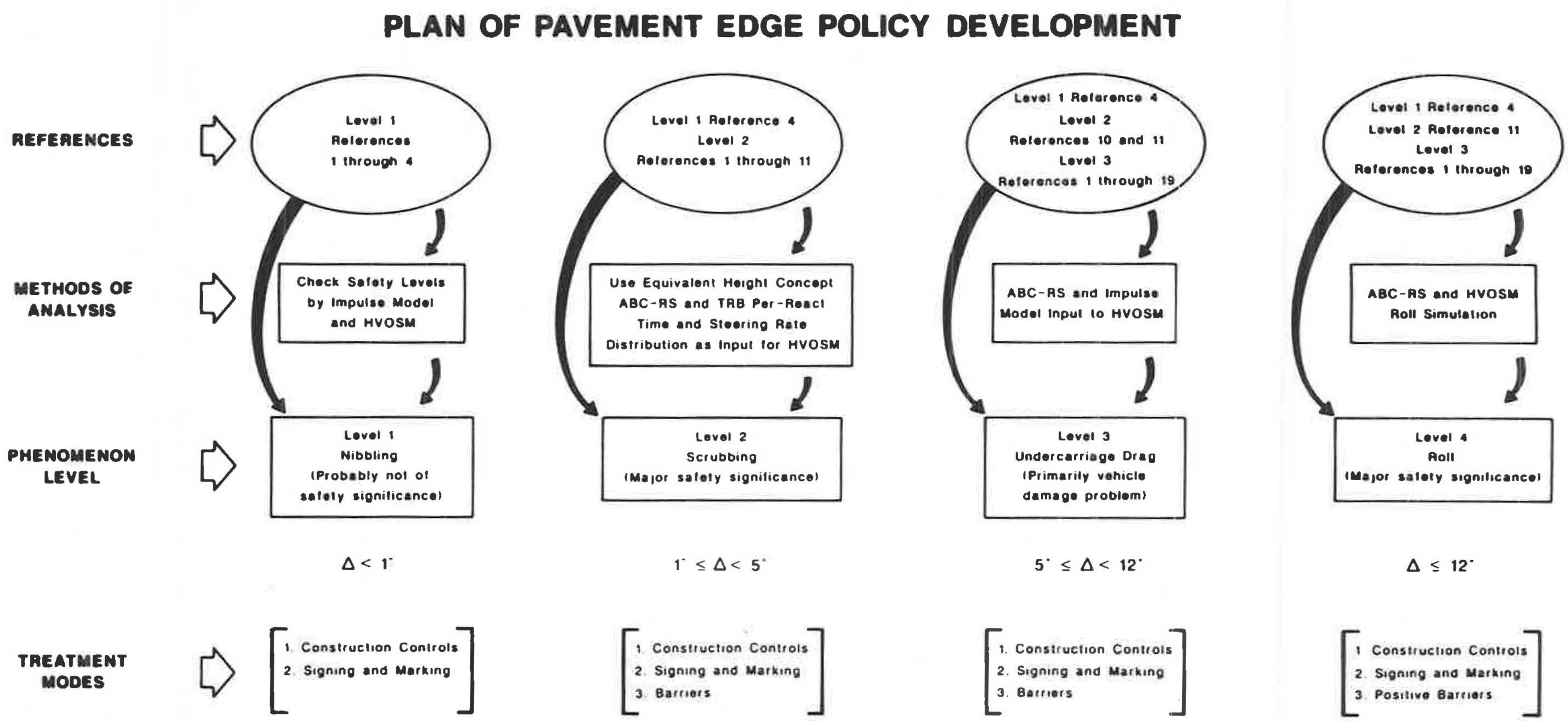


FIGURE 1 Categorization of pavement edges for study planning.

indicates that significant nibbling only occurs when there is a very sharp edge that is from 0.5 to 1 in. high.

Figure 2 shows the tire lateral forces that occur when a tire crosses a small edge or "seam," which is the British term. The "road data" curve is the most interesting one. Lateral forces of up to 160 lb are generated over the time period necessary to traverse the edge.

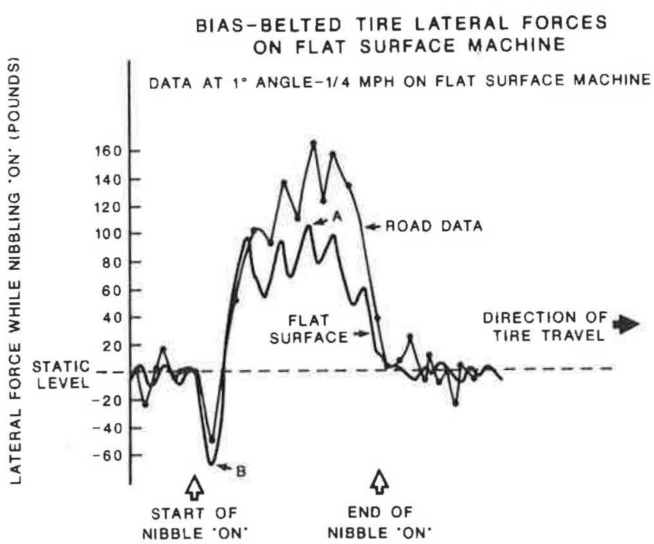


FIGURE 2 Edge-mounting forces involved in the nibbling phenomenon [after Pottinger (*6*)].

To check the way in which this pair of impulses, first on front and then on rear wheel, would change the path of a vehicle, the simulation HVOSM (*6*) was used. A mini-compact vehicle was selected in the belief that the path deviation of a small vehicle would be greater than that of a larger vehicle. The small influence of nibbling forces was illustrated by applying the impulse first to the right front wheel and then, 0.11 sec later, beginning the impulse to the right rear wheel. Each lateral force of 100 lb at the tire-pavement interface was applied for 0.33 sec. No steering was applied to the vehicle during these impulses and for 2.5 sec thereafter. The time 2.5 sec was chosen because it is a common value used by AASHTO for "design" perception-reaction time. The lateral movement of the simulated vehicle was less than 1 ft from the straight line path, confirming the belief of the current authors that nibbling was possibly a factor of irritation for an automobile driver but not one related to safety. This is illustrated in Figure 3.

One possible exception to that conclusion should be stated. If an edge capable of producing tire nibbling is located 9 to 4 ft laterally from a significant pavement edge (i.e., one that might produce scrubbing), a vehicle might be influenced adversely if the driver allowed it to cross the higher edge to avoid the irritation of the nibbling edge. It is also possible that if a "nibbling" edge occured within the 9 to 4 ft specified, it would move or influence the driver to inadvertently move the vehicle laterally into contact with a construction barrier or channeling device. The 9-ft distance was chosen as 1 ft greater than the track width of the largest typical highway truck or tractor-trailer. The 4-ft distance is slightly less than the track width of the smallest automobile.

SCRUBBING

Scrubbing is a factor that has been recognized as a significant safety problem since the term was defined by Klein et al. (*7*) in 1978. The phenomenon of control loss after the occurrence of edge scrubbing was described by Zimmer and Ivey (*2*) as follows:

- A vehicle is under control in a traffic lane adjacent to a pavement edge where an unpaved shoulder is lower than the pavement.
- Because of inattention, distraction, or some other reason the vehicle is allowed to move so that the right wheels are on the unpaved shoulder and just off the paved surface.
- The driver then carefully tries to steer the vehicle gently to bring the right wheels gradually back up onto the paved surface without reducing speed significantly.
- 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 steering 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 4 (1a).
- The driver continues to increase the steering input until the critical steering 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 4, 1b).
- 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 penetration into the oncoming traffic lane (Figure 4, 1c).
- A collision with oncoming vehicles or spin-out and possible vehicle roll may then occur.

An earlier research effort (*2*) developed Figure 5. This figure shows the potential of a given shape and height edge to cause a vehicle control loss. The pavement edge shapes are a relatively sharp 90-degree edge (Shape A), a rounded edge (Shape B), and a 45-degree sloped edge (Shape C). The "safety zones" that the curve for each shape goes through 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

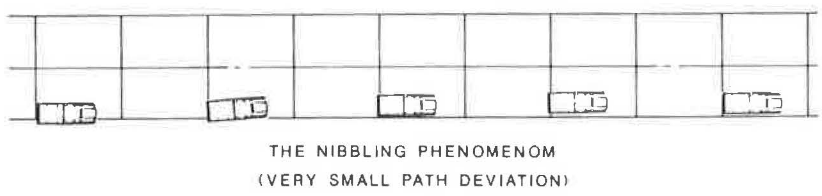


FIGURE 3 Automobile path disturbance by nibbling compared with a critical scrubbing maneuver.

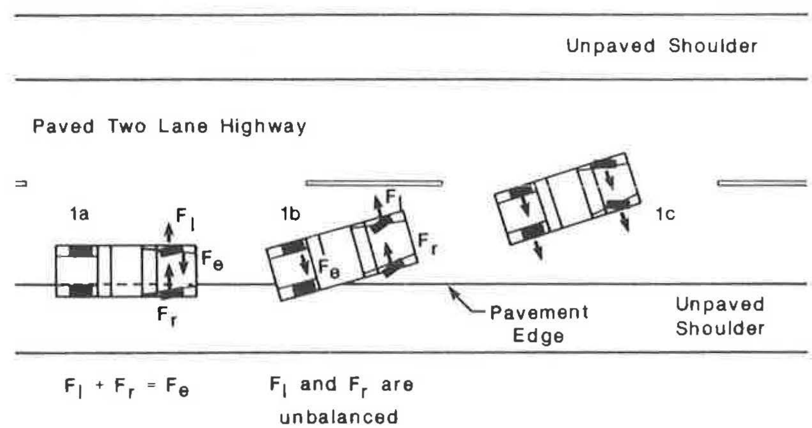


FIGURE 4 Pavement edge influence on vehicle stability.

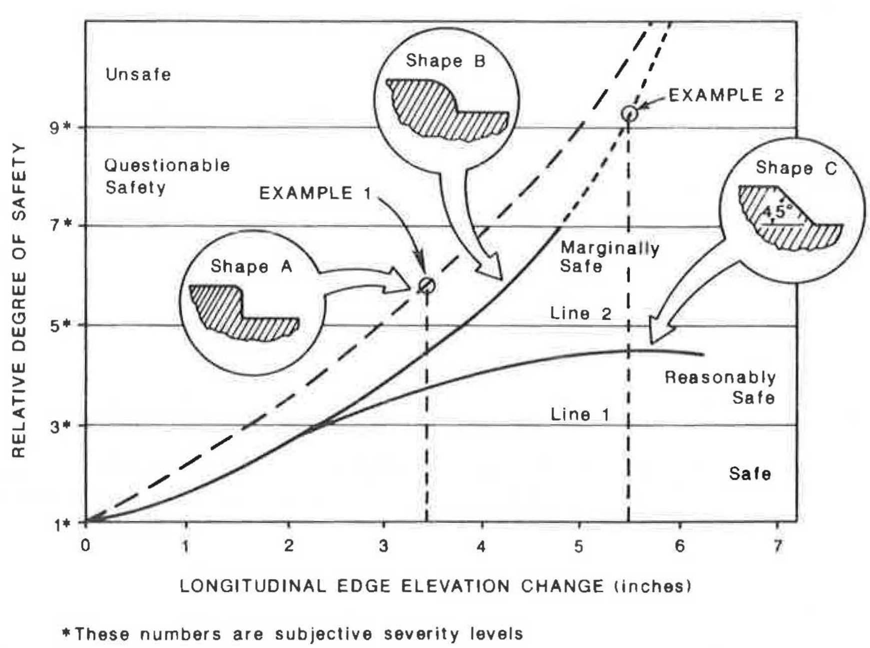


FIGURE 5 Relative degrees of safety for various edge conditions (*3*).

the scrubbing maneuver and remaining within the adjacent traffic lane (includes severity values 5 through 7).

Questionably Safe: 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).

In interpreting the influence of different edge shapes, Ivey and Sicking (*4*) developed the concept of effective edge height and presented a theory for its determination. Figures 6 and 7 show a series of pavement edge profiles along with effective edge heights related to the cross section of a tire. This illustrates graphically how the effective edge height is dictated as the point at which the tire rubs on the edge to generate an edge-mounting force system. For other edge profiles, Table 1 gives the wheel steering angle necessary for the tire to mount the edge. These angles can be determined for any edge condition on the basis of the theory developed by Ivey (*4*) and can be used to determine the post-edge-mounting vehicle trajectory on the basis of the protocol for HVOSM developed by Sicking (*4*). It was this protocol, along with the driver response parameters developed by Olson et al. (*8*), that was used to examine the severity of several pavement edges and to develop the curves relating pavement total edge height (TEH) to pavement effective edge height (EEH) that were used in this study (Figure 8). The concept of effective edge heights was one of the most important considerations in the development of these construction zone guidelines.

DRAGGING

Dragging is an interaction with the pavement edge that can occur when edge heights are greater than the clearance underneath an automobile. In assessing this clearance value, publications of the Motor Vehicle Manufacturers Association were analyzed. The data base included 266 makes of automobiles, ranging in weight from 1,500 to 5,000 lb. Figure 9 shows clearance values of 2.4–8.0 in. About 75 percent of the automobiles analyzed had clearance values of 4.8–6.4 in. Figure 10 shows that only about 4 percent of the automobiles had clearance values less than 4.8 in. and about 15 percent had values above 6.4 in. Note that the frequencies given are not an accurate estimate of the exposure of each clearance value because the number of automobiles of each make was not included in the analysis.

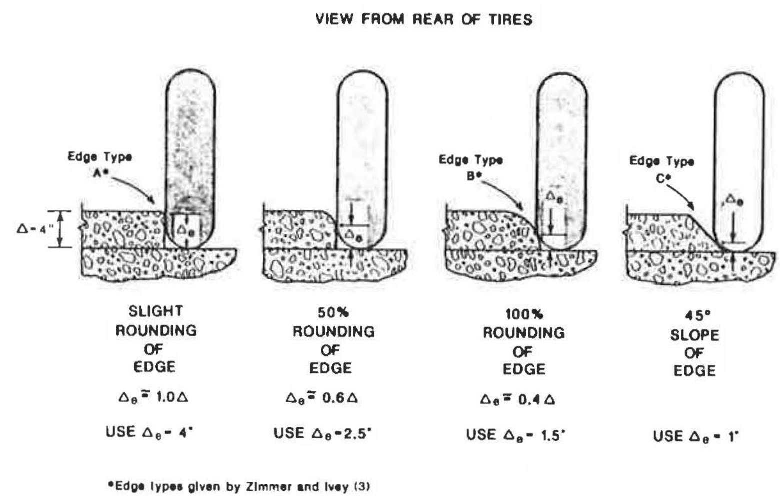


FIGURE 6 Effective edge heights for different edge shapes.

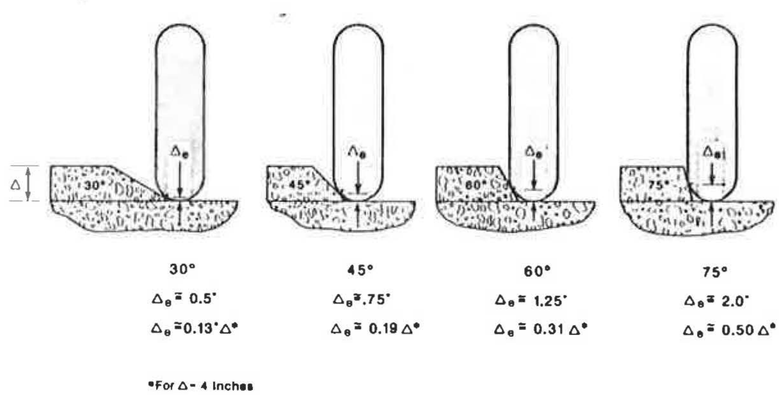
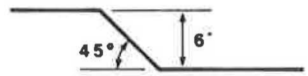
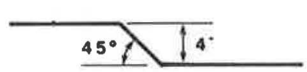
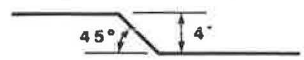
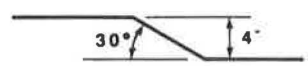
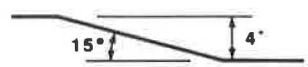


FIGURE 7 Effective edge heights for different edge slopes.

TABLE 1 PAVEMENT EDGE PROFILES, EFFECTIVE EDGE HEIGHTS, AND INITIAL STEERING ANGLES

Condition	Pavement Edge Profile	Effective Edge Height, Δ_e, inches	Initial Steer Angle, α_c degrees
1		4.0 (From Figure 6)	7.5*
2		2.5 (From Figure 6)	3.8*
3		1.5 (From Figure 6)	2.1*
4		0.75 (From Figure 7)	1.1*
5		0.75 (From Figure 7)	1.1*
6		0.75 (From Figure 7)	1.1*
7		0.75 (From Figure 7)	1.1*
8		0.50 (From Figure 7)	0.7*
9		0.20 (From Figure 7)	0.5*

*These values determined from the effective edge height and Figure 8.

It is clear that where pavement edge drops are within these ranges, a significant portion of automobiles will drag undercarriage elements on the pavement edge. This drag will generate a force proportional to the weight supported by the edge and the capacity for friction between the edge and undercarriage elements. Additional forces may be generated by edge gouging.

A friction value of 0.5 has frequently been used for contact between metal and pavement. If the various shapes of undercarriage elements and the lack of stability of a relatively sharp ACP edge are considered, however, that value might be somewhat low. In this work, to assure a conservative solution, that value will be increased by 20 percent to a level of 0.6.

Figure 11 shows two possible situations. The most common is probably the case in which the drag force is to the right of the cg if the vehicle runs off the edge at a shallow angle to the right. If the drag force is acting just inboard of the right front wheel, the maximum yaw moment is generated.

This maximum yaw moment can be calculated by the following equation:

$$M_y = F_d\left(\frac{T}{2} - m\right) = \frac{W}{2}\left(\frac{T}{T - m}\right) f \left(\frac{T}{2} - m\right)$$

where

F_d = drag force;
W = total vehicle weight;
T = track width;
m = distance inbound of the tire center where F_d acts; and
f = friction between undercarriage and edge.

The most critical case would be that in which there is no contact between the right-hand tires and the lower road (possibly shoulder) surface. If a 1,800-lb vehicle with a wheel base of 52 in. were under consideration, the value of M_y for the specific case considered would be

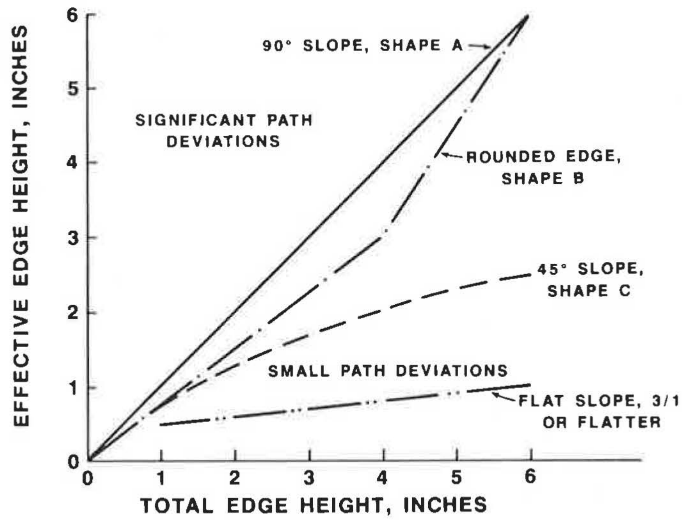


FIGURE 8 Effective edge height on the basis of edge shape and total edge height.

$$M_y = \frac{1{,}800}{2}\left(\frac{52}{52-6}\right)0.6\left(\frac{52}{2}-6\right)$$

so that M_y = 12,204 in. lb or 1,017 ft lb. This is more than sufficient to cause a yaw in the vehicle that would bring the right rear tire into contact with the pavement edge and gradually move the vehicle to where the cg is coincident with the pavement edge. At that point the moment arm of the drag force becomes zero and the yaw moment becomes zero.

If the average drag force over the entire "fall off edge–drag to stop" maneuver is considered to be

$$\frac{1}{2}\left[fW + f\frac{W}{2}\left(\frac{T}{T-m}\right)\right] = f\frac{W}{2}\left[1 + \frac{1}{2}\left(\frac{52}{52-6}\right)\right]$$

$$= 0.78\,f\,W \text{ or } 0.47W$$

then the distance to stop for a vehicle moving 45 mph would be S, where

$$S = \frac{V^2}{2a} = \frac{66^2}{2\,(0.47)\,32.2} = 144 \text{ ft}$$

at a deceleration rate of 0.47 g's, or 15 ft/sec^2. This deceleration is tolerable for the occupants of the stopping vehicle but is an abrupt deceleration from the viewpoint of another driver following closely behind, because the vehicle would stop in about 4.4 sec. For this reason the drag interaction is considered a safety influence primarily because of the possibility of collision with following vehicles.

The other type of drag situation is shown by Figure 11*b*. Here the departure angle, speed, or combination of both would be sufficient to have the drag force act on a line to the left of the cg. The resultant vehicle rotation would be counterclockwise and would not be limited by edge-wheel interference, as in 11*a*. Other factors would tend to reduce the effect of the drag moment. First, as yaw progressed and the drag force moved toward the left front wheel, the load carried by the edge would decrease, going to zero as the left front wheel approached the edge brink. Second, the cornering force developed on the right rear tire, which must be in contact with the lower surface, would oppose the yaw of the vehicle. If the yaw developed quickly enough, possibly induced by major gouging into the edge, and if very high cornering forces were developed on the right-side tires, a vehicle roll might be induced. The result of these considerations is that the drag situation should be considered the primary control loss phenomenon for automobiles where edge drops of 5–20 in. occur.

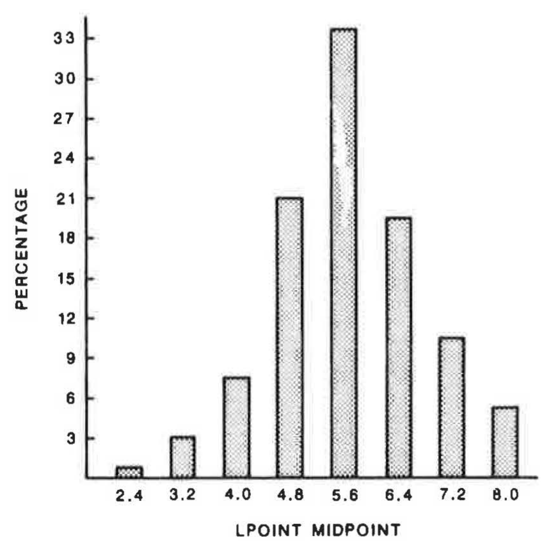


FIGURE 9 Frequency distribution of automobile clearance values.

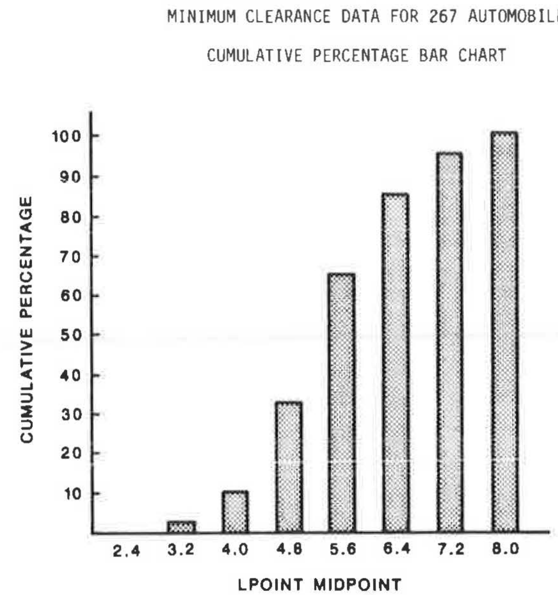


FIGURE 10 Cumulative percentage distribution of automobile clearance values.

ROLLING

Trucks

In deciding whether a truck will roll when it traverses an edge drop, several items must be considered. These are first, the fact that one side moves to a lower elevation and the center of gravity moves outboard with respect to the right-side wheels; second, the compression of right-side tires as the load shifts to the low-elevation side (causing larger axle rotation); third, the compression of right-side springs, which causes further rotation of the body (thus shifting the cg farther to the right); and finally, whether any cornering is induced by the driver's trying to steer back. If this cornering occurs, a lateral acceleration is generated. This resulting inertial force provides an additional overturning moment. Figure 12 shows a truck approaching the critical roll condition.

Ervin et al. (*9*) have shown that typical tractor-trailers have a threshold roll lateral acceleration of 0.24–0.34 gs (see Table 2). If the case of the geometrics alone is considered and if the lower threshold acceleration is chosen, the maximum edge drop for a trailer to remain upright would be given by

Max angle θ where $\sin \theta = 0.24$

$$\theta = 13.8 \text{ degrees}$$

If a trailer track width is 6 ft, then

$$\sin \theta = \frac{\Delta}{T}$$

or

$$\Delta = T \sin \theta = 6(0.24) = 1.44 \text{ ft} = 17.3 \text{ in.}$$

In this situation, the trailer is influenced by the overturning component of gravity, which is equal to the sine of the rotation angle, θ. Ross has recently shown by Phase IV simulation (*10*) that a van trailer subjected to this level of lateral acceleration would have a net body roll of about 3 degrees, including the effect of both tire deflection and suspension. If this roll is considered, then the critical edge height would be estimated by

$$\theta = 13.8 \text{ degrees} - 3 \text{ degrees} = 10.8 \text{ degrees}$$

$$\sin 10.8 \text{ degrees} = 0.187$$

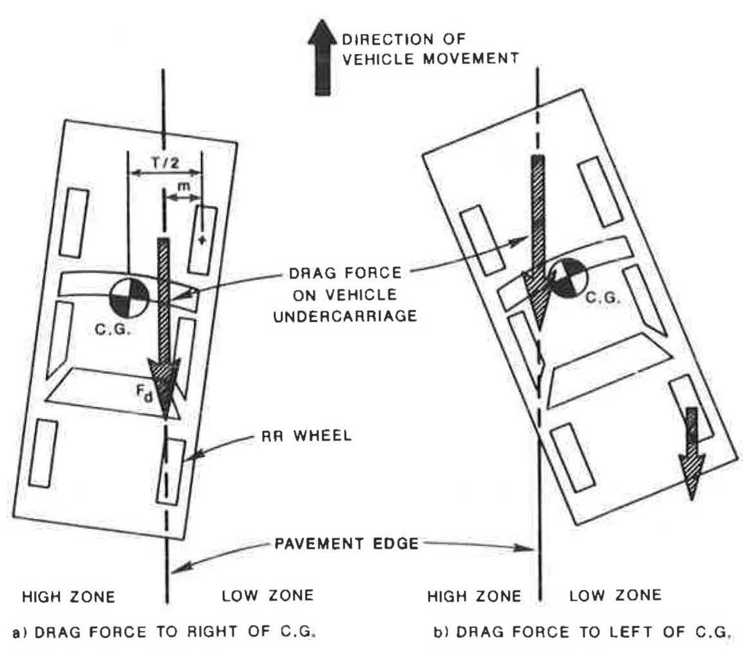


FIGURE 11 Vehicle movements in response to drag force.

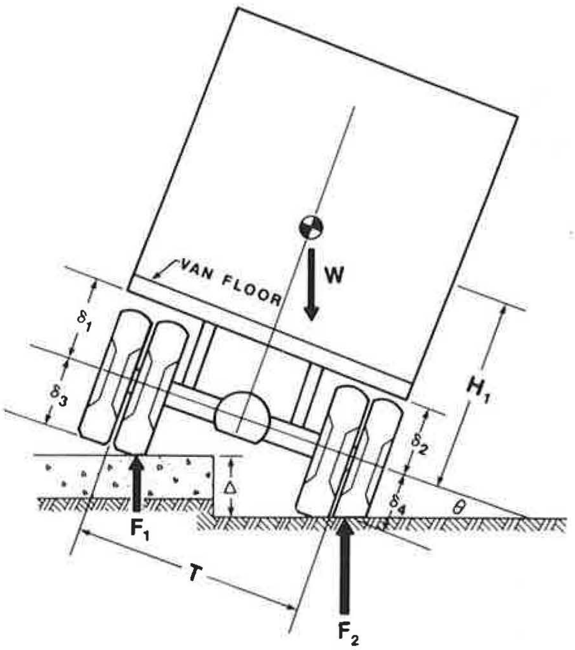


FIGURE 12 Trailer approaching critical roll condition.

$$\Delta = T \sin \theta = 6(0.187) = 1.12 \text{ ft} = 13.5 \text{ in.}$$

This would be the critical edge drop to cause rolling for a small segment of the truck population. If the driver's steering back to the left increased the roll moment, or if a soft soil condition increased the effective edge height, or finally, if load shift produced significant lateral cg movement, trucks with lower cg heights might also roll. There are other compromising conditions, including a shoulder slope away from the traffic lanes. The result of these considerations is the recognition that at least some portion of the truck fleet would be expected to roll when traversing an edge drop of only 1 ft.

Because trucks have a relatively high cg compared to track width, they represent a more critical situation when vehicle roll is considered than do passenger automobiles. Although trucks are certainly fewer in number than automobiles, significant percentages of trucks are present on major highways. These major highways generally require maintenance and reconstruction more often.

A static stability factor, $T/2H$, is often chosen to show gross differences in the stability factors of the vehicle fleet. T is the track width and H is the cg height of a given vehicle. Figure 13 shows these values for a wide spectrum of vehicles, illustrating further that the truck end of the spectrum, with $T/2H$ values shown here as low as 0.3, is the most critical.

AUTOMOBILES

The phenomenon of rolling for an automobile is different. If an edge interaction similar to that shown in Figure 12 is considered for an automobile, it may seem obvious that a higher edge

TABLE 2 LOADING DATA AND RESULTING ROLLOVER THRESHOLDS FOR EXAMPLE TRACTOR-SEMI-TRAILERS AT FULL LOAD (*9*)

CASE	CONFIGURATION	WEIGHT (lbs.) GVW	PAYLOAD CG HEIGHT (in.)	ROLLOVER THRESHOLD (G's)
A (55" TYP.)	Full Gross, Medium-Density Freight (34 lb/ft^3)	80,000	83.5	.34
B (50 in. 30% of Pyld. Wt; 50 in. 70% of Pyld. Wt)	"Typical" LTL Freight Load	73,000	95.0	.28
C (100 in.)	Full Gross, Full Cube, Homogeneous Freight (18.7 lb/ft^3)	80,000	105.0	.24
D (88.6 in.)	Full Gross Gasoline Tanker	80,000	88.6	.32
E	Cryogenic Tanker (He_2 and H_2)	80,000	100.0	.26

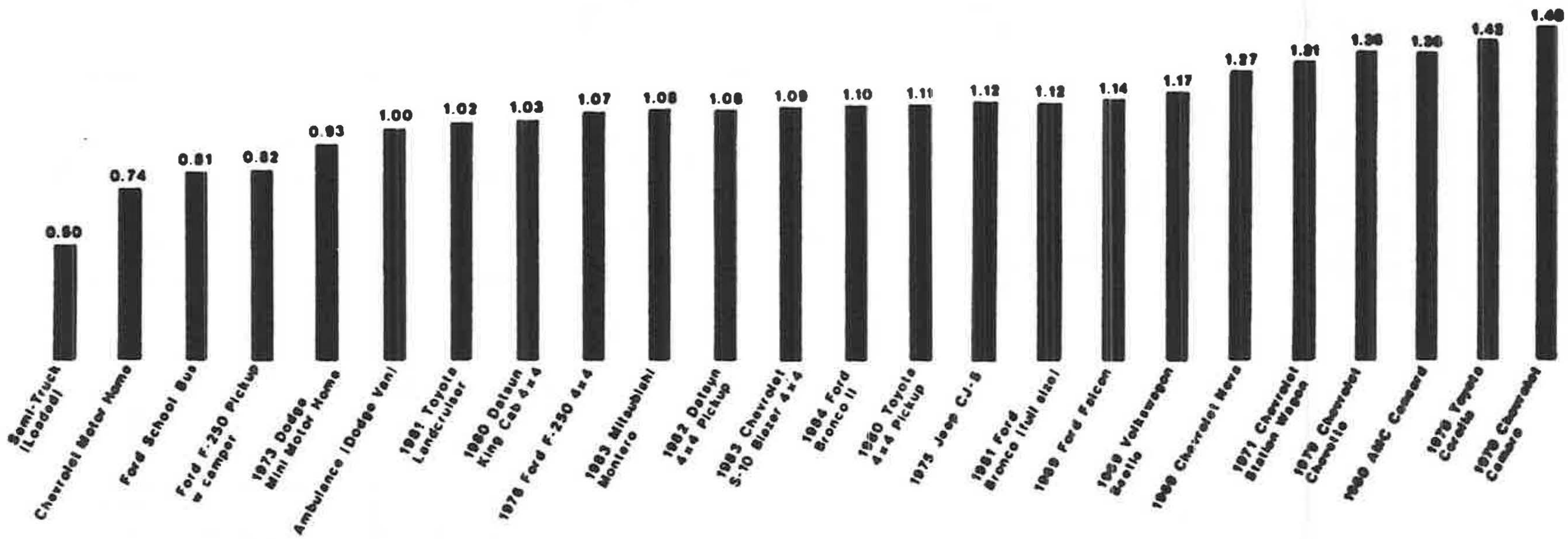


FIGURE 13 Static stability ratios for selected vehicles (*11*).

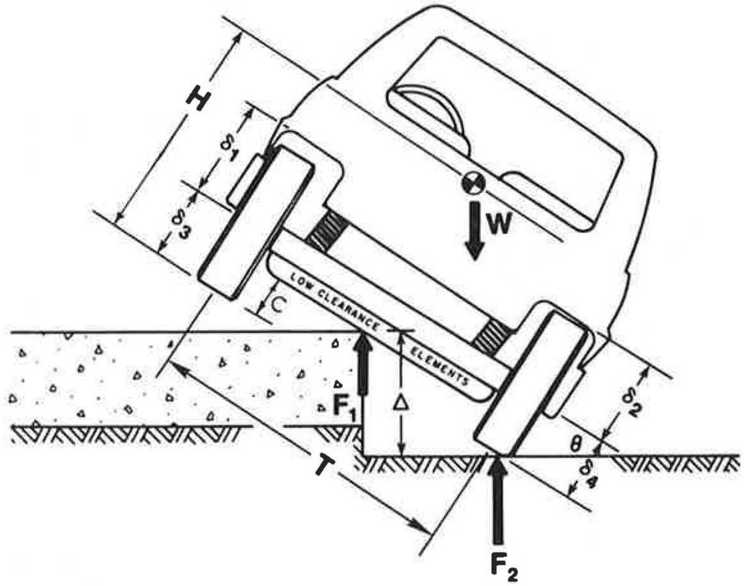


FIGURE 14 Automobile approaching critical roll condition.

is required to produce roll than the one estimated for a tractor-trailer. This may not be so obvious, however, if the interaction shown by Figure 14 is considered. Here the "low clearance elements" of the automobile are in contact with the edge of the pavement at a point about midway between the wheels.

If a $T/2H$ value of 1.2 is chosen as representative of a large part of the automobile fleet, and if the typical track width is 58 in. and a typical clearance is 5.6 in. (Figure 9), a typical cg height of

$$H = \frac{T}{2\,(1.2)} = \frac{58}{2.4} = 24 \text{ in.}$$

can be calculated. Further consideration of Figure 14 would allow the development of the following equation to predict when the line of action of W would become coincident with the line of action of $F2$, that is, when the moment preventing rollover becomes zero:

$$(H - C)\sin\theta = \left(\frac{T}{2} - c\tan\theta\right)\sin\theta$$

where

H = cg height;
T = track width;
C = ground clearance; and
θ = critical angle.

If the values suggested previously are used in this equation, θ is equal to 62 degrees. Now the force causing body roll is equal to W sin 62 degrees, or 0.88 W. This would be equivalent to a lateral acceleration of 0.88 g's. By using HVOSM, Sicking showed that a typical body roll value of a vehicle subjected to about 0.9 g's of lateral acceleration is about 10 degrees. Thus a critical angle would be about 62 degrees less 10 degrees, or 52 degrees. The following relationship can be derived by using geometric considerations:

$$\sin\theta = \frac{\Delta - (c/\cos\theta)}{(T/2) - c\tan\theta}$$

If the following values are substituted,

T = 58 in. C = 5.6 in. θ = 52 degrees

the value of Δ is found to be 26 in., roughly double the critical value of Δ for trucks.

This would be the maximum edge drop that the typical automobile could encounter without rolling, if the driver input of steering back to the left did not increase the roll moment, if a soft soil condition did not increase the effective edge height, and finally, if the right front lower corner or suspension elements did not dig into the lower surface, causing vehicle spin-out. The result of all these considerations and a selected number of HVOSM runs using a mini-compact vehicle leads to the conclusion that a small segment of the vehicle population, namely high-cg tractor-trailers, could experience rollover on edge drops as low as 1 ft, but that most vehicles would not be expected to roll until edge drops approached 2 ft, unless certain aggravating circumstances were present.

STUDY APPROACH

The authors have previously published guidelines for the maintenance of pavement edges (*2, 3*). Those guidelines dealt with a range of pavement edge heights up to 6 in. In the case of construction zones, however, the range of edge drops can be much larger. In a recent study of the use of barriers in construction zones, five sites were observed at which the drop was 10–20 ft and one at which the drop was 80 ft. In this work the small values are again considered, but the scope is increased to include much larger edge drops. There is another reason that recommendations for construction zones might be significantly different from recommendations for maintenance. In construction zones the time of exposure may be small, the existence of the edge or drop can be predicted, and appropriate warning devices can be placed. In contrast, on completed highways the knowledge of small edge drops must be based on surveillance, and the maintenance operations, when required, must be funded and scheduled. Finally, if surveillance does not detect the condition, the exposure of traffic to the situation may be long term, or even until an accident brings it to the attention of the highway agency.

The approach that was taken here (*11*) is that the degree of exposure to a certain condition is estimated, the result of that condition on vehicles that encounter it is predicted, the severity index and cost of specific types of accidents are estimated, and the costs of warning, delineation, edge treatment, and barriers determined. As a result of these estimates, predictions, and determinations, a benefit/cost ratio for various situations can be determined and used as a basis for treatment guidelines. These cost estimates are developed in detail elsewhere (*11*), including a matrix of predicted accident costs for a wide range of traffic and pavement edge conditions.

BENEFIT-COST FORMULATION

Accident Costs

The determination of accident costs requires the estimate of the number of accidents that are expected to occur and the severity of those accidents. The probabilities and severities used were developed by Ivey et al. (*11*). This work considered these five categories: (a) nibbling, (b) scrubbing, (c) scrubbing-drag, (d) drag-roll, and (e) rolling. Table 3, from the ABC-RS model by Sicking and Ross (*12*) was used to relate accident costs to accident severity index (SI).

By using the predictions of hazardous event probability and severity developed by Ivey et al. (*11*) and the ABC-RS accident costs, the accident costs due to edges and dropoffs in construction zones were predicted for the situations given in Table 4. A detailed presentation of accident costs was made for 524 combinations of these conditions. These results reveal that predicted accident costs cover an extremely wide range, varying from nothing for the 1 in. edge to over $100,000 per month per 1,000 ft of construction zone for 40-in. edge drops and high values of average daily traffic (ADT). Table 5 gives some of these values for the most critical situation investigated, the four-lane undivided highway.

TABLE 3 ACCIDENT COSTS FOR VARIOUS SEVERITY INDEX LEVELS

Severity Index	Accident Costs (1986 dollars)
0	2,120
1	4,290
2	6,450
3	8,620
4	18,230
5	49,450
6	103,020
7	238,500
8	463,340
9	604,820
10	723,970

Barrier Costs

After the costs of certain countermeasures are developed, they may be used to determine whether the countermeasures could be justified on a benefit-cost basis. One thing is apparent: a positive barrier, such as a precast concrete barrier (PCB), would not be economically justified to protect against edges unless ADT values are high (usually above 50,000) and edge drops are close by and deep.

TABLE 4 CONDITIONS USED TO PREDICT ACCIDENT COST

Highway Type	ADT	Edge Height (in.)	Lateral Position (ft)
Two-lane undivided	1,000 to 30,000	1 to 24	0 to 20
Four-lane, undivided	10,000 to 200,000	1 to 24	0 to 30
Six-lane, undivided	25,000 to 225,000	1 to 24	0 to 20

TABLE 5 REPRESENTATIVE ACCIDENT COSTS FOR 1,000 FT OF A SPECIFIED EDGE CONDITION IN A CONSTRUCTION ZONE

Lateral Clearance (ft)	Dropoff Height (in.)	Accident Cost[a] ($/month/1,000 ft)
ADT = 10,000		
0	5	30
5	5	28
20	5	13
0	24	639
5	24	587
20	24	263
ADT = 100,000		
0	5	442
5	5	402
20	5	182
0	24	9,302
5	24	8,539
20	24	3,833
ADT = 200,000		
0	5	1,493
5	5	1,370
20	5	615
0	24	31,498
5	24	28,851
20	24	12,949

[a]Dollars per month per 1,000 feet of edge condition.

By using the data from Table 4, Figures 15–17 were developed. These three figures show zones where a positive barrier is cost effective if the cost of the barrier is $2.00, $5.00, or $10.00/ft/month. Discussions with contractors, barrier suppliers, and highway engineers across the United States indicate a wide range in the cost of concrete barriers for construction zones. New barriers may cost from 25 to 30 dollars per foot, but this cost is not indicative of the cost in construction zones. If a highway department buys a portable barrier and uses it for several years, the ultimate cost per month of use may be only a fraction of the original cost. Further, if the concrete barrier is supplied by the contractor for use during construction and then ultimately installed as permanent barrier, the costs of temporary use are difficult to determine. It seems apparent, however, that they would again be only a fraction of the permanent barrier cost. In some states (Indiana, for example), concrete barriers are leased from a barrier precaster. The cost of these barriers is highly dependent on the distance from the storage yard to the job site but may approach as little as $2.00/ft/month on some jobs.

Figures 15–17, which were not used in the final section of the guidelines, are presented here as additional cost effectiveness tests that may be used in conditions where the guidelines show that positive barriers are optional. In terms of the edge height and the lateral distance from the nearest traffic lane to that edge, these curves define boundaries of cost effectiveness. All combinations of edge height and lateral distance that plot above a given curve would be expected to be cost effective; that is, the savings in accident costs would be less than or equal to the cost of providing a barrier. Obviously, the position of these curves is highly dependent on the cost of providing the barrier. For this reason, curves are provided at the barrier cost levels of $2.00, $5.00, and $10.00/ft/month.

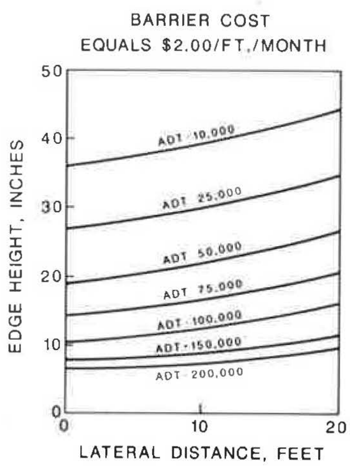


FIGURE 15 Edge height and lateral distance conditions related to cost effectiveness of concrete barrier rail (at $2.00/ft/month).

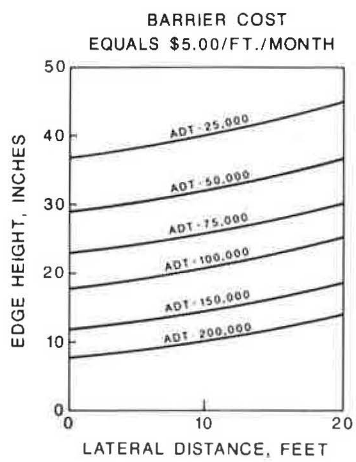


FIGURE 16 Edge height and lateral distance conditions related to cost effectiveness of concrete barrier rail (at $5.00/ft/month).

These curves are considered to be conservatively placed in that the accident costs of colliding with the barrier instead of interacting with the edge are not considered. Since the edge condition is usually only one of the factors considered when the decision to provide or not provide a barrier is reached, greater levels of sophistication in determining the cost-effective zones were not considered appropriate.

DEVELOPMENT OF GUIDELINES

In developing guidelines for the use of warning and protective devices in construction zones, the authors relied on the understanding of potential hazards of certain types of edges, as described in the first part of this paper, on the warning and protective devices considered practical and effective, and on the costs of positive barriers, such as portable concrete barriers. In the case of warning devices, every effort was made to be conservative (i.e., to provide, if anything, more than adequate guidance and warning). In the case of justifying positive barriers, simplifying and conservative assumptions were made in the guidelines suggesting use (i.e., barriers were recommended even in cases where cost effectiveness is marginal). It was also considered necessary to build flexibility into these guidelines so that the special cases could be treated in special ways.

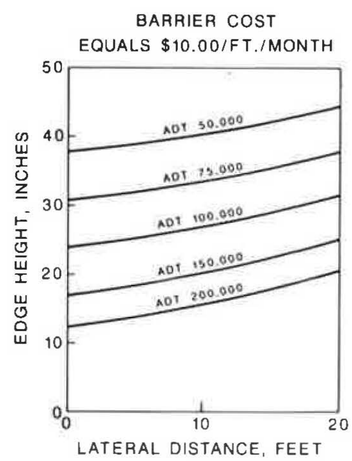


FIGURE 17 Edge height and lateral distance conditions related to cost effectiveness of concrete barrier rail (at $10.00/ft/month).

Because the authors have attempted to present their work succinctly, they have only been able to summarize the research that went into the guidelines. A more complete understanding of the factors that contributed to the final form of the guidelines may be gained by consulting previous work by the authors and their colleagues (*13–17*).

The resulting guidelines are given in the Appendix (after the Discussion and Authors' Closure). They are presented here for the consideration of states and other governmental agencies. These guidelines have been reviewed by the State Department of Highways and Public Transportation and the Federal Highway Administration, and numerous revisions were made before the guidelines were accepted. Many appropriate suggestions were made by state and federal reviewers, resulting in guidelines that are believed to be both practical and effective. The guidelines were provided to all Texas districts on November 30, 1987.

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DISCUSSION

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The need for tested and proven standards and guidelines for treating pavement edge dropoffs is critical. Edge dropoffs in construction work zones and on existing highways have become a recognized cause of accidents and have become an increasing cause of tort litigation in many states. Unfortunately, the treatments proposed in this paper and adopted by the Texas Department of Highways and Public Transportation are neither tested nor proven. The assumptions used with regard to the types of vehicles, vehicle response, and the expected actions of drivers who leave the road and encounter an edge dropoff raise substantial questions.

MOTORCYCLES

The paper does not discuss the effects of pavement edge dropoffs on the possibility of motorcycle instability when a rider encounters a vertical edge dropoff of less than 1.5 in. The paper states that vertical edge dropoffs between lanes of travel should not exceed 1.5 in. Author Ivey, in response to a question at the 1988 TRB meeting presentation of this paper, responded that edge heights of less than 1 in. could cause instability in a motorcycle. In fact, he said that any vertical edge can be a problem for a motorcycle. Clearly, the guidelines do not consider this hazard adequately and thus are flawed.

HAZARDS TO AUTOMOBILE OCCUPANTS

The authors assume only one hazard to occupants of an automobile that drops one or two wheels off the edge of a dropoff of 5–20 in. in depth and slides along the edge with its underside in contact with the pavement. This hazard is that the automobile may be rear-ended by another vehicle because of sudden slowing. The authors rule it "improbable" that either the drag on the automobile's underside or cornering forces on the tires could cause a rollover or other loss of control or spinout. This assumption is unsupported and could prove dangerous. Another real hazard to occupants of automobiles that should be considered is the presence of fixed objects along the pavement edge, such as bridge abutments or construction equipment and materials. Furthermore, construction workers can be struck by an out-of-control vehicle that slides along an edge dropoff or that may completely leave the pavement in an uncontrolled manner. Loss of vehicle control can be a complex event. No research, which might have included field testimony and observations, was presented to support assumptions made about the events being analyzed in this paper. The assumptions are far too simplistic and limiting to be accepted without more in-depth research.

TRUCKS

The parameters used to analyze the potential hazard to trucks from edge dropoffs are even more limited than those used for cars. The authors discount a number of events that can occur when a truck drops its wheels off the pavement. While the authors do discuss the high center of gravity characteristics of trucks, they discount the effects of shifting cargo. There is no mention of the worst case cargo—liquid. The surge of liquid loads, particularly partial loads, can overturn a truck on a pavement surface. When this same truck encounters a dropoff of 1, 2, or 3 ft, the hazard is magnified. Liquid loads, in addition to causing vehicle instability, can be composed of hazardous commodities that can injure large populations. (It should be noted that hazardous cargos are quite prevalent in many areas of Texas, where petrochemical plants are located.)

The authors also discount the sideward acceleration forces on the truck due to the driver's attempts to steer back onto the pavement. It is unrealistic to expect that drivers of cars or trucks will continue to steer their vehicles parallel to the pavement's edge after the wheels have dropped. Basic driver instinct is to return to the pavement. Any analysis that assumes otherwise makes an erroneous and dangerous assumption. The authors conclude that

> a small segment of the vehicle population, namely high-cg tractor-trailers, could experience rollover on edge drops as low as 1 ft, but that most vehicles [i.e., mini-compact automobiles] would not be expected to roll until edge drops approached 2 ft, unless certain aggravating circumstances were present.

There is no quantification of the "small segment," nor of the consequences to vehicle occupants. Such unsupported assumptions, which ignore "segments" of drivers, do not constitute an acceptable method of risk analysis in the vital area of public safety.

COST ANALYSIS

The authors discuss a benefit/cost approach to selecting treatments for edge dropoffs in construction zones. Unfortunately, the only basis for the costs used is a paper by one of the authors, and no mention is made of its availability. Thus an important aspect of the paper cannot be analyzed. As previously discussed, there is no discussion of accidents involving trucks carrying hazardous materials and the risk to people or public facilities (e.g., public water supplies). Any benefit/cost analysis is incomplete without an analysis of costs involved in these types of accidents and the potential reduction of cost and risk resulting from improved treatments.

DISCUSSION OF TREATMENT

In spite of the shortcomings of the analytical approach used by the authors, the guidelines are an improvement over previous guidelines recommended for maintenance of highways by Ivey and other researchers at TTI. Earlier TTI maintenance guidelines, published in 1982, recommended that a 6-in. dropoff have a slope of 45 degrees or 1 to 1. The new guidelines for construction provide that if an edge dropoff is more than 2 in. in depth (called "Edge Condition I"), a slope should be constructed outward from the pavement surface of compacted fill material at a 3-to-1 or flatter slope. If the sloped fill material is not added and the edge dropoff is within 30 ft of the travel lane's edge, then traffic control devices must be installed.

Under Edge Condition II, in which an edge is 5–24 in. or more in depth, the recommendation is to use a slope of 3 to 1 or to use signs, vertical panels, and barrels with steady burn lights if the drop is within 20 ft of the lane's edge. This provision allowing use of traffic control devices alone for a 24-in. edge dropoff is not adequate. Traffic control devices at the edge of a traveled lane, particularly where traffic is heavy, are often knocked off the road. As a result, the edge dropoff is exposed without warning. In addition, traffic control devices do not provide any shielding of the dropoff to contain or redirect an errant vehicle. Urban areas where high traffic volumes are common and trucks carry highly hazardous cargo are precisely where precautions must be exercised. Edge Condition II treatment is an apparent result of the flawed analytical approach used for this report. Such provisions encourage road designers and contractors to create edge dropoff hazards that may otherwise be prevented.

CONCLUSION

While the guidelines are an improvement over previous methods used by the Texas Department of Highways and Public Transportation for edge dropoffs up to 5 in., improvements are still needed in the adopted policy for edge dropoffs of 5–24 in. This paper, in supporting the guidelines, advocates an approach limited by unrealistic assumptions. These faulty assumptions could mislead engineers who follow the analytical example provided and thus create a more dangerous condition for the road user and construction worker than can be justified.

The lack of vehicular testing of the guidelines is a major shortcoming of the research. The end result of adopting these guidelines will surely be unnecessary accidents, injuries, and litigation.

AUTHORS' CLOSURE

The authors are pleased that Anderson has taken the time to discuss this paper. He is certainly sincerely concerned about safety but has apparently missed certain key statements and references that are important to developing a thorough understanding of these guidelines.

One of the basic problems that a reviewer has in understanding a paper that has been condensed to the degree necessitated by TRB publication and presentation requirements is the authors' reliance on extensive prior research. Unless the reviewer is already familiar with a dozen or more references or takes the trouble to read and understand them, he is operating from a very different perspective than that of the writers. It takes time and space for a writer to discuss these references. In this case that luxury is simply not available under TRB length requirements. The present TRB paper is a condensation of a report of over 100 pages that goes into much greater detail. In an effort to relieve Anderson's concerns, specific paragraphs will be discussed under the heading of his discussion.

Concerning the statement that "the treatments . . . are neither tested nor proven," the delineation and barrier devices have been in use for over 15 years and are qualified under state, AASHTO, and FHWA guidelines, policies, and standards.

Experience has proven that the recommended devices are quite effective in construction zone applications. No set of guidelines for a specific purpose is ever *proven* until it has been successfully *used* and *evaluated.* The State Department of Highways and Public Transportation (SDHPT) has taken the initiative to bring together *all* that is known about this particular problem as the basis of these guidelines. In so doing, we believe that SDHPT has acted in an extremely progressive and responsible manner.

