OFFTRACKING OF TRUCK COMBINATIONS AT LOW AND HIGH SPEED

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SYNOPSIS:

The mechanics of low speed offtracking are presented, first employing the classic considerations of the steady state turning case. Longitudinal dimensions between axles and hitch points are seen to directly determine the extent of offtracking at steady state. Transient offtracking at low speed is illustrated for 90 and 180 degree turns with nondimensional expressions which permit estimating the transient paths of certain simple vehicles.

The tendency for a trailing unit to offtrack toward the outside of the curve at increasing speed depends not only upon the longitudinal dimensions of the vehicle, but also the nominal cornering stiffness of the installed tires, given the tire loads. The high speed offtracking of differing vehicles is further noted to depend upon the extent of the low speed, or inboard, offtracking values as well as the strength of the outboard tendency with increasing speed. Most generally, vehicles which track well inboard at low speed exhibit lesser net outboard offtracking at high speed.

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This section treats the articulated vehicle which employs conventional trailer coupling mechanisms. Accordingly, the vehicle under consideration is a tractor-semitrailer unit coupled with a traditional fifth wheel and towing one or more full trailers. A full trailer is made up of a semitrailer and a converter dolly--the dolly using a single, wagon-tongue connection to its leading element and employing a conventional axle.

2.1 Low-Speed Offtracking

When an articulated vehicle tracks a steady-state circular trajectory at low speed, each axle of the train subtends a circular path whose radius is smaller than that of the preceding axle. Figure 1 illustrates this phenomenon for a three-axle tractor-semitrailer. The "offtracking" (OT) is defined as the difference in the turn radius of the first and last axle. An expression for OT, according to the notation employed in Figure 1, can be derived to yield

$$OT = R_1 - R_3 = R_1 - \sqrt{R_1^2 + KO^2 - L_1^2 - L_2^2} \qquad (1)$$

Figure 2 illustrates a generalized scheme for labeling the significant length parameters (ignoring the rather insignificant kingpin offset dimensions, for example, KO). Using this notation, a generalized expression for the offtracking of the rearmost axle of a multiply articulated vehicle is given by the following equation:

$$OT = R_1 - \sqrt{R_1^2 - \sum_{i=1}^{n-1} (L_{i1}^2 + L_{i2}^2 - L_{i3}^2) + L_{n1}^2 + L_{n2}^2} \qquad (2)$$

where n is the number of units in the train, with i=1 denoting dimensions which apply to the tractor-semitrailer and i>1 denoting dimensions applying to full trailers.

