

# Horizontal Curve Design for Passenger Cars and Trucks

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The adequacy of the 1990 AASHTO geometric design policy for safely accommodating both passenger cars and trucks on horizontal curves is evaluated. The evaluation includes both the high-speed or open-highway horizontal curve design criteria in AASHTO Green Book Table III-6 and the low-speed design criteria for intersections and turning roadways in AASHTO Green Book Table III-17. The evaluation of current horizontal curve design policy is conducted by means of a sensitivity analysis that evaluates the margin of safety against vehicle skidding and rollover for both passenger cars and trucks traveling at the design speed on minimum-radius curves designed in accordance with AASHTO policy. It is concluded that current AASHTO horizontal curve design policy for rural highways and high-speed urban streets in Green Book Table III-6 provides an adequate margin of safety against both skidding and rollover as long as vehicles do not exceed the design speed of the curve. However under nearly worst-case conditions, skidding and rollover can occur on a horizontal curve, particularly at lower design speeds, if vehicles exceed the design speed by only a small amount. This finding suggests the importance of selecting a realistic horizontal curve design speed that will not be exceeded by substantial portions of the traffic stream. The AASHTO horizontal curve design criteria for intersections and turning roadways and low-speed urban streets, presented in Green Book Tables III-16 and III-17, are generally adequate for passenger cars that do not exceed the design speed, but may not be adequate for all trucks.

Geometric design policy for horizontal curves is presented in the AASHTO Green Book (1). This paper evaluates the adequacy of these existing criteria for safely accommodating both passenger cars and trucks on horizontal curves. The paper presents an analysis of the effect of minimum radius of curvature and maximum superelevation rate on the margins of safety against vehicle skidding and rollover and the vehicle speeds at which skidding and rollover will occur.

This paper focuses on the adequacy for passenger cars and trucks of the high-speed or open-highway design criteria for horizontal curves presented in AASHTO Green Book Table III-6. The evaluation of these high-speed design criteria is based on an analysis by Harwood et al. (2) from a recent FHWA study. The paper also assesses the adequacy for passenger cars and trucks of the low-speed horizontal curve design criteria that apply to urban streets, intersections, and turning roadways and that are presented in Green Book Tables III-16 and III-17.

## CURRENT HIGH-SPEED DESIGN CRITERIA FOR HORIZONTAL CURVES

Under the current AASHTO policy, a vehicle on a horizontal curve is represented as a point mass. From the basic laws of New-

tonian physics, the lateral acceleration of a point mass traveling at constant speed on a circular path can be represented by the relationship:

$$a = \frac{V^2}{15R} \quad (1)$$

where

$a$  = lateral acceleration ( $g$ ),  
 $V$  = vehicle speed (km/hr or mph), and  
 $R$  = radius of curve (m or ft)

The lateral acceleration is expressed in units of the acceleration of gravity ( $g$ ), which is equal to  $9.8 \text{ m/s}^2$  ( $32.2 \text{ ft/s}^2$ ). On a superelevated curve, the superelevation offsets a portion of the lateral acceleration, such that:

$$a_{\text{net}} = \frac{V^2}{15R} - e \quad (2)$$

where  $a_{\text{net}}$  is unbalanced portion of lateral acceleration ( $g$ ) and  $e$  is superelevation (ft/ft). The unbalanced portion of the lateral acceleration of the vehicle is a measure of the forces acting on the vehicle that tend to make it skid off the road or overturn. The side frictional demand of the vehicle is mathematically equivalent to the unbalanced lateral acceleration ( $a_{\text{net}}$ ). For this reason Equation 2 appears in the Green Book in the form:

$$f = \frac{V^2}{15R} - e \quad (3)$$

where  $f$  is side friction demand. The tendency of the vehicle to skid must be resisted by tire-pavement friction. The vehicle will skid off the road unless the tire-pavement friction coefficient exceeds the side friction demand. However it is also critical for safe vehicle operations that vehicles not roll over on horizontal curves. The tendency of the vehicle to overturn must be resisted by the roll stability of the vehicle. The vehicle will roll over unless the rollover threshold of the vehicle exceeds the unbalanced lateral acceleration ( $a_{\text{net}}$ ).

## Selection of Radius and Superelevation

The objective of AASHTO criteria for horizontal curve design is to select the radius and superelevation so that the unbalanced lateral acceleration is kept within comfortable limits. AASHTO policy limits the unbalanced lateral acceleration for horizontal curves

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to a maximum of 0.17 *g* at 32 km/hr (20 mph), decreasing to a maximum of 0.10 *g* at 113 km/hr (70 mph). This limitation is based on the results of research performed in 1936 through 1949 that established 0.17 *g* as the maximum unbalanced lateral acceleration at which drivers felt comfortable (see Green Book Figure III-5). Thus it is important to note that these AASHTO criteria are based on maintaining comfort levels for passenger car drivers and passengers.

The AASHTO Green Book provides design charts for maximum superelevation rates ( $e_{max}$ ) from 0.04 to 0.12. Highway agencies have established their own policies concerning the maximum superelevation rate that will be used on horizontal curves. Most highway agencies use maximum superelevation rates of either 0.06 or 0.08; states that experience snow and ice conditions typically use lower superelevation rates. For any particular maximum superelevation rate and maximum side friction demand, the minimum radius of curvature can be determined as:

$$R_{min} = \frac{V_d^2}{15 (e_{max} + f_{max})} \tag{4}$$

where

$R_{min}$  = minimum radius of curvature (m or ft),

$V_d$  = design speed of curve (km/hr or mph),

$e_{max}$  = specified maximum superelevation rate (m/m or ft/ft),  
and

$f_{max}$  = specified maximum side friction demand.

Table 1 presents the minimum radius of curvature for specific combinations of maximum superelevation rate and maximum side friction demand recommended by AASHTO. The maximum side friction demand ( $f_{max}$ ) values that appear in Table 1 are the maximum comfortable lateral acceleration values recommended by AASHTO for high-speed rural highways and urban streets. The data in the tables in this paper are presented in customary units for consistency with the 1990 Green Book.

In the design of a horizontal curve under AASHTO policy, the first major decision is to select its radius of curvature. Next the selected radius is checked to ensure that it is not less than  $R_{min}$  for the design speed of the highway. Finally if the selected radius is greater than  $R_{min}$ , a superelevation less than  $e_{max}$  is selected by using Tables III-8 through III-12 of the AASHTO Green Book.

**TABLE 1 AASHTO Criteria for Maximum Degree of Curve and Minimum Radius for Horizontal Curves on Rural Highways and High-Speed Urban Streets (1)**

Design Speed (mph)	Maximum e	Maximum f	Total (e+f)	Maximum Degree of Curve	Rounded Maximum Degree of Curve	Maximum* Radius (ft)
20	.04	.17	.21	44.97	45.0	127
30	.04	.16	.20	19.04	19.0	302
40	.04	.15	.19	10.17	10.0	573
50	.04	.14	.18	6.17	6.0	955
55	.04	.13	.17	4.83	4.75	1,186
60	.04	.12	.16	3.81	3.75	1,528
20	.06	.17	.23	49.25	49.25	116
30	.06	.16	.22	20.94	21.0	273
40	.06	.15	.21	11.24	11.25	509
50	.06	.14	.20	6.85	6.75	849
55	.06	.13	.19	5.40	5.5	1,061
60	.06	.12	.18	4.28	4.25	1,348
65	.06	.11	.17	3.45	3.5	1,637
70	.06	.10	.16	2.80	2.75	2,083
20	.08	.17	.25	53.54	53.5	107
30	.08	.16	.24	22.84	22.75	252
40	.08	.15	.23	12.31	12.25	468
50	.08	.14	.22	7.54	7.5	764
55	.08	.13	.21	5.97	6.0	960
60	.08	.12	.20	4.76	4.75	1,206
65	.08	.11	.19	3.85	3.75	1,528
70	.08	.10	.18	3.15	3.0	1,910
20	.10	.17	.27	57.82	58.0	99
30	.10	.16	.26	24.75	24.75	231
40	.10	.15	.25	13.38	13.25	432
50	.10	.14	.24	8.22	8.25	694
55	.10	.13	.23	6.53	6.5	877
60	.10	.12	.22	5.23	5.25	1,091
65	.10	.11	.21	4.26	4.25	1,348
70	.10	.10	.20	3.50	3.5	1,637
20	.12	.17	.29	62.10	62.0	92
30	.12	.16	.28	26.65	26.75	214
40	.12	.15	.27	14.46	14.5	395
50	.12	.14	.26	8.91	9.0	637
55	.12	.13	.25	7.10	7.0	807
60	.12	.12	.24	5.71	5.75	996
65	.12	.11	.23	4.66	4.75	1,206
70	.12	.10	.22	3.85	3.75	1,528

NOTE: In recognition of safety considerations, use of  $e_{max} = 0.04$  should be limited to urban conditions.  
\*Calculated using rounded maximum degree of curve.

Figure III-9 of the AASHTO Green Book summarizes the superelevation rates used for curves with radii greater than  $R_{min}$ .

### Transition Design

Most horizontal curves are circular curves that directly adjoin tangent roadway sections at either end with no transition curve. Thus a vehicle entering a curve theoretically encounters an instantaneous increase in lateral acceleration from a minimal level of the tangent section to the full lateral acceleration required to track the particular curve. The opposite occurs as a vehicle leaves a horizontal curve. In fact there is a gradual (rather than an instantaneous) change in lateral acceleration, because drivers steer a spiral or transition path as they enter or leave a horizontal curve. The design of the superelevation transition section is used to partially offset the changes in lateral acceleration that do occur. First, a superelevation runoff section is used on the tangent roadway to remove the adverse crown slope. Next a superelevation runoff section is provided in which the pavement is rotated around its centerline or inside edge to attain the full required superelevation; typical design practice is to place two-thirds of the superelevation runoff on the tangent approach and one-third on the curve. Table III-15 in the AASHTO Green Book presents the required length for superelevation runoff on two-lane pavements.

The AASHTO Green Book encourages the use of spiral transition curves to provide a smooth transition between tangents and circular curves. In a spiral curve, the degree of curvature varies linearly from zero at the tangent end to the degree of the circular arc at the circular curve end. The length of the spiral curve can be made the same as that of the superelevation runoff, so that the degree of curvature and pavement cross-slope change together.

## DISCUSSION OF HORIZONTAL CURVE DESIGN POLICY

### Consideration of Driver Comfort

The authors are concerned that nearly 50 years have passed since the completion of the research on driver comfort levels on which the AASHTO policy is based. Obviously, vehicle design has changed dramatically since 1949. There is a definite need for research to reevaluate the driver comfort levels used in AASHTO policy, and the authors understand that FHWA plans to conduct such research in the near future. This research may identify a need for changes in the AASHTO horizontal curve design policy to ensure driver comfort.

Beyond the concern for maintaining comfortable levels of lateral acceleration for drivers, there is a safety concern in minimizing accidents associated with vehicle skidding or rollover. The AASHTO horizontal curve design criteria are not based explicitly on estimates of available tire-pavement friction levels or vehicle rollover thresholds. Rather it is assumed implicitly that the available friction levels and rollover thresholds are higher than the specified driver comfort levels. A driver who chooses to exceed the design speed of a curve will experience a level of lateral acceleration that may make him or her uncomfortable. This lack of comfort does not, by itself, necessarily create a safety problem, since an accident need not occur just because a driver chooses to experience a slightly uncomfortable level of lateral acceleration.

Furthermore drivers who consistently choose to exceed the design speeds of horizontal curves are probably those with a higher tolerance for lateral acceleration. Safety concerns enter if the driver chooses a travel speed on a horizontal curve that could lead to vehicle skidding or rollover. The review of horizontal curve design policy in the remainder of this paper examines the adequacy of the margins of safety against rollover for vehicles traversing minimum-radius horizontal curves at speeds at or above the design speed.

### Consideration of Friction Demand

The point mass representation of a vehicle that forms the basis for Equations 1 to 3 is not based on any particular set of vehicle characteristics and is theoretically as applicable to trucks as it is to passenger cars. However in light of the differences between passenger cars and trucks in size, number of tires, tire characteristics, and suspension characteristics, the suitability for trucks of the point mass assumption was recently reexamined.

A 1985 FHWA study (3) found that the point mass representation in Equation 3 can be used to determine the net side friction demand of both passenger cars and trucks, because the basic laws of physics apply to both. However that study found that although the friction demands at the four tires of a passenger car are approximately equal, the friction demands at the various tires of a tractor-trailer truck vary widely. The net result of this tire-to-tire variation in friction demand is that trucks typically demand approximately 10 percent higher side friction than passenger cars. The authors have termed this higher side friction demand the *effective side friction demand* of trucks.

The point mass representation of a vehicle has another weakness, however, that applies to both passenger cars and trucks. Equation 3 is based on the assumption that vehicles traverse curves following a path of constant radius equal to the radius of the curve. However field studies have shown that all vehicles oversteer at some point on a horizontal curve. At the point of oversteering, the vehicle is following a path radius that is less than the radius of the curve (4). Thus at some point on each curve, the friction demand of each vehicle will be slightly higher than that suggested by Equation 3. Oversteering by passenger cars is not considered in the AASHTO design policy for horizontal curves, but it is probably not critical because the AASHTO maximum lateral acceleration requirements are based on driver comfort levels rather than the available pavement friction. No data are available on the amount of oversteering by trucks relative to passenger cars.

### Consideration of Rollover Threshold

The AASHTO criteria for horizontal curve design do not explicitly consider vehicle rollover thresholds. The rollover threshold for passenger cars may be as high as 1.2 g, so a passenger car will normally skid off a road long before it would roll over (5). Thus the consideration of rollover threshold is not critical for passenger cars. However, tractor-trailer trucks have relatively high centers of gravity and consequently tend to have low rollover thresholds. Furthermore because of suspension characteristics, the rollover threshold of tractor-trailer trucks is substantially less than it would be if a truck were a rigid body.

Recent research has determined the rollover thresholds of a number of common trucks with typical loading configurations (2,6,7). Some trucks with rollover thresholds of as low as 0.30  $g$  are found on the road. Since AASHTO design policy permits a lateral acceleration of as great as 0.17  $g$ , the margin of safety for trucks with low rollover thresholds on some horizontal curves is not great. Furthermore as discussed above, oversteering will generally result in a lateral acceleration greater than  $f_{max}$  at some point on the curve for vehicles traveling at the design speed, which will tend to reduce the margin of safety.

## EVALUATION OF MARGIN OF SAFETY FOR PASSENGER CARS AND TRUCKS

An evaluation has been conducted to determine whether the existing AASHTO high-speed horizontal curve design criteria are adequate to keep both passenger cars and trucks from skidding off the road and to keep them from rolling over.

### Margins of Safety Against Skidding

Current design criteria for horizontal curves are intended to keep vehicles from skidding off the road on wet pavements. The criteria are based on the standard curve formula in Equation 3, which provides that a portion of the lateral acceleration developed by the vehicle will be resisted by superelevation and the remainder will be resisted by tire-pavement friction.

The margin of safety against skidding for a passenger car or truck on a horizontal curve is defined as the difference between the available tire-pavement friction and the friction demand of the vehicle as it tracks the curve. Friction demand is the portion of the vehicle's lateral acceleration that is not offset by superelevation. The margin of safety represents the additional lateral acceleration that the vehicle could undergo without skidding. The objective of the analysis is to determine the margin of safety against skidding for both passenger cars and trucks on minimum-radius curves designed in accordance with AASHTO criteria. Horizontal curves with longer radii would have larger margins of safety than those calculated here.

The assumptions made in computing the margin of safety against skidding for passenger cars and trucks are as follows:

- Both passenger cars and trucks traverse the curve at the design speed on a path that follows a constant radius equal to the radius of the curve.
- The pavement has a relatively poor wet pavement friction level equivalent to the pavement assumed by AASHTO for stopping sight distance (see locked-wheel braking coefficients for passenger cars for specific design speeds in Green Book Table III-1). These range from a braking friction coefficient of 0.40 at 32 km/hr (20 mph) to 0.28 at 113 km/hr (70 mph). The locked-wheel braking coefficient for a dry pavement is assumed to be 0.65. The cornering friction coefficient at a specific speed is assumed to be 1.45 times the locked-wheel braking coefficient (1,8).
- The tire pavement friction generated by truck tires is only 70 percent of that generated by passenger car tires (8).
- The effective friction demand for a truck is 10 percent higher than that for a passenger car, as discussed above (2,3).

A simple example will show how the margin of safety against skidding is calculated. A horizontal curve with a design speed of 32 km/hr (20 mph) and a maximum superelevation rate of 0.04 has a maximum tolerable lateral acceleration ( $f_{max}$ ) of 0.17  $g$ , in accordance with Green Book Table III-6. The minimum radius derived from Equation 4 is

$$R_{min} = \frac{20^2}{15 (0.04 + 0.17)} = 127 \text{ ft (39 m)}$$

The friction demand for a passenger car traversing this curve at the design speed is equivalent to  $f_{max}$  (0.17).

The available tire-pavement friction under wet pavement conditions is 1.45 times the assumed AASHTO locked-wheel braking coefficient of 0.40:  $(0.40) (1.45) = 0.58$ .

The margin of safety for a passenger car is  $0.58 - 0.17 = 0.41$ . In other words, a passenger car could undergo 0.41  $g$  of additional lateral acceleration without skidding.

For a truck, the effective friction demand would be 10 percent higher than that for a passenger car:  $(0.17) (1.10) = 0.19$ .

The tire-pavement friction for a truck is only 70 percent of that for a passenger car:  $(0.58) (0.70) = 0.41$ . Therefore, the margin of safety for a truck is  $0.41 - 0.19 = 0.22$ . In other words, a truck could undergo additional lateral acceleration of only 0.22  $g$  without skidding, in contrast to 0.41  $g$  for a passenger car.

The results of similar calculations for design speeds from 32 to 113 km/hr (20 to 70 mph) and a maximum superelevation rates from 0.04 to 0.10 are presented in Table 2. Table 2 shows that the current AASHTO criteria provide a margin of safety of 0.31 to 0.41  $g$  against a passenger car skidding when traveling on wet pavement at the design speed of a minimum-radius curve. Table 2 also shows that the margins of safety against skidding on dry pavement are much higher than those on wet pavement.

The margins of safety against skidding by trucks are in the range of from 0.17 to 0.22  $g$ , which is lower than that for passenger cars. A later section of the paper expresses these results in terms of the vehicle speed at which skidding would occur. The margins of safety for passenger cars and trucks in Table 2 are large enough to provide safe operations if there are no major deviations from the basic assumptions used in horizontal curve design. The effects of such deviations are considered below.

### Margin of Safety Against Rollover

The margin of safety against rollover is the magnitude of the additional lateral acceleration that a vehicle could undergo without rolling over. The rollover margin of safety has been computed on the basis of the following assumptions:

- Passenger cars have very high rollover thresholds, possibly as high as 1.2  $g$  (5).
- The most unstable trucks have rollover thresholds in the range of from 0.27 to 0.40  $g$ . Most trucks have substantially higher rollover thresholds.

The following example shows how the margin of safety against rollover is calculated by using the same computational example as that given above for the minimum-radius curve for a 32-km/hr (20-mph) design speed and a maximum superelevation rate of 0.04. The lateral acceleration for a passenger car traversing such

TABLE 2 Margins of Safety Against Skidding on Horizontal Curves (2)

Design speed (mph)	Passenger car							Truck					
	Maximum super-elevation e	Maximum comfortable lateral acceleration (g)	Maximum demand f	Minimum radius (ft)	Available f (wet)	Margin of safety (wet)	Margin of safety (dry)	Maximum comfortable lateral acceleration (g)	Minimum radius (ft)	Maximum demand f	Truck available f (wet)	Margin of safety (wet)	Margin of safety (dry)
20	0.04	0.17	0.17	127	0.58	0.41	0.77	0.17	127	0.19	0.41	0.22	0.47
30	0.04	0.16	0.16	302	0.51	0.35	0.78	0.16	302	0.18	0.36	0.18	0.48
40	0.04	0.15	0.15	573	0.46	0.31	0.79	0.15	573	0.17	0.32	0.18	0.49
50	0.04	0.14	0.14	955	0.44	0.30	0.80	0.14	955	0.15	0.30	0.15	0.51
60	0.04	0.12	0.12	1,528	0.42	0.30	0.82	0.12	1,528	0.13	0.29	0.16	0.53
20	0.06	0.17	0.17	116	0.58	0.41	0.77	0.17	116	0.19	0.41	0.22	0.47
30	0.06	0.16	0.16	273	0.51	0.35	0.78	0.16	273	0.18	0.36	0.18	0.48
40	0.06	0.15	0.15	509	0.46	0.31	0.79	0.15	509	0.17	0.32	0.18	0.49
50	0.06	0.14	0.14	849	0.44	0.30	0.80	0.14	849	0.15	0.30	0.15	0.51
60	0.06	0.12	0.12	1,348	0.42	0.30	0.82	0.12	1,348	0.13	0.29	0.16	0.53
70	0.06	0.10	0.10	2,083	0.41	0.31	0.84	0.10	2,083	0.11	0.28	0.17	0.55
20	0.08	0.17	0.17	107	0.58	0.41	0.77	0.17	107	0.19	0.41	0.22	0.47
30	0.08	0.16	0.16	252	0.51	0.35	0.78	0.16	252	0.18	0.36	0.18	0.48
40	0.08	0.15	0.15	468	0.46	0.31	0.79	0.15	468	0.17	0.32	0.18	0.49
50	0.08	0.14	0.14	764	0.44	0.30	0.80	0.14	764	0.15	0.30	0.15	0.51
60	0.08	0.12	0.12	1,206	0.42	0.30	0.82	0.12	1,206	0.13	0.29	0.16	0.53
70	0.08	0.10	0.10	1,910	0.41	0.31	0.84	0.10	1,910	0.11	0.28	0.17	0.55
20	0.10	0.17	0.17	99	0.58	0.41	0.77	0.17	99	0.19	0.41	0.22	0.47
30	0.10	0.16	0.16	231	0.51	0.35	0.78	0.16	231	0.18	0.36	0.18	0.48
40	0.10	0.15	0.15	432	0.46	0.31	0.79	0.15	432	0.17	0.32	0.18	0.49
50	0.10	0.14	0.14	694	0.44	0.30	0.80	0.14	694	0.15	0.30	0.15	0.51
60	0.10	0.12	0.12	1,091	0.42	0.30	0.82	0.12	1,091	0.13	0.29	0.16	0.53
70	0.10	0.10	0.10	1,637	0.41	0.31	0.84	0.10	1,637	0.11	0.28	0.17	0.55

a curve at the design speed is  $f_{max}$ , or 0.17  $g$ . The margin of safety against rollover by a passenger car on this horizontal curve is calculated as  $1.20 - 0.17 = 1.03$ . A passenger car could undergo an additional lateral acceleration of 1.03  $g$  without rolling over.

The lateral acceleration for a truck traversing the same minimum-radius curve while traveling at the design speed is also equal to 0.17  $g$ . [The 10 percent increase in friction demand for trucks, based on the work by MacAdam et al. (3), is applicable only to the consideration of tire-pavement friction in skidding calculations and, thus, does not enter into the rollover calculations.] A truck with a rollover threshold of 0.30  $g$  traversing the curve at the design speed would have a much smaller margin of safety against rollover than a passenger car:  $0.30 - 0.17 = 0.13$ . This truck could undergo an additional lateral acceleration of only 0.13  $g$  without rolling over.

The results of similar calculations for design speeds of from 32 to 113 km/hr (20 to 70 mph) and maximum superelevation rates of from 0.04 to 0.10 are presented in Table 3. Table 3 shows the margins of safety against rollover in units of the acceleration of gravity ( $g$ ) for passenger cars and for trucks with rollover thresholds (RT) of 0.27, 0.30, 0.35, and 0.40  $g$ .

Table 3 shows that the margin of safety against rollover for passenger cars traveling at the design speed ranges from 1.03 to 1.10  $g$ . At all design speeds, the margin of safety against rollover for a passenger car is much higher than the margin of safety against skidding on either a wet or a dry pavement. Thus, rollover is not a major concern for passenger cars because, unless they collide with another vehicle or object, they will skid rather than roll over. In contrast to the related issue of skidding off the road, the margin of safety against rollover is not dependent on whether the pavement is wet or dry.

A conservative value of the truck rollover threshold appropriate for use in design is 0.30  $g$ . The margin of safety for a truck with a rollover threshold of 0.30  $g$  ranges from 0.13 to 0.20  $g$ . This margin of safety is adequate to prevent rollover for trucks traveling at or below the design speed. The margin of safety against rollover increases with increasing design speed, whereas the margin of safety against skidding decreases with increasing design speed.

Comparison of Tables 2 and 3 indicates that rollover is a particular concern for trucks. Under the assumed design conditions for horizontal curves, a truck will roll over before it will skid on a dry pavement. Under the assumed design conditions on a wet pavement, a truck will roll over before it skids at design speeds of 64 km/hr (40 mph) and below; above that speed, a truck will skid before it rolls over.

### Deviations from Assumed Design Conditions

The margins of safety against skidding and rollover are a measure of the extent to which real-world drivers, vehicles, and highways can deviate from the assumed conditions without resulting in a skid or a rollover. Deviations from assumed conditions that can increase the likelihood of skidding include:

- Vehicles traveling faster than the design speed.
- Vehicles turning more sharply than the curve radius (oversteering).
- Lower pavement friction than assumed by AASHTO.
- Poorer tires than assumed by AASHTO.

Traveling faster than the design speed and turning more sharply than the curve radius would also increase the likelihood of rollovers. The likelihood of rollover would also be increased for a truck with a rollover threshold less than the assumed value of 0.30  $g$ .

It would seem logical that the practice of providing less than full superelevation at the point of curvature (PC) would also increase the likelihood of rollovers, but this is not necessarily the case. Horizontal curves without spiral transitions are typically designed with two-thirds of the superelevation runoff on the tangent in advance of the PC and one-third of the superelevation runoff on the curve itself. Thus only two-thirds of the design superelevation is available at the PC, and this lack of full superelevation at the PC would appear to have the potential to offset up to approximately 0.30  $g$  of the available margin of safety. However AASHTO policy assumes and field and simulation studies (for passenger cars) confirm that even on horizontal curves without spiral transitions, drivers tend to steer a spiral path. Thus when maximum superelevation is not available, the driver is usually not steering a minimum-radius path.

Computer simulation studies of trucks traversing horizontal curves (2) have found that the development of full superelevation on the tangent approach to a conventional circular curve actually results in slightly more lateral acceleration than development of superelevation with the two-thirds-one-third rule. Although the difference in lateral acceleration is small—at most 0.03  $g$ —it is in the wrong direction, so development of full superelevation on the tangent is not a desirable approach to reducing truck rollovers. The same study found a small decrease in lateral acceleration—typically less than 0.01  $g$ —when spiral transitions rather than the two-thirds-one-third rule were used to develop the superelevation. Thus the use of spiral transitions is desirable, but because of the small reduction in lateral acceleration, the use of spirals is unlikely to provide a major reduction in rollover accidents.

Field data for passenger cars and simulation results for trucks show that vehicles traversing a curve do not precisely follow the curve (2,4). Thus, although the path may have a larger radius than the curve at the PC, it will also have a smaller radius than the curve at some point in the curve. Simulation results show that the maximum lateral acceleration occurs several hundred feet after entering a curve. However, simulation results also show that the maximum deviation of lateral acceleration above the value obtained from the standard curve formula is approximately 0.02  $g$ , which would offset a small portion of the margins of safety against rollover and skidding (2). Field studies for passenger cars suggest that this is a reasonable average value, but more extreme values can occur. Truck drivers may follow the curve more closely than passenger car drivers, but there are no data on this issue.

The review of the potential for safety problems created by deviations from the design assumptions indicates that traveling faster than the design speed of the curve is the single greatest concern. This is a particular concern on freeway ramps for two reasons. First, freeway ramps generally have lower design speeds than mainline roadways, which means that they have lower margins of safety against rollover (but higher margins of safety against skidding). Second, vehicles are especially likely to travel faster than the design speed on off-ramps, where vehicles traveling at higher speeds enter the ramp from the mainline roadway.

Table 4 compares the speeds at which skidding or rollover would occur for passenger cars and trucks traversing minimum-radius curves designed in accordance with current AASHTO cri-

**TABLE 3 Margins of Safety Against Rollover on Horizontal Curves (2)**

Design speed (mph)	Passenger car				Truck					
	Maximum e	Maximum comfortable lateral acceleration	Minimum radius (ft)	Rollover margin of safety RT = 1.20 g	Maximum comfortable lateral acceleration	Minimum radius (ft)	Rollover margin of safety			
							RT = 0.27	RT = 0.30	RT = 0.35	RT = 0.40
20	0.04	0.17	127	1.03	0.17	127	0.10	0.13	0.18	0.23
30	0.04	0.16	302	1.04	0.16	302	0.11	0.14	0.19	0.24
40	0.04	0.15	573	1.05	0.15	573	0.12	0.15	0.20	0.25
50	0.04	0.14	955	1.06	0.14	955	0.13	0.16	0.21	0.26
60	0.04	0.12	1,528	1.08	0.12	1,528	0.15	0.18	0.23	0.28
20	0.06	0.17	116	1.03	0.17	116	0.10	0.13	0.18	0.23
30	0.06	0.16	273	1.04	0.16	273	0.11	0.14	0.19	0.24
40	0.06	0.15	509	1.05	0.15	509	0.12	0.15	0.20	0.25
50	0.06	0.14	849	1.06	0.14	849	0.13	0.16	0.21	0.26
60	0.06	0.12	1,348	1.08	0.12	1,348	0.15	0.18	0.23	0.28
70	0.06	0.10	2,083	1.10	0.10	2,083	0.17	0.20	0.25	0.30
20	0.08	0.17	107	1.03	0.17	107	0.10	0.13	0.18	0.23
30	0.08	0.16	252	1.04	0.16	252	0.11	0.14	0.19	0.24
40	0.08	0.15	468	1.05	0.15	468	0.12	0.15	0.20	0.25
50	0.08	0.14	746	1.06	0.14	746	0.13	0.16	0.21	0.26
60	0.08	0.12	1,206	1.08	0.12	1,206	0.15	0.18	0.23	0.28
70	0.08	0.10	1,910	1.10	0.10	1,910	0.17	0.20	0.25	0.30
20	0.10	0.17	99	1.03	0.17	99	0.10	0.13	0.18	0.23
30	0.10	0.16	231	1.04	0.16	231	0.11	0.14	0.19	0.24
40	0.10	0.15	432	1.05	0.15	432	0.12	0.15	0.20	0.25
50	0.10	0.14	694	1.06	0.14	694	0.13	0.16	0.21	0.26
60	0.10	0.12	1,091	1.08	0.12	1,091	0.15	0.18	0.23	0.28
70	0.10	0.10	1,637	1.10	0.10	1,637	0.17	0.20	0.25	0.30

**TABLE 4 Vehicle Speed at Impending Skidding or Rollover on Horizontal Curves for AASHTO High-Speed Design Criteria (2)**

Design speed (mph)	Maximum e	Maximum comfortable lateral acceleration	Minimum radius (ft)	Passenger car available cornering f	Passenger car speed (mph)			Truck speed (mph)					
					At impending skid (wet)	At impending skid (dry)	At rollover RT = 1.20 g	At impending skid (wet)	At impending skid (dry)	At rollover			
										RT = 0.27 g	RT = 0.30 g	RT = 0.35 g	RT = 0.40 g
20	0.04	0.17	127	0.58	34.4	43.3	48.6	27.9	34.9	24.3	25.4	27.3	29.0
30	0.04	0.16	302	0.51	49.8	66.7	74.9	40.5	53.8	37.5	39.2	42.0	44.6
40	0.04	0.15	573	0.46	65.8	91.9	103.2	53.7	74.2	51.6	54.1	57.9	61.5
50	0.04	0.14	955	0.44	82.5	118.6	133.3	67.4	95.7	66.6	69.8	74.7	79.4
60	0.04	0.12	1,528	0.42	102.7	150.1	168.6	84.0	121.1	84.3	88.3	94.5	100.4
20	0.06	0.17	116	0.58	33.4	41.8	46.8	27.3	33.9	24.0	25.0	26.7	28.3
30	0.06	0.16	273	0.51	48.2	64.1	71.8	39.6	52.0	36.8	38.4	41.0	43.4
40	0.06	0.15	509	0.46	63.3	87.5	98.1	52.1	71.0	50.2	52.4	55.9	59.3
50	0.06	0.14	849	0.44	79.4	113.0	126.7	65.5	91.7	64.8	67.7	72.3	76.5
60	0.06	0.12	1,348	0.42	98.6	142.4	159.6	81.4	115.5	81.7	85.3	91.1	96.4
70	0.06	0.10	2,083	0.41	120.7	177.0	198.4	99.7	143.6	101.5	106.1	113.2	119.9
20	0.08	0.17	107	0.58	32.5	40.5	45.3	26.8	33.0	23.7	24.7	26.3	27.8
30	0.08	0.16	252	0.51	47.0	62.2	69.6	39.0	50.7	36.4	37.9	40.3	42.6
40	0.08	0.15	468	0.46	61.8	84.7	94.8	51.3	69.1	49.6	51.6	54.9	58.0
50	0.08	0.14	764	0.44	76.8	108.2	121.1	63.9	88.3	63.3	66.0	70.2	74.2
60	0.08	0.12	1,206	0.42	95.2	136.0	152.2	79.3	110.9	79.6	82.9	88.2	93.2
70	0.08	0.10	1,910	0.41	118.0	171.2	191.5	98.5	139.6	100.1	104.3	111.0	117.3
20	0.10	0.17	99	0.58	31.8	39.3	43.9	26.4	32.2	23.4	24.4	25.9	27.2
30	0.10	0.16	231	0.51	45.9	60.1	67.1	38.3	49.2	35.8	37.2	39.5	41.6
40	0.10	0.15	432	0.46	60.5	82.2	91.8	50.6	67.3	49.0	50.9	54.0	56.9
50	0.10	0.14	694	0.44	74.6	104.2	116.3	62.6	85.4	62.1	64.5	68.4	72.1
60	0.10	0.12	1,091	0.42	92.3	130.6	145.9	77.6	107.0	77.8	80.9	85.8	90.5
70	0.10	0.10	1,637	0.41	111.5	160.0	178.7	93.8	131.1	95.3	99.1	105.1	110.8

**TABLE 5 Lateral Acceleration Developed by Overdriving Design Speed for Horizontal Curves Designed to AASHTO Minimum Radii for High-Speed Design (2)**

Design speed (mph)	Maximum superelevation ( $e_{max}$ )	Maximum comfortable lateral acceleration	Minimum radius of curvature (ft)	Side friction demand for overdriving design speed of curve by:				
				0 mph	5 mph	10 mph	15 mph	20 mph
20	0.04	0.17	127	0.17	0.29	0.43	0.60	0.80
30	0.04	0.16	300	0.16	0.23	0.32	0.41	0.52
40	0.04	0.15	561	0.15	0.20	0.26	0.32	0.39
50	0.04	0.14	926	0.14	0.18	0.22	0.26	0.31
60	0.04	0.12	1,500	0.12	0.15	0.18	0.21	0.24
20	0.06	0.17	116	0.17	0.30	0.46	0.64	0.86
30	0.06	0.16	273	0.16	0.24	0.33	0.43	0.55
40	0.06	0.15	508	0.15	0.21	0.27	0.34	0.41
50	0.06	0.14	833	0.14	0.18	0.23	0.28	0.33
60	0.06	0.12	1,333	0.12	0.15	0.18	0.22	0.26
65	0.06	0.11	1,657	0.11	0.14	0.17	0.20	0.23
70	0.06	0.10	2,042	0.10	0.13	0.16	0.18	0.20
20	0.08	0.17	107	0.17	0.31	0.48	0.69	0.92
30	0.08	0.16	250	0.16	0.25	0.35	0.46	0.59
40	0.08	0.15	464	0.15	0.21	0.28	0.35	0.44
50	0.08	0.14	758	0.14	0.19	0.24	0.29	0.35
60	0.08	0.12	1,200	0.12	0.15	0.19	0.23	0.28
65	0.08	0.11	1,482	0.11	0.14	0.17	0.21	0.24
70	0.08	0.10	1,815	0.10	0.13	0.16	0.19	0.22
20	0.10	0.17	99	0.17	0.32	0.51	0.73	0.98
30	0.10	0.16	231	0.16	0.25	0.36	0.49	0.62
40	0.10	0.15	427	0.15	0.22	0.29	0.37	0.46
50	0.10	0.14	694	0.14	0.19	0.25	0.31	0.37
60	0.10	0.12	1,091	0.12	0.16	0.20	0.24	0.29
65	0.10	0.11	1,341	0.11	0.14	0.18	0.22	0.26
70	0.10	0.10	1,633	0.10	0.13	0.16	0.19	0.23

teria. These speeds are computed by setting the value of  $f$  in Equation 3 equal to the available pavement friction coefficient or rollover threshold and solving for the vehicle speed ( $V$ ). Table 4 shows that on a dry pavement a passenger car will skid at a lower speed than it will roll over, and a truck with a rollover threshold of 0.30  $g$  will roll over at a lower speed than it will skid. On a wet pavement, a passenger car will still skid at a lower speed than it will roll over. However a truck will skid before it will roll over at design speeds of 64 km/hr (40 mph) or less under the assumed values for wet pavement conditions. If a wet pavement has above-minimum friction, however, the truck may still roll over at a lower speed than it will skid. Finally for horizontal curve design speeds over 64 km/hr (40 mph), the truck will always roll over before it will skid under the assumed design conditions.