MOTORCYCLES

Anderson is concerned about the fact that motorcycles may sometimes prove unstable if brought into contact with very small edges, the type of edge sometimes produced by a single lift of asphaltic concrete. Motorcycles are probably more difficult to control when in contact with any type of surface discontinuity, but to reach the conclusion that their omission in these guidelines is inappropriate is a mistake for several reasons. To this date there have been at least eight papers written on the pavement edge phenomenon. None have considered motorcycles. The reason for that is twofold. First, there is no precedent for use of a motorcycle as a "design vehicle" for highways. Consider the examples of median barriers, crash cushions, curbs, guardrails, breakaway structures, vertical curves, and horizontal curves. In fact, if the index of the 1984 *Policy on Geometric Design of Highways and Streets* is consulted, the word motorcycle will not be found (*1*). The same is true of the second edition of the *Transportation and Traffic Engineering Handbook* (2). Neither will certain types of large trucks be found in these documents. The highways are designed for automobiles and common types of trucks. It has never been considered practical to cover the entire spectrum of vehicles that may be found on a highway. The usual MUTCD signing of a construction zone should be enough to put the motorcycle rider on notice that he is moving into an area that may put unique requirements on him to drive with care. It was not considered appropriate to post warnings for extremely small sloped edges that have no significant influence on automobiles. The guidelines *do* suggest that the sharper edges (50–90 degrees, Edge Condition III) should be treated with warning signs (CW 21-13 or 14) and delineation (vertical panels) even when the edge height is less than 2 in. (see Figure A2, Edge Condition III of the guidelines).

HAZARDS TO CAR OCCUPANTS

These are guidelines for protection against the hazard caused by edges *only*. Note this sentence in the guidelines: "It does not consider the hazards of other conditions in the construction zones, such as heavy machines or the hazards to construction workers." Anderson is concerned about the guidelines' not doing something that it was never their purpose to accomplish. Use of the HVOSM model and careful assessment of the literature on vehicle stability strongly support the improbability of a vehicle roll as a result of underside drag.

TRUCKS

We are puzzled by Anderson's statement here. It is emphasized in the report that high-cg tractor semi-trailers are nearly twice as sensitive to rolling as are automobiles. The concerns he expresses are *all* dealt with in two sentences of the paper:

> This would be the critical edge drop to cause rolling for a small segment of the truck population. If the driver's steering back to the left increased the roll moment, or if a soft soil condition increased the effective edge height, or finally, if load shift produced significant lateral cg movement, trucks with lower cg heights might also roll. There are other compromising conditions, including a shoulder slope away from the traffic lanes.

and finally, on the subject of frequency:

> Although trucks are certainly fewer in number than automobiles, significant percentages of trucks are present on major highways. These major highways generally require maintenance and reconstruction more often.

It was recognized that no detailed investigations of truck instability problems had been made when this work was completed. In the time since presentation, however, such an investigation was made. The following quote is significant concerning the allegations of "simplistic assumptions" (*3*):

> Finally, it is concluded that the guidelines recommended for edge and shoulder maintenance in 1983 . . . and the recent guidelines for treatment of edges in construction zones . . . are as appropriate for TST's as they are for the vehicle which was then given primary consideration, the automobile.

COST ANALYSIS

The need to have this paper comply with TRB length guidelines prompted the removal of 37 pages of benefit-cost analysis. That analysis is in a report that is available from both SDHPT and TTI (*4*).

DISCUSSION OF TREATMENT

Perhaps is has been difficult for Anderson to recall the previous maintenance guidelines. A 6-in. dropoff was *never* recommended to have a slope of 45 degrees. The following was stated (*5*):

> If shape C (45-degree edge) 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 a significant advantage in resisting pavement edge deterioration.

and (*5*)

> Pavement edge heights more than 5 in. in height can interfere with the underneath clearance and thus create safety problems for small automobiles.

Furthermore, Anderson has misinterpreted recommendations of the current guidelines. Edge Condition I is the result of the construction of an edge fill. The edge fill is not required; it is simply an option that will allow the use of minimum signing and delineation.

Here Anderson seems to be saying that traffic control devices are not adequate if they are not maintained. We would agree only with that part of his ideas, obvious as it may seem. It is true that some heavy trucks may roll when erroneously driven across such a edge. This has been discussed in detail in the section on trucks. It is not true that positive barriers are necessarily warranted in these conditions by high-cg trucks carrying hazardous materials. In fact, there are *no temporary construction barriers* commonly available that were designed for trucks. They are *all* designed for automobiles (*6, 7*). If by the term "flawed analytical approach," Anderson means that the benefit-cost analysis is imperfect, we certainly acknowledge that fact. As engineers, we have used the information available to arrive at a reasonable analysis. Where information is unavailable or is known to have certain limitations (is that what "flawed" means?), we have used well-considered engineering estimates. To do otherwise would have been to acknowledge that the job was impossible. It was not.

CONCLUSION

These methods are not "improvements" over previous methods used by SDHPT. These methods are for construction zones. The previous methods are for shoulder maintenance. The two have much time the same basis, however, and are in fact quite consistent.

It is *impossible* to do "vehicular testing of the guidelines." It is *possible* to test the *guidelines* but ultimately only through application.

The end result of adopting these guidelines "will surely be" a reduction of accidents and injuries. Considering that only a few highway agencies have adopted any type of comprehensive plan to deal with pavement edges, SDHPT must be considered a pioneer in this area.

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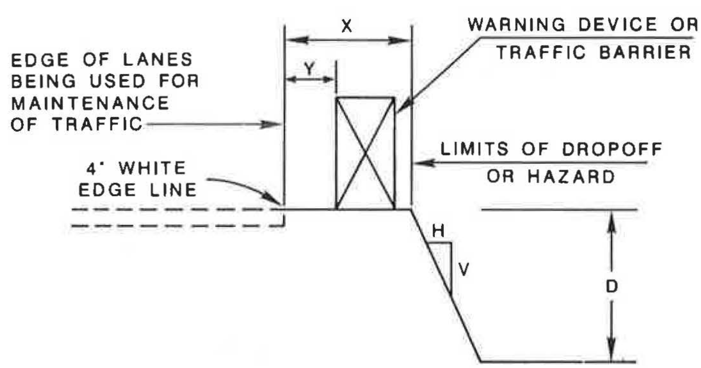
APPENDIX: GUIDELINES FOR WARNING AND PROTECTIVE DEVICES FOR PAVEMENT DROPOFFS

These guidelines are applicable to construction work where continuous pavement edges or dropoffs exist parallel and adjacent to a lane used for traffic.



NOTE: Minimum Lane Width = 10 ft.
Desirable Lane Width = 11–12 ft.

1. Distance "X" (lateral clearance) is to be the maximum practical under job conditions.
2. Distance "Y" is to be a minimum of 2 feet if feasible.
3. Warning devices must not encroach on lanes required for maintenance of traffic at any time.
4. When optional devices are specified, the contractor may select the type to be used. If distance "X" must be less than 3 feet use of positive barrier (e.g., concrete traffic barrier, metal beam guard fence, barrel mounted guard fence) may not be feasible. If in this case a positive barrier is needed according to Figure 4, considerations should be given to moving the lane of travel laterally to provide the needed space or to providing an edge slope such as Condition I.

FIGURE A1 Definition of terms.

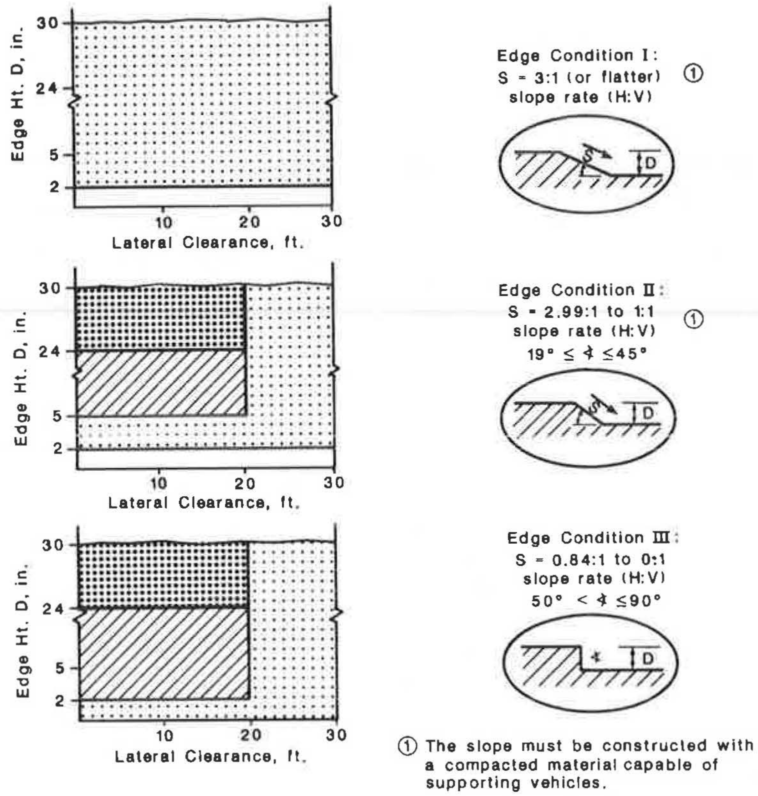


FIGURE A2 Definition of treatment zones for various edge conditions.

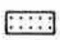
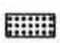
Zone	Usual Treatment
	CW 21-13 or CW 21-14 signs plus vertical panels (15).
	CW 21-13 or CW 21-14 signs plus drums with steady burn lights. Where restricted space precludes the use of drums, use vertical panels. An edge fill may be provided to change the edge slope to that of the preferable Edge Condition I (15, 16).
	Check indications (Figure 4) for positive barrier. Where positive barrier is not indicated, the treatment shown above for zone may be used after consideration of all other applicable factors.

FIGURE A3 Treatment selection guidelines (to be used with Figure A2) (*15, 16*).

The type of warning device and/or protective barrier selected depends upon several factors including traffic volume, lateral distance from the edge of travel lane to hazardous condition, depth of dropoff, duration of the hazardous condition, and shape of the edge or slope of the dropoff.

In urban areas where speeds of 30 mph or less can be predicted for traffic in a particular construction zone, these lower speeds may indicate less stringent requirements for signing, delineation, and the use of barriers. Still, less stringent requirements are not recommended for sharp 90-degree edges from 2 to 6 in. in height or for edges over 18 in. in height if located within a lateral offset distance of six feet or less from a traffic lane.

These guidelines are premised on a duration period of the edge condition of overnight or longer. Considerations of practicality will dictate against the use of positive barriers for very short periods of time. Figure A1 shows pertinent dimensions and terms, and Figure A2 gives a definition of the treatment zones for various edge conditions. Figure A3 gives the suggested treatments for each of these zones. Under certain circumstances the suggested treatment indicated by Figures A2 and A3 may not be practical and a unique treatment should be devised and its proper function substantiated. Figure A4 depicts traffic volume and dropoff offset conditions that justify positive barriers to shield hazardous edges.

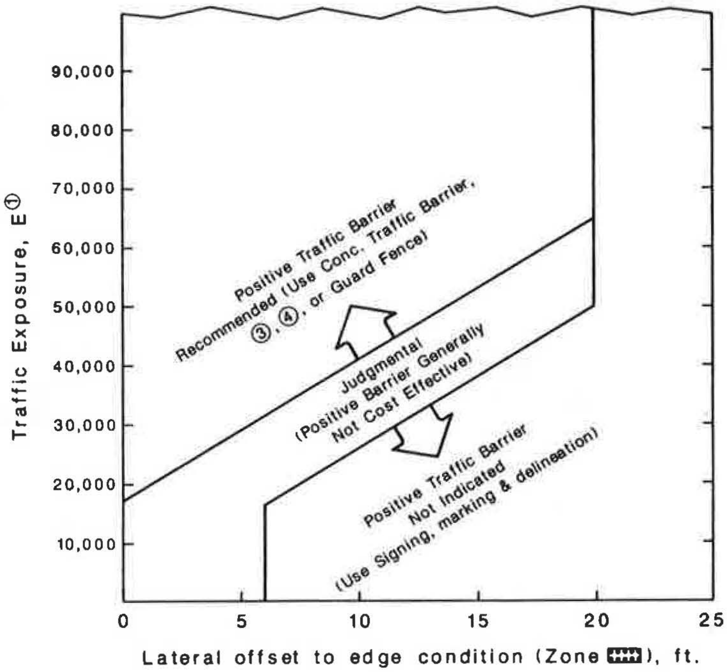
Several factors are important in applying Figure A2 and selecting an appropriate treatment:

Edge Condition I

Most vehicles are able to traverse an edge condition with a slope rate of 3:1 or flatter.

Edge Condition II

Most vehicles are able to traverse this edge as long as *D* does not exceed 5 in. Undercarriage drag on most automobiles will



Notes:

① E = ADT x T
Where ADT is that portion of the average daily traffic volume traveling within 20 feet (generally two adjacent lanes) of the edge dropoff condition; and, T is the duration time in years of the dropoff condition.

② Primarily applicable to high speed conditions only.

③ Barrel Mounted Guard Fence may be used in lieu of CTB where speeds of 45 mph or less and impacting angles of 15 degrees or less are anticipated.

④ An approved end treatment should be provided for any positive barrier end located within a lateral offset of 20' from the edge of the travel lane.

FIGURE A4 Conditions indicating use of positive barrier.

occur as *D* exceeds 6 in. As *D* exceeds 24 in., the possibility of rollover will be greater for most vehicles.

Edge Condition III

Edges where *D* is greater than 2 in. can present a problem to drivers if not properly treated. In the zone where *D* is 2 to 24 in., different types of vehicles have safety-related problems at different edge heights. Automobiles have more difficulty in the 2- to 5-in. zone. Trucks, particularly those with high loads, have more difficulty in the 5- to 24-in. zone. As *D* exceeds 24 in., the possibilities of rollover will be greater for most vehicles.

Limitations of Figure A4

This figure is an effort to provide a practical approach to the use of positive barriers for the protection of vehicle passengers from the hazards of pavement dropoffs. It does not consider the hazards of other conditions in the construction zones, such as heavy machines or the hazards to construction workers. These other factors may make the choice of a positive barrier appropriate even when the edge condition would not justify the barrier.

Unusual Conditions

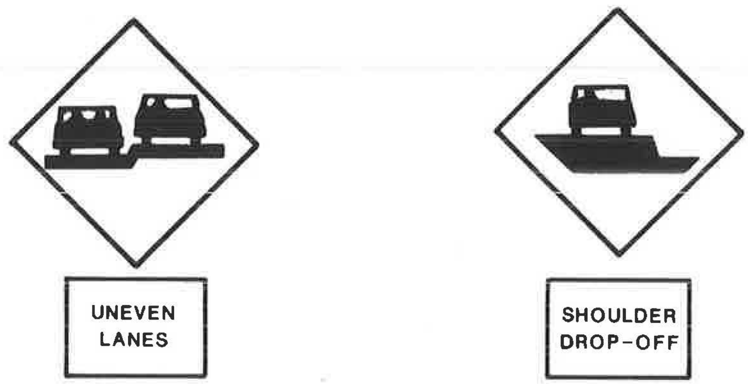
Under certain circumstances a higher type treatment is appropriate for the pertinent conditions. For example, a dropoff located along the outside of a sharp horizontal curve is more vulnerable, and a treatment exceeding that indicated for usual conditions may be appropriate. Although most construction zones may be signed for a slower speed, a higher type treatment may be appropriate if the posted speed through the construction zone exceeds 50 miles per hour.

Edges Across Travel Lane

An Edge Condition II or III that traffic is expected to cross during construction should not have a height (value of *D*) greater than 1.5 in. Any height greater than that but not to exceed 3 in. should be treated using an ACP wedge to produce Edge Condition I where the slope is 3:1 or flatter. This

6B-28.4 Uneven Lanes Sign (CW21-14) (15)

The UNEVEN LANES sign is intended to be used during resurfacing operations which create a difference in elevation between adjacent lanes greater than one (1) inch. The image may be mirrored to indicate the proper elevations of the lane.



CW21-9
30" x 30"

CW21-13
36" x 36"
24" x 18"

6B-28.3 Shoulder Drop-Off Sign (CW21-13) (15)

The SHOULDER DROP-OFF sign is intended for use when a shoulder drop-off exceeds three (3) inches in height and is not protected by a positive protective barrier. The image may be mirrored to show a drop-off on the left.

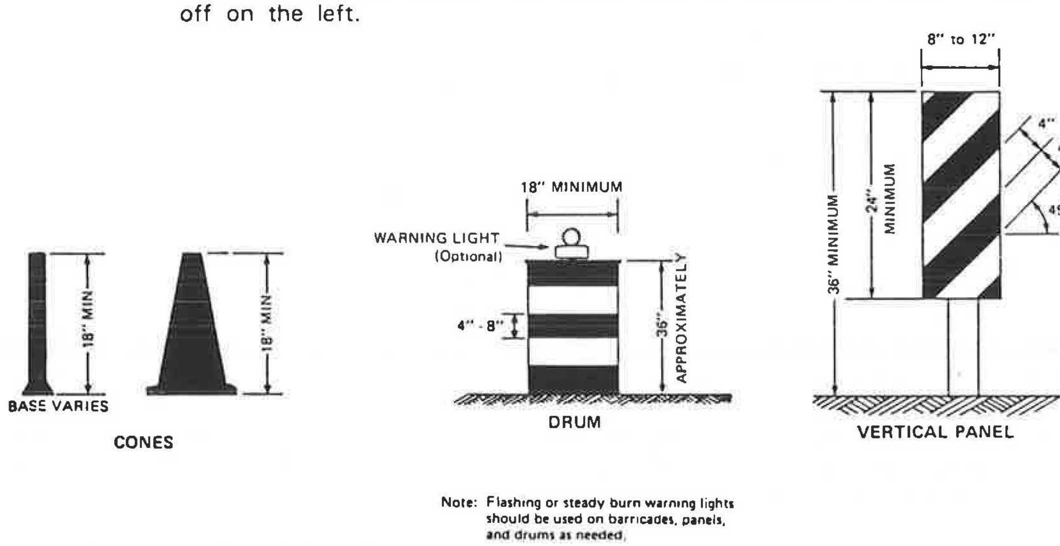


FIGURE A5 Definition of warning devices (*15, 16*).

treatment should be maintained as long as traffic is traversing the edge.

Each dropoff situation should be individually analyzed, taking into account cross sectional features, traffic volume, posted speed, and the practicality of treatment options. Figures A2, A3, and A4 are not a rigid standard or policy; rather, they are a guide that is based on certain, but not all, factors that should be considered.

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