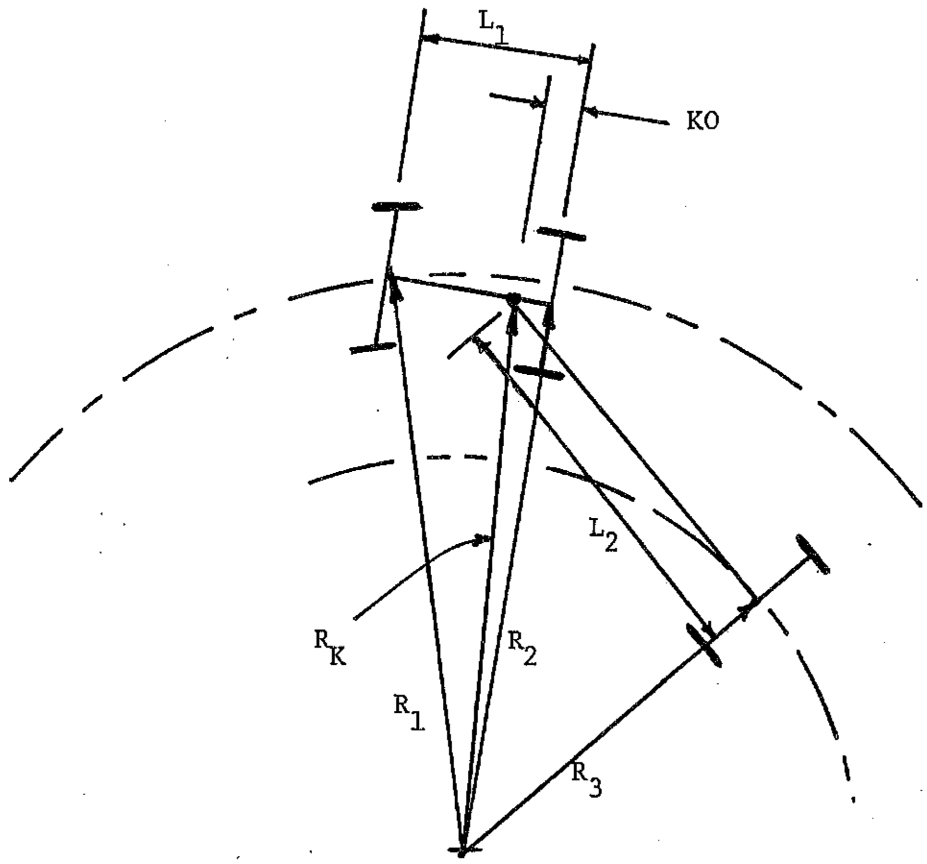

Figure 1. Maximum low-speed offtracking of a tractor-semitrailer

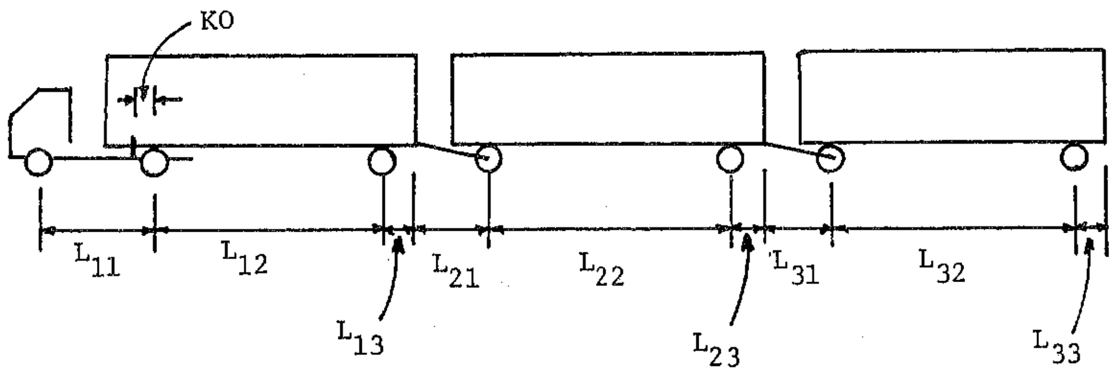

Figure 2. Definition of length dimensions applicable to low-speed offtracking calculation.

Equation (2) illustrates the advantage of adding articulation joints to reduce offtracking. For example, consider two vehicles, each of the same overall wheelbase (first axle to last axle). One vehicle is a single-unit truck and the other is assumed to be composed of a very large number of units, each with individual wheelbases approaching zero. The single-unit truck will exhibit the maximum offtracking for a vehicle of this length:

$$OT(1) = R_1 - \sqrt{R_1^{\,2} - L_{11}^{\,2}} \qquad (3)$$

The second vehicle, however, will have no offtracking since each length dimension approaches zero. That is:

$$OT(2) = R_1 - \sqrt{R_1^{\,2}} = 0 \qquad (4)$$

Thus it can be seen that, for a vehicle of a given length, steady-state offtracking is reduced by each additional articulation joint. When economic incentives promote the use of long vehicles to increase freight capacity, practical issues of maneuverability in confined spaces, as in terminal yards and urban environments, promote the use of multiple articulation joints.

In practice, the offtracking exhibited by long vehicles on real roads is not simply a function of this steady-state offtracking performance, but is also determined by the arc length of the curved path being followed by the lead axle. In effect, there is a transient offtracking phenomenon whose analysