

Superelevation and Body Roll Effects on Offtracking of Large Trucks

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Past research has shown that vehicles, especially large trucks, offtrack on curves and turns; at low speeds the rear axles track inside the front axle (negative offtracking), and at sufficiently high speeds the reverse is true. New research shows that typical amounts of superelevation tend to increase low-speed, negative offtracking of trucks by 10 to 20 percent. Superelevation also tends to reduce the amount of high-speed outward offtracking. The magnitude of the superelevation effect is independent of speed. The superelevation effect is greater with more heavily loaded trucks, trucks with newer tires, and trucks with larger roll steer coefficients. This research also shows that body roll affects both high-speed offtracking and the superelevation contribution to total offtracking. Trucks with softer suspensions are more affected. The net effect is to increase outward offtracking at normal and high speeds and to slightly increase negative offtracking at very low speeds.

When any vehicle makes a turn, its rear wheels do not follow the same path as its front wheels. The magnitude of this difference in paths, known as offtracking, generally increases with the spacing between the axles of the vehicle and decreases for larger-radius turns. Offtracking of passenger cars is minimal because they have relatively short wheelbases; however, many trucks offtrack substantially. The most appropriate descriptor of offtracking for use in highway design is the "swept path width," shown in Figure 1 as the difference in paths between the outside front tractor tire and the inside rear trailer tire.

The AASHTO Green Book (1,2) notes two distinct types of offtracking: low-speed and high-speed. Low-speed offtracking is a purely geometrical phenomenon wherein the rear axles of a truck track toward the inside of a horizontal curve, relative to the front axle. Figure 1 illustrates low-speed offtracking. Because considerable research has been performed concerning low-speed offtracking, as a function of truck and roadway geometrics, it is well understood on level surfaces. However, pavement cross-slope, including superelevation on horizontal curves, has an effect on low-speed offtracking that has not been documented in previous research.

High-speed offtracking, on the other hand, is a dynamic, speed-dependent phenomenon. It is caused by the tendency of the rear of the vehicle to move outward because of the lateral acceleration of the vehicle as it negotiates a horizontal curve at higher speeds. High-speed offtracking is less well understood than low-speed offtracking; it is a function not only of truck and roadway geometrics, but also of the vehicle speed and the vehicle's suspension, tire, and loading characteristics.

Current AASHTO criteria for intersection and channelization geometrics and for pavement widening on horizontal curves consider only low-speed offtracking. The design of intersection and channelization geometrics is properly a function only of low-speed offtracking, because truck operations at intersections usually occur at low speeds. Pavement cross-slope effects on offtracking can generally be ignored in the design of intersection and channelization geometrics because normal pavement cross-slopes are small. Turning roadways at channelized intersections do not require much superelevation because operations there usually occur at low speeds. However, pavement widening at horizontal curves should consider both low-speed and high-speed offtracking, as well as superelevation effects.

LOW-SPEED OFFTRACKING WITHOUT SUPERELEVATION

Low-speed offtracking has been researched extensively and is considered in current AASHTO design criteria. An offtracking model for the Apple microcomputer was developed for FHWA in 1983 (3), and an IBM PC version of this model was subsequently developed (4). The user specifies the turning path to be followed by the front axles of the truck, and the models plot the path of the rear axle and other specified points on the truck. The Apple and IBM PC models provide plotted output but have no capability for numerical output. Recently the California Department of Transportation (Caltrans) enhanced the IBM PC version of the model to include numerical output of offtracking and swept path widths, as well as the turning plot (5). The Caltrans model runs on an IBM mainframe computer.

The Caltrans model was run as part of a recent study (6) to compare the offtracking performance of the design vehicles specified in Table 1. These vehicles are representative of those defined by the 1982 Surface Transportation Assistance Act (STAA). The offtracking performance of these vehicles was compared with those of a conventional tractor and 37-ft semitrailer (the AASHTO WB-50 design vehicle) and a conventional tractor and 45-ft semitrailer, the largest semitrailer in widespread use before the STAA.

As a truck proceeds into a 90-degree turn, the amount of offtracking increases (see Figure 1). As the truck negotiates the turn, the amount of offtracking reaches a maximum and then gradually decreases as the truck proceeds in the new direction. Figure 2 shows this maximum offtracking for various values of turn radius and total turning angle for the WB-50 design vehicle. Maximum offtracking does not continue to

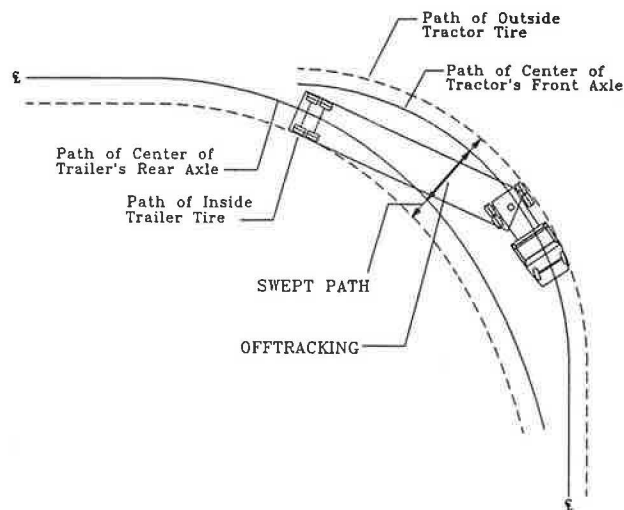


FIGURE 1 Swept path width and offtracking of a truck negotiating 90-degree intersection turn.

increase with turn angle, but reaches a constant value (becomes fully developed) after some angle that depends on the radius. For the WB-50, for example, at a turn radius of 100 ft, offtracking reaches about 6.5 ft for an angle of 90 degrees and does not increase further at larger angles, as shown in Figure 2. The turn angle required to fully develop offtracking is greater for smaller radii, and may exceed 180 degrees for very small radii.

The amount of offtracking depends most significantly on the distance between the kingpin and the center of the rear axles, which is dimension D in Table 1. The data shown in Figure 2, and elsewhere in this paper unless specified otherwise, assume that the rear axles are placed at the rear of the

trailer, as indicated in Table 1. Many longer trailers are designed to allow these axles to be moved forward to decrease the low-speed offtracking. In fact, it is common for users of 53-ft trailers to slide the axles forward 5 ft, so their offtracking is essentially the same as the STAA single with a 48-ft trailer. Similar offtracking plots for the other design vehicles shown in Table 1 have been presented by Harwood et al. (6).

Swept path widths can be calculated directly by adding the effective truck width to the maximum offtracking values such as those shown in Figure 2. Because the Caltrans model calculates offtracking along the truck centerline and the swept path width is the difference in path between the front outside axle and the rear inside axle, the difference between offtracking and swept path width is one-half of the tractor axle width plus one-half of the rear trailer axle width. The front tractor axle is typically 6.66 ft wide, and the rear trailer axle is typically 8.5 ft wide, so half of their sum is 7.58 ft.

The maximum offtracking for all of the design vehicles considered for selected combinations of turn radius and turn angle is compared in Table 2. The data show that for the single-trailer configurations, the amount of offtracking increases nearly linearly with trailer length. For 90-degree turns, the offtracking of a 53-ft trailer, with axles in the furthest rear position, is almost double that of the WB-50 configuration. The offtracking of doubles is much less than that of STAA singles and is approximately the same as that of the WB-50.

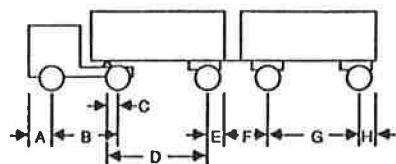
MODEL FOR LOW-SPEED AND HIGH-SPEED OFFTRACKING INCLUDING SUPERELEVATION EFFECTS

Various models and formulas have been developed to estimate offtracking by trucks in turns so that turning plots, like

TABLE 1 DETAILED AXLE SPACINGS FOR LONGER DESIGN VEHICLES

Design vehicle	Dimension (ft)								Overall length
	A	B	C	D	E	F	G	H	
Single-unit truck	4.0	-	-	20.0	6.0	-	-	-	30.0
Single-trailer truck with 37-ft trailer (WB-50)	2.5	18.0	0.0-2.0	30.0	4.0	-	-	-	52.5-54.5
Single-trailer truck with 45-ft trailer	2.5	18.0	0.0-2.0	37.5	4.5	-	-	-	60.5-62.5
STAA single with 48-ft trailer and conventional tractor	2.5	18.0	0.0-2.0	40.5	4.5	-	-	-	63.5-65.5
STAA single with 48-ft trailer and long tractor	2.5	20.0	0.0-2.0	40.5	4.5	-	-	-	65.5-67.5
Long single with 53-ft trailer	2.5	18.0	0.0-2.0	45.5	4.5	-	-	-	68.5-70.5
STAA double with cab-over-engine tractor	2.5	10.0	0.0-2.0	22.5	2.5	6.0	22.5	2.5	66.5-68.5
STAA double with cab-behind-engine tractor	2.5	13.0	0.0-2.0	22.5	2.5	6.0	22.5	2.5	69.5-71.5

Note: Dimensions A through H are defined below.



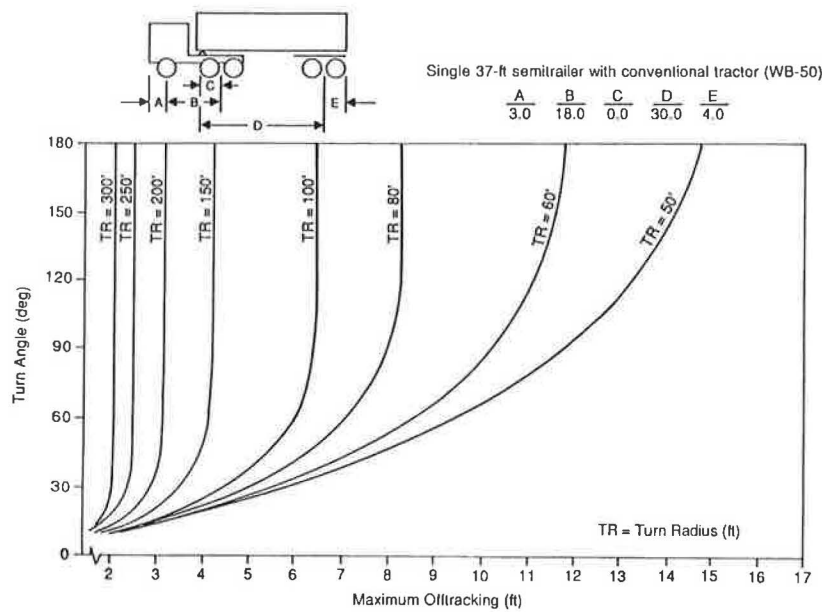


FIGURE 2 Offtracking plot for single 37-ft semitrailer truck with conventional tractor (WB-50).

TABLE 2 OFFTRACKING FOR SELECTED COMBINATIONS OF TURN RADIUS AND TURN ANGLE

Turn radius (ft)	Maximum offtracking (ft) ^a								
	50			100			300		
	60°	90°	120°	60°	90°	120°	60°	90°	120°
Single with 37-ft trailer (WB-50)	9.3	11.8	13.3	6.0	6.5	6.6	2.1	2.1	2.1
Single with 45-ft trailer	12.1	15.5	-	8.0	9.0	9.4	2.9	2.9	2.9
STAA single with 48-ft trailer and conventional tractor	13.0	16.9	-	8.8	10.0	10.5	3.3	3.3	3.3
STAA single with 48-ft trailer and long tractor	13.4	17.4	-	9.1	10.4	10.8	3.4	3.4	3.4
Long single with 53-ft trailer	14.4	19.5	23.4	10.3	12.1	12.8	4.1	4.1	4.1
STAA double with cab-over-engine tractor	9.2	11.3	12.6	5.8	6.1	6.2	1.9	1.9	1.9
STAA double with cab-behind-engine tractor	9.6	11.9	13.4	6.0	6.4	6.4	2.1	2.1	2.1

^a Add 7.58 ft to entries in this table to get maximum swept path width.

Figure 1, need not be developed for every application. An early example is the Western Highway Institute (WHI) offtracking formula (7). Low-speed offtracking develops gradually as a truck traverses a turn, as shown in Figures 1 and 2. The WHI formula estimates the magnitude of fully developed low-speed offtracking, that is, the maximum offtracking that will occur for a given radius of turn if the turn angle is large enough.

In 1981, Bernard and Vanderploeg developed an offtracking model that includes both the low-speed and high-speed contributions to offtracking (8). However, their model applies only to vehicles on a level surface. The new model developed here extends the Bernard and Vanderploeg model by incorporating the added effect of superelevation on offtracking, as well as an explicit accounting for the roll of the truck body

on its suspension relative to the axles. Both the Bernard and Vanderploeg model and the new model give values for fully developed offtracking. On shorter curves, the actual offtracking may be less than the fully developed offtracking indicated by turning templates (e.g., Figure 1) or computer models such as the Caltrans model (5).

The new model for offtracking of a second axle or axle set (i.e., tandem or triaxle), or hitch point, relative to a leading axle, and so forth, is

$$OT = -\frac{l^2}{R} \left[0.5 + \frac{\sum_i (a_i/l^2)}{n(1 + t/l)} \right] + \frac{lU^2}{R} \left[\frac{1}{\bar{C}_{ag}(1 + t/l)} + S \right] - \frac{l\theta}{\bar{C}_o(1 + t/l)} - Slg\theta \quad (1)$$

where

- OT = fully developed offtracking (ft), where offtracking to the inside of the turn is treated as negative, by convention;
 l = distance between the two consecutive axles or centerlines of axle sets or hitch points (ft);
 R = radius of curvature (ft);
 a_i = distance from centerline of axle set to i th axle (ft) (for single axles, $a_1 = 0$; for tandem axles, $a_1 = a_2 = 2$ ft; for triaxles, $a_1 = a_3 = 2$ ft; $a_2 = 0$);
 n = number of axles in set ($n = 1$ for single axle, $n = 2$ for tandem axle, $n = 3$ for triaxle);
 t = pneumatic trail (ft) [for typical values, see Fancher et al. (9, p. 31)];
 U = speed of vehicle (ft/sec);
 g = acceleration of gravity (ft/sec²) (equivalent to 32.2 ft/sec² or 9.8 m/sec²);
 \bar{C}_α = ratio of total cornering stiffness to total normal load (rad⁻¹) (see Equation 2);
 S = roll steer angle (see Equation 3); and
 θ = superelevation of curve (ft/ft).

All vehicle axle characteristics (a_i , n , t , \bar{C}_α , and S) refer to the second axle set. The ratio of the total cornering stiffness to total normal load is determined as

$$\bar{C}_\alpha = \frac{n(C_\alpha/F_{zr})(F_{zr})(n_i)(57.296)}{W_a f} \quad (2)$$

where

- C_α = cornering stiffness of tires (lb⁻¹ deg⁻¹) [Fancher et al. (9, p. 29) indicate that C_α/F_{zr} is in the range from 0.1 to 0.2 deg⁻¹];
 F_{zr} = rated load of tire (lb) [typical values are given by Fancher et al. (9, p. 27)];
 n_i = number of tires per axle (usually four);
 W_a = load (weight) carried by the tires for the axle set (lb); and
 f = fraction of W_a supported by the suspension for the axle set ($W_a f$ is the sprung weight for the axle set).

The roll steer angle is determined as

$$S = \frac{M_a f s h}{k_r - M_a f g h} \quad (3)$$

where

- $M_a f$ = sprung mass supported by axle set (lb-sec²/ft) ($= W_a f/g$);
 s = suspension roll steer coefficient (degrees of steer per degree of roll) [for typical values, see Fancher et al. (9, p. 66)];
 k_r = composite roll stiffness for the axle set (ft-lb/rad) [for typical values, see Fancher et al. (9, p. 60); these values are given on a per-axle basis, so must be multiplied by n];
 h = distance between load center of gravity and suspension roll center, $h_{CG} - h_{RC}$;
 h_{CG} = height of center of gravity of load carried by the axle set (ft); and

h_{RC} = height of roll center of suspension system for the axle set (ft) [for typical values, see Fancher et al. (9, p. 65)].

Equation 1 consists of four terms. The first term represents the traditional low-speed offtracking, without superelevation. For a single axle ($a_i = 0$), the first term reduces to

$$OT = -\frac{0.5l^2}{R} \quad (4)$$

which is the WHI offtracking formula (7).

The second term in Equation 1 is the speed-dependent term and represents high-speed offtracking. The sign of the second term is positive, indicating that high-speed offtracking tends to offset the low-speed offtracking.

The third and fourth terms account for the effect of superelevation on offtracking. The third term represents the influence of the superelevation itself, and the fourth term is the contribution to offtracking of roll steer caused by the superelevation. The factor k_r accounts for the roll of the truck body and affects the second and fourth terms of the equation.

Equation 1 provides the offtracking for one axle, axle set, or hitch point relative to the preceding axle, axle set, or hitch point. To determine the offtracking for the entire vehicle, Equation 1 is applied successively to each pair of consecutive axles and the results are combined. Thus,

$$\text{Total } OT = \sum_j (X_j)(OT_j) \quad (5)$$

where

- $X_j = 1$ for an axle or axle set,
 $X_j = -1$ for a hitch point, and
 OT_j = offtracking for axle, axle set, or hitch point determined from Equation 1.

The reason for the minus sign when the second "axle" is a hitch point is that it is normally located ahead of the axles it "follows," so all offsets are in the opposite direction to those given by the convention developed for Equation 1.

The derivation of this new offtracking model is presented in the next section. The following section examines the sensitivity of the offtracking model to typical ranges of the variables in Equations 1, 2, and 3.

DERIVATION OF OFFTRACKING MODEL

Several years ago, Bernard and Vanderploeg described the mathematics of offtracking, including both the commonly known low-speed offtracking and the less studied high-speed offtracking (8). They developed the basic equation of motion for a trailer as a function of the trailer characteristics and the motion of the hitch point. They then examined in detail the special case of most interest—the motion when the trailer is making a steady turn of radius R at speed U .

The present derivation follows that of Bernard and Vanderploeg, but is limited to the special case of constant R and U . However, it incorporates two added features. First, it explicitly includes the effects of superelevation. The superelevation directly reduces high-speed offtracking and interacts

with the roll steer behavior of the vehicle. Second, roll of the body of the trailer relative to the axles also contributes to roll steer. This derivation uses the basic nomenclature and derivation of Bernard and Vanderploeg, but with the noted changes. A fuller presentation has been given by Harwood et al. (6).

Figure 3 is a schematic of a trailer with its hitch point traveling at speed U on a circular path of radius R . The center of gravity of the trailer is a distance c from the hitch point, along the trailer centerline. From Figure 3, applying Newton's second law in the direction perpendicular to the trailer centerline gives

$$M(A_y) = H_f + \sum_i F_{ri} \quad (6)$$

where

- M = trailer mass,
- A_y = lateral acceleration,
- H_f = lateral force on the trailer at hinge point, and
- F_{ri} = lateral force at the tires on axle i .

From Figure 4

$$\sum_i F_{ri} = \sum_i F_{fi} \cos \theta + \sum_i F_{ni} \sin \theta \quad (7)$$

where $\sum_i F_{ri}$ is the horizontal component of the tire/pavement forces. The superelevation angle is θ . Also from Figure 4, summing forces in the vertical direction yields

$$\sum_i F_{ni} \cos \theta = \sum_i W_i + \sum_i F_{fi} \sin \theta \quad (8)$$

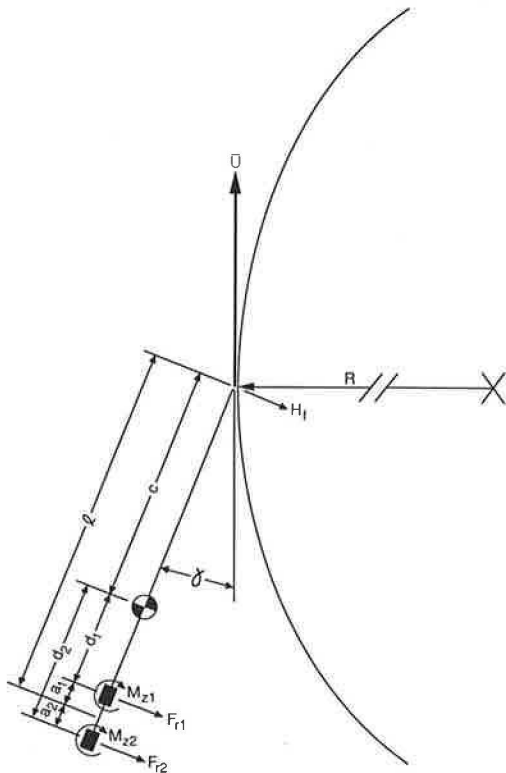


FIGURE 3 Forces and moments on trailer.

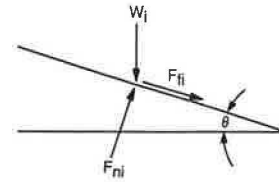


FIGURE 4 Tire/pavement forces with superelevation.

where W_i is the portion of the trailer weight on the tires of axle i . Eliminating $\sum_i F_{ni}$ between Equations 7 and 8 yields

$$\begin{aligned} \sum_i F_{ri} &= \sum_i F_{fi} \cos \theta \\ &+ \left(\sum_i W_i + \sum_i F_{fi} \sin \theta \right) \tan \theta \end{aligned} \quad (9)$$

Next, consider the sum of moments in the horizontal plane about the trailer CG:

$$I(\dot{r} + \ddot{\gamma}) = H_f(c) - \sum_i F_{ri}(d_i) + \sum_i M_{zi} \quad (10)$$

where

- I = trailer moment of inertia about its CG,
- r = rotation rate of the velocity vector, \bar{U} , and
- γ = angle between the trailer centerline and the velocity vector. (Note: $\dot{\gamma}$ and $\ddot{\gamma}$ are the first and second time derivatives, respectively, of γ , and \dot{r} is the time derivative of r .)

The side friction force, F_{fi} , and aligning moment, M_{zi} , are defined by $F_{fi} = -C_{\alpha_i}(\alpha_i)$ and $M_{zi} = K_i(\alpha_i)$, respectively. C_{α_i} is the combined cornering stiffness for the tires on axle i , K_i is the combined aligning moment for those tires, and α_i is the slip angle [angle between the direction of motion of the trailer (\bar{U}) and the plane of the tire]. This can be shown to be (8)

$$\tan \alpha_i = -\tan \delta_i - \tan \gamma - \frac{(l + a_i)(r + \dot{\gamma})}{U \cos \gamma} \quad (11)$$

where δ_i is the steer angle of the axle (Figure 5).

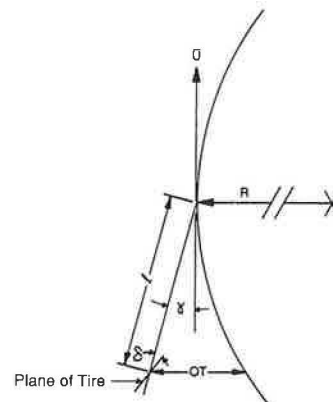


FIGURE 5 Slip and steer angles.

The lateral acceleration of the trailer CG is

$$A_y = Ur \cos \gamma - (\dot{r} + \ddot{\gamma})c \quad (12)$$

When the trailer tends to roll on its suspension, the rolling forces cause the tires to rotate (steer) slightly about a vertical axis. As such, they no longer track in the same direction as the axis of the trailer, as indicated in Figure 5. The amount of this steering depends on the rolling moment and the suspension characteristics.

Figure 6 shows the roll angle, ϕ , of the trailer negotiating a curve with superelevation, θ . The roll center (RC in Figure 6) is the point in space about which the trailer rolls. It is located a distance h below the center of gravity of the portion of the trailer $M_a f$ supported by the suspension. (M_a is the trailer mass supported by the tires of the axle set; f is the fraction that is suspended.) Now, summing moments about the roll center and making the usual small angle assumptions for θ and ϕ (e.g., $\sin \theta \approx \theta$, $\cos \theta \approx 1$), yields

$$\phi = M_a f h (A_y - g\theta) / (k_r - M_a f g h) \quad (13)$$

where k_r , the roll stiffness, is a property of the trailer suspension; $k_r \phi$ is the suspension-created restoring moment (clockwise in Figure 6). Then the steer angle, δ_i , is (by definition of s_i), $\delta_i = -s_i \phi$, where s_i is the suspension's roll steer coefficient. If we define

$$S_i \equiv M_a f s_i h / (k_r - M_a f g h) \quad (14)$$

then

$$\delta_i = -S_i (A_y - g\theta) \quad (15)$$

This equation compares with Bernard and Vanderploeg's equation (A-7) (8) except for the inclusion of the $g\theta$ term to denote the superelevation and a more inclusive definition of S_i to explicitly include the fact that the roll offsets the CG of the trailer, thus negating some of the suspension restoring moment.

Next, for a constant speed and radius turn, $\dot{r} = \dot{\gamma} = \ddot{\gamma} = 0$. Using Equations 6, 12, and 9 in Equation 10; using Equation 11 for α_i ; noting from Figure 3 that $c + d_i =$

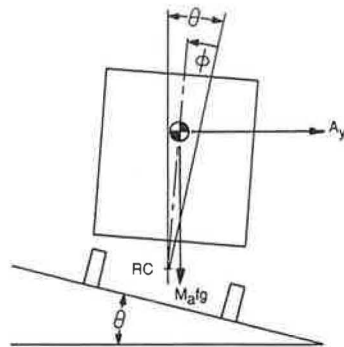


FIGURE 6 Trailer roll with superelevation.

$l + a_i$; and making the customary small angle assumptions for θ yields

$$\gamma = \frac{c M U r}{\sum_i [C_{\alpha_i} (l + a_i) + K_i]} - \frac{r}{U} \frac{\sum_i [C_{\alpha_i} (l + a_i) + K_i] (l + a_i)}{\sum_i [C_{\alpha_i} (l + a_i) + K_i]} - \frac{\sum_i [C_{\alpha_i} (l + a_i) + K_i] \delta_i}{\sum_i [C_{\alpha_i} (l + a_i) + K_i]} - \frac{\sum_i W_i (l + a_i)}{\sum_i [C_{\alpha_i} (l + a_i) + K_i]} \quad (16)$$

At this point we simplify by setting all $K_i = K$, all $C_{\alpha_i} = C_{\alpha}$, and $W_i = W_a/n$, where n is the number of axles in the axle set and W_a is the total load on all tires of the axle set. We note that $\sum \alpha_i = 0$ and that $W_a = (c/l) M g$ because some of the weight is carried by the hinge point. We also define the pneumatic trail t as K/C_{α} , and C_{α} as $n C_{\alpha_i} n_i / W_a f$. The number of tires per axle, n_i , is introduced because C_{α} is usually given on a per-tire basis. Finally, noting that for a steady turn the rotation rate r is U/R , Equation 16 becomes

$$\gamma = -\frac{t}{R} \left[1 + \frac{\sum_i (a_i/l)^2}{n(1 + t/l)} \right] + \frac{U^2}{R} \left[\frac{1}{C_{\alpha} g (+t/l)} + S \right] - S_g \theta - \frac{\theta}{C_{\alpha} (1 + t/l)} \quad (17)$$

where the definition of S_i in Equation 14 has also been used, and all $S_i = S$. Finally, defining the offtracking distance, OT , as $l\gamma + l^2/2R$ (see Figure 5), Equation 1 evolves.

SENSITIVITY OF OFFTRACKING TO TRUCK CHARACTERISTICS

Sensitivity analyses were conducted to determine the sensitivity of offtracking to truck characteristics using the new offtracking model. The sensitivity analyses used a simple computer program to exercise the model given by Equations 1, 2, and 3. The truck used for the sensitivity analyses was the STAA single with 48-ft trailer and conventional tractor described in Table 1. Both empty and loaded trucks were considered. The typical axle spacings, axle loads, and CG height assumed for empty and loaded trucks are given in Table 3. Table 4 shows both typical values and typical ranges for the other truck parameters in the offtracking model (9).

Vehicle Speed and Superelevation

Table 5 illustrates the sensitivity of offtracking to vehicle speed and superelevation for the loaded truck documented in Table 4 using the typical truck parameters presented in Table 4. The values in Table 5 are for a truck on a 500-ft (150-m) radius; shorter-radius turns, such as those made at intersections, are not addressed in this sensitivity analysis because

TABLE 3 ASSUMED CHARACTERISTICS FOR LOADED AND EMPTY TRUCKS USED IN OFFTRACKING SENSITIVITY ANALYSES

	Tractor drive axle		Rear trailer axle	
<u>Parameter</u>				
Type of axle set	Tandem (n = 2)		Tandem (n = 2)	
Distance from previous axle (ℓ) (ft)	18.0 ^a		40.5 ^a	
	<u>Empty</u>	<u>Loaded</u>	<u>Empty</u>	<u>Loaded</u>
Load (weight) carried by suspension for the axle set (W) (lb)	11,500	30,000	5,000	30,000
Height of center of gravity (in)	51	71.4	60	80

^a Values of dimensions B and D for STAA 48-ft trailer truck from Table 1. Dimension C (fifth wheel offset) is assumed to be zero.

TABLE 4 TYPICAL VALUES OF PARAMETERS FOR OFFTRACKING MODEL (8)

Parameter	Typical value	Typical range
Cornering coefficient (C_a/F_{zt})	0.15 deg ⁻¹	0.12 to 0.19
Rated load of tire (F_{zt})	6,040 lb for radial tires 5,150 lb for bias ply tires	
Number of tires per axle	4	2 to 4
Pneumatic trail (t)	0.179 ft	0.15 to 0.23
Suspension roll steer coefficient (s) (degrees of steer per degree of roll)	0.18	-0.04 to 0.213
Composite roll stiffness (k_r), per axle	0.158 x 10 ⁸ in-lb/deg	0.070 to 0.165 x 10 ⁸
Height of roll center (h_{RC})	22 in	21 to 33

speeds are lower and superelevation is less common for such turns. The 60-mph values in Table 5 are presented for illustrative purposes only; in accordance with AASHTO policies, the design speed for a 500-ft radius curve is less than 60 mph. For example, with a maximum superelevation of 0.06, a 500-ft radius curve would have a design speed of about 40 mph.