Table 5 presents the results of an alternative sensitivity analysis that shows the lateral accelerations that result from overdriving horizontal curves at speeds of up to 32 km/hr (20 mph) above the design speed. Table 5 addresses curves designed to the AASHTO minimum radius for specified values of design speed and maximum superelevation rate. Curves designed with larger radii than the AASHTO minimum will produce lower lateral accelerations than those shown in Table 5. The results shown in Table 5 are in accord with operational experience. At lower design speeds, overdriving of the design speed by even a small amount can produce side friction demands above the rollover thresholds of some trucks. On the other hand, at higher design speeds, overdriving of the design speed by as much as 32 km/hr (20 mph) does not produce enough lateral acceleration to produce a truck rollover.

## LOW-SPEED HORIZONTAL CURVE DESIGN FOR INTERSECTIONS AND TURNING ROADWAYS

The low-speed horizontal curve design criteria presented in Green Book Table III-17 are intended for use at intersections and turning roadways with design speeds of 64 km/hr (40 mph) or less. Harwood and Mason (9) have presented an evaluation of the situations in which the low-speed criteria in contrast to the high-speed or open-highway criteria should be used.

The low-speed design criteria are based on higher values of maximum side friction demand ( $f_{max}$ ) than can be used in high-speed design. A comparison of the permitted values of  $f_{max}$  is presented in Table 6. At design speeds of 32 and 48 km/hr (20 and 30 mph), substantially more side friction demand is permitted under the low-speed design criteria than under the high-speed design criteria.

Green Book Table III-17 is based on an assumed *minimum* superelevation rate for each design speed rather than a user-selected

*maximum* superelevation rate. The table shows specified values of minimum radius, although it is not clear how a minimum radius can be computed from a maximum side friction factor and a *minimum* (rather than a maximum) superelevation rate. Green Book Table IX-12 presents the range of superelevation rates permitted for particular horizontal curve radii. The Green Book does not make clear whether horizontal curve radii less than those specified in Table III-17 can be used when higher-than-minimum superelevation rates are used. In high-speed design, increasing the maximum superelevation rate ( $e_{max}$ ) decreases the minimum radius for a horizontal curve.

Table 7 compares the vehicle speed for passenger cars and trucks at impending skidding and rollover for design speeds of from 16 to 48 km/hr (10 to 40 mph). Table 7 compares vehicle speeds at impending skidding and rollover for

- High-speed design on the basis of Green Book Table III-6.
- Low-speed design on the basis of the minimum radii in Green Book Table III-17.
- Low-speed design for radii equal to the lesser of the minimum radii in Table III-17 and the radii calculated from Equation 3 by using the values of  $f_{max}$  specified in Table III-17.

All other assumptions concerning vehicle and pavement characteristics remain the same as in earlier analyses.

For horizontal curves designed in accordance with the minimum radii specified in Green Book Table III-17, there do not appear to be any critical skidding or rollover problems for passenger cars. However Table 7 shows that in every case for design speeds of 16 and 32 km/hr (10 and 20 mph) a truck could skid or roll over by exceeding the design speed of a minimum-radius curve by 6.4 km/hr (4 mph) or less. This analysis suggests that the low-speed design criteria in Green Book Table III-17 may not be adequate to safely accommodate some trucks in very critical situations.

As discussed above, the Green Book does not make clear whether, for low-speed design, it is permissible to use a smaller-curve radius than that shown in Table III-17 if an above-minimum superelevation rate is used. However, Table 7 shows that on curves with a 16-km/hr (10-mph) design speed, trucks could skid—and the most unstable trucks could roll over—at speeds less than the design speed. On curves with a 32-km/hr (20-mph) design speed, the most unstable trucks could roll over when traveling at less than 1.6 km/hr (1 mph) above the design speed.

Low-speed design criteria for urban streets presented in Green Book Table III-16 are based on assumed values of  $f_{max}$  that are slightly higher even than those in Table III-17. Thus, the same issues discussed above with respect to Green Book Table III-17 are an even greater concern with respect to Table III-16.

## CONCLUSIONS AND RECOMMENDATIONS

### High-Speed Horizontal Curve Design Criteria

The following conclusions and recommendations have been drawn from the results presented in this paper concerning the AASHTO high-speed or open-highway horizontal curve design criteria presented in Green Book Table III-6.

1. On horizontal curves designed in accordance with AASHTO high-speed criteria, a passenger car with poor tires on a poor wet

TABLE 6 Comparison of Permitted Values of  $f_{max}$

Design Speed (mph)	High-Speed Design (Table III-6)	Low-Speed Design (Table III-17)
10	—	0.38
20	0.17	0.27
30	0.16	0.20
40	0.15	0.16
50	0.14	—
60	0.12	—
70	0.10	—

**TABLE 7 Vehicle Speed at Impending Skidding or Rollover on Horizontal Curves for AASHTO High-Speed and Low-Speed Design Criteria**