The data in Table 5 verify that the traditional low-speed component of offtracking, as defined, does not vary with either speed or superelevation. It is a function solely of the truck characteristics and the turning path. The negative sign of the

low-speed offtracking component indicates that the rear trailer axle tracks inside the tractor steering axle. The value of the low-speed offtracking component, -1.98 ft, represents the maximum offtracking that could occur on a 500-ft radius curve (without superelevation) that is long enough for offtracking to fully develop; the Caltrans model could be used to determine the actual offtracking for any curve that is too short to develop that maximum.

Table 5 shows that because the high-speed component of offtracking increases with the square of speed, its value at 40

TABLE 5 COMPONENTS OF TOTAL OFFTRACKING ON 500-ft RADIUS CURVE

Truck speed (mi/h)	Superelevation (ft/ft)	Offtracking (ft)			Total
		Low-speed component	High-speed component	Superelevation component	
20	0.00	-1.98	0.28	0.00	-1.70
	0.02	-1.98	0.28	-0.10	-1.80
	0.04	-1.98	0.28	-0.21	-1.91
	0.06	-1.98	0.28	-0.31	-2.02
	0.08	-1.98	0.28	-0.43	-2.12
	0.10	-1.98	0.28	-0.53	-2.23
40	0.00	-1.98	1.13	0.00	-0.85
	0.02	-1.98	1.13	-0.10	-0.96
	0.04	-1.98	1.13	-0.21	-1.07
	0.06	-1.98	1.13	-0.31	-1.17
	0.08	-1.98	1.13	-0.43	-1.28
	0.10	-1.98	1.13	-0.53	-1.38
60	0.00	-1.98	2.53	0.00	0.55
	0.02	-1.98	2.53	-0.10	0.45
	0.04	-1.98	2.53	-0.21	0.34
	0.06	-1.98	2.53	-0.31	0.24
	0.08	-1.98	2.53	-0.43	0.13
	0.10	-1.98	2.53	-0.53	0.03

mph is four times its value at 20 mph. The positive sign of the high-speed offtracking term shows that it is in the opposite sense to the low-speed offtracking term, tending to move the rear trailer axle toward the outside of the turn. For the specific truck and radius of curvature shown in Table 5, the low-speed and high-speed offtracking terms would completely offset one another on a level surface (i.e., with no superelevation). At that speed, the rear trailer axle would exactly follow the tractor steering axle and there would be no offtracking. At higher speeds, the rear trailer axle would track outside the tractor steering axle. The values of the high-speed component of offtracking represent fully developed or steady state offtracking. However, there is no information in the literature about how the high-speed component develops as a truck enters a turn. This issue could be investigated with a computer simulation model of vehicle dynamics, such as the Phase-4 model (10).

Table 5 also shows that the effect of superelevation on offtracking increases linearly with the magnitude of the cross-slope and that this component of offtracking is in the same direction as the low-speed component. In addition, this superelevation effect is independent of speed, so it would contribute to offtracking in low-speed turns at intersections, as well as high-speed turns on horizontal curves, whenever there is a pavement cross-slope. Thus, the effect of superelevation

is to increase the inside offtracking at low speeds and to reduce the outside offtracking at high speeds. This superelevation effect represents the fully developed offtracking. No information is available about how the superelevation effect develops as a truck enters a turn.

Empty Versus Loaded

The loading of a truck has an important effect on offtracking, which was investigated in a sensitivity analysis for standard test conditions, including a 500-ft radius curve with superelevation of 0.060, a truck travel speed of 40 mph, and the typical values of truck parameters given in Table 4. The analysis considered the empty and loaded conditions shown in Table 3. The added load does not affect the low-speed component of offtracking, but strongly increases the high-speed component and the (negative) superelevation component. The $1/\bar{C}_a$ term is proportional to the axle load, and S is nearly so. The loaded condition has offtracking of -1.17 ft, as shown in Table 5. The empty or unloaded condition has offtracking of -1.80 ft. Thus, empty trucks have greater negative offtracking than loaded trucks.

Further sensitivity analyses for empty and loaded trucks were conducted using the standard test conditions and varying

the truck parameters in Table 4 one at a time over their typical ranges. The results are presented in Table 6.

Cornering Coefficient

The cornering coefficient (C_α/F_{zr} in Equation 2) is the ratio of the cornering stiffness to the rated load of the tire. The offtracking estimates in Table 5 were made using a cornering coefficient of 0.15 deg^{-1} , which represents a typical new radial tire. Cornering coefficients for radial tires typically range from 0.12 to 0.19 deg^{-1} depending on the tire model and the degree of wear (9).

The cornering coefficient has only a modest effect on offtracking. Increasing the cornering coefficient increases negative offtracking. Over the range from 0.12 to 0.19 deg^{-1} , total offtracking varies by only 0.07 ft for an empty truck and by 0.30 ft for a loaded truck for the defined standard test conditions. As tires wear, their cornering coefficient increases, causing the net offtracking to be more negative.

Rated Load of Tire

Variations over the typical range of rated load of the tires have very little effect on offtracking. Bias-ply tires have lower rated loads than radial tires and reduce negative offtracking by 0.03 ft for empty trucks and by 0.11 ft for loaded trucks. For all practical purposes, the rated load of the tire could be set to a constant value of $6,040 \text{ lb}$ in the investigation of offtracking on horizontal curves.

Pneumatic Trail

The pneumatic trail of the tire determines the magnitude of the steering moment that is applied to the tire during cor-

nering (10). Although the pneumatic trail theoretically influences offtracking (see Equation 1), this influence is so small—less than 0.01 ft for the standard test conditions—that for all practical purposes the pneumatic trail can be treated as a constant.

Suspension Roll Steer Coefficient

The suspension roll steer coefficient (degrees of roll per degree of steer) has very little effect on offtracking for empty trucks and has a moderately important effect for loaded trucks. An increase in the roll steer coefficient decreases the amount of negative offtracking. For the standard test conditions, variation of the roll steer coefficient over its typical range from -0.04 to 0.23 results in a variation in offtracking of 0.05 ft for empty trucks and 0.23 ft for loaded trucks.

Composite Roll Stiffness

The composite roll stiffness of a truck suspension system represents the relationship between the suspension roll angle and the restoring moment that tends to keep the truck body from rolling further. Increases in the composite roll stiffness result in increases in negative offtracking. For the standard test conditions, variation of the composite roll stiffness over its typical range, from 0.165 to $0.070 \text{ million in.-lb/deg}$, results in an increase in positive offtracking of 0.05 ft for empty trucks and 0.27 ft for loaded trucks. Thus, composite roll stiffness has a very small effect on offtracking for empty trucks and a moderate effect for loaded trucks.

Height of Roll Center

The height of the roll center has very little effect on offtracking over its typical range of variation. Negative offtracking in-

TABLE 6 OFFTRACKING RESULTS FROM SENSITIVITY ANALYSES

Parameter	Offtracking (ft) ^a			
	Empty truck		Loaded truck	
	High value	Low value	High value	Low value
Cornering coef.	-1.83	-1.76	-1.31	-1.01
Rated tire load	-1.80	-1.77	-1.17	-1.06
Pneumatic trail	-1.80	-1.80	-1.17	-1.17
Roll steer coef.	-1.79	-1.84	-1.14	-1.37
Roll stiffness	-1.80	-1.75	-1.18	-0.91
Roll center ht.	-1.80	-1.80	-1.21	-1.17
No. of axles ^b	-1.80	-1.53	-1.17	-0.48

^a For 48 ft STAA semitrailer truck on 500 ft radius turn with 6 percent superelevation, at 40 mi/h.

^b For 1 axle on rear of tractor and on trailer, truck weights and roll stiffnesses reduced appropriately.

creases as the roll center is raised. For the standard test conditions, variation in the height of the roll center from 21 to 33 in. changes offtracking by less than 0.01 ft for empty trucks and by 0.04 ft for loaded trucks. For all practical purposes, the height of the roll center can be set as a constant at its typical value of 22 in.

Number of Axles

The effect on offtracking of n , the number of axles, can be realistically addressed only by varying several related parameters. If the tractor and trailer have only one rear axle instead of two, the supported weight must be reduced in accordance with rated tire load and bridge-formula axle loads. The analysis used a maximum load of 20,000 lb on these axles. Also, the roll stiffness is generally much less for a single-axle suspension; 0.070×10^6 in.-lb/deg was used.

As shown in Table 6, the single-axle drive and trailer combination has significantly less negative offtracking than the tandem axle combination. This is primarily because the high-speed component is greater for the single-axle combination. This truck type will thus generate positive (outside) offtracking at lower speeds than tandem axle combinations.

CONCLUSIONS

The offtracking of vehicles, especially large trucks, is noticeably affected by the superelevation of the curve that the vehicle is traversing. This effect is proportional to the amount of superelevation and is independent of the vehicle speed.

At low speeds, the vehicle offtracking to the inside of the curve is made larger by the presence of superelevation. For a tractor with a 48-ft trailer, the low-speed offtracking on a 500-ft radius turn is increased by 20 percent with a superelevation of 8 percent. At high speed, where a truck might exhibit offtracking to the outside of the curve, the amount of offtracking is reduced or even canceled in the presence of superelevation.

The superelevation effect is dependent on the weight of the truck, the tire cornering coefficient, and the roll steer coefficient. Superelevation influences loaded trucks more than empty trucks; the effect is nearly proportional to the truck weight. The offtracking of trucks with worn tires, which have larger cornering coefficients, is less influenced by superelevation, especially at higher weights. Trucks with larger roll steer coefficients are more influenced by superelevation, although the effect is less than the opposite, high-speed effect, which is also a function of the roll steer coefficient.

A truck's suspension allows the truck body to roll toward the outside of the curve, relative to the axles. This body roll increases the high-speed offtracking. The amount of the increase depends on the stiffness of the suspension, being greater with softer suspensions, heavier loads, and larger roll steer coefficients. This body roll also increases (negatively) the

amount of superelevation-related offtracking, although this effect is not as large as the high-speed effect. For a tractor with a 48-ft trailer traveling at 40 mph on a 500-ft radius turn with a 6 percent superelevation, the net effect on offtracking can be as much as +0.27 ft for a realistically rigid suspension.

Finally, it was found that lighter tractor-semitrailers, with only a single drive axle and trailer axle, are more subject to high-speed offtracking than heavier trucks when both are loaded close to their capacities.

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