Design speed (mph)	Maximum e	High-speed design					Low-speed design									
		Minimum radius as specified in Table III-6					Minimum radius as specified in Table III-17					Minimum radius calculated from maximum f in Table III-17 or minimum radius in Table III-17 (if smaller)				
		Radius (ft)	Passenger car		Truck		Radius (ft)	Passenger car		Truck		Radius (ft)	Passenger car		Truck	
			Speed at impending skid	Speed at impending rollover	Speed at impending skid	Speed at impending rollover		Speed at impending skid	Speed at impending rollover	Speed at impending skid	Speed at impending rollover		Speed at impending skid	Speed at impending rollover		
Maximum e = 0.02																
10	0.02	--	--	--	--	--	25	15.9	21.4	12.8	11.0	17	13.0	17.5	10.4	8.9
20	0.02	--	--	--	--	--	90	28.5	40.6	22.9	20.8	90	28.5	40.6	22.9	20.8
30	0.02	--	--	--	--	--	230	42.7	64.9	34.4	33.2	230	42.7	64.9	34.4	33.2
40	0.02	--	--	--	--	--	430	55.9	88.7	45.1	45.4	430	55.9	88.7	45.1	45.1
Maximum e = 0.04																
10	0.04	--	--	--	--	--	25	16.1	21.6	13.1	11.3	16	12.8	17.2	10.4	9.0
20	0.04	127	34.4	48.6	27.9	25.4	90	28.9	40.9	23.5	21.4	86	28.3	40.0	23.0	20.9
30	0.04	302	49.8	74.9	40.5	39.2	230	43.5	65.4	35.4	34.2	230	43.5	65.4	35.4	34.2
40	0.04	573	65.8	103.2	53.7	54.1	430	57.0	89.4	46.5	46.8	430	57.0	89.4	46.5	46.8
Maximum e = 0.06																
10	0.06	--	--	--	--	--	25	16.3	21.7	13.3	11.6	15	12.7	16.9	10.4	9.0
20	0.06	116	33.4	46.8	27.3	25.0	90	29.4	41.2	24.1	22.0	81	27.9	39.1	22.8	20.9
30	0.06	273	48.2	71.8	39.6	38.4	230	44.2	65.9	36.3	35.2	230	44.2	65.9	36.3	35.2
40	0.06	509	63.3	98.1	52.1	52.4	430	58.1	90.1	47.8	48.2	430	58.1	90.1	47.3	48.2
Maximum e = 0.08																
10	0.08	--	--	--	--	--	25	16.6	21.9	13.6	11.9	14	12.6	16.7	10.4	9.1
20	0.08	107	32.5	45.3	26.8	24.7	90	29.8	41.6	24.6	22.6	76	27.5	38.2	22.7	20.8
30	0.08	252	47.0	69.6	39.0	37.9	230	45.0	66.5	37.3	36.2	214	43.5	64.1	36.0	34.9
40	0.08	468	61.8	94.8	51.3	51.6	430	59.2	90.9	49.2	49.5	430	59.2	90.9	49.2	49.5
Maximum e = 0.10																
10	0.10	--	--	--	--	--	25	16.0	22.1	13.3	12.2	14	11.9	16.5	9.9	9.1
20	0.10	99	31.8	43.9	26.4	24.4	90	30.3	41.9	25.2	23.2	72	27.1	37.5	22.5	20.8
30	0.10	231	45.9	67.1	38.3	37.2	230	48.4	67.0	40.2	37.1	200	45.2	62.4	37.5	34.6
40	0.10	432	60.5	91.8	50.6	50.9	430	62.2	91.6	55.0	50.8	410	64.7	89.4	53.7	49.6

NOTE: Shaded areas are not permitted by Green Book Table III-17 which specifies minimum superelevation.

pavement will generally skid at a lower speed than it will roll over. However, even minimum-radius curves designed in accordance with AASHTO policy provide an adequate margin of safety against both vehicle skidding and rollover for passenger cars traveling at the design speed.

2. On minimum-radius curves designed in accordance with AASHTO high-speed criteria, the most unstable trucks (i.e., those with the highest centers of gravity) will roll over before they will skid off the road on a dry pavement. However, on a poor wet pavement, a truck with poor tires on a minimum-radius curve will generally skid at a lower speed than it will roll over on curves with design speeds of up to 64 km/hr (40 mph). For horizontal-curve design speeds above 64 km/hr (40 mph), the most unstable trucks will roll over at a lower speed than they will skid off the road.

3. The margins of safety against skidding and rollover by trucks appear to be adequate for trucks that do not exceed the design speed on curves designed in accordance with Green Book Table III-6.

4. Variations in the methods for developing superelevation on horizontal curves, such as the provision of spiral transitions, have only very small effects on the likelihood of skidding or rolling over by trucks.

5. On horizontal curves with lower design speeds that are designed in accordance with Green Book Table III-6, the most unstable trucks can roll over when traveling as little as 8 to 16 km/hr (5 to 10 mph) above the design speed. This is a particular concern on freeway ramps, many of which have unrealistically low design speeds in comparison with the design speed of the mainline roadway. A recent paper by Harwood and Mason (9) reviews the existing AASHTO criteria for selecting the design speed of a ramp as it relates to the highway design speeds. The selection of realistic design speeds is critical to safety, particularly for trucks.

On the basis of these evaluation results there does not appear to be a need to modify existing criteria for determining the radii and superelevations of horizontal curves in Green Book Table III-6. Existing design policies provide adequate margins of safety against skidding and rollover by both passenger cars and trucks as long as the design speed of the curve is selected realistically. Special care should be taken for curves with design speeds of 48 km/hr (30 mph) or less to ensure that the selected design speed will not be exceeded, particularly by trucks. Design of superelevation transitions according to the two-thirds-one-third rule provides an acceptable design, although spiral transitions would provide marginally lower lateral accelerations.

### Low-Speed Horizontal Curve Design Criteria

AASHTO policy permits the low-speed design criteria presented in Green Book Table III-17 to be used for horizontal curves at

intersections and turning roadways with design speeds of 64 km/hr (40 mph) or less. The following conclusions and recommendations were drawn from the evaluation of these low-speed design criteria.

1. Minimum-radius horizontal curves designed in accordance with the low-speed criteria in Green Book Table III-17 generally provide adequate margins of safety against skidding and rollover for passenger cars traveling at the design speed.

2. For design speeds of 16 to 32 km/hr (10 to 20 mph), minimum-radius horizontal curves may not provide adequate margins of safety for trucks with poor tires on a poor wet pavement or for trucks with low rollover thresholds. Revision of the criteria in Green Book Table III-17 should be considered, especially for locations with substantial truck volumes. This same concern is applicable to the horizontal curve design criteria for low-speed urban streets based on Green Book Table III-16.

3. The Green Book should be revised to state explicitly that minimum radii smaller than those shown in Table III-17 should not be used, even when they appear justified by above-minimum superelevation rates.

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*Publication of this paper sponsored by Committee on Geometric Design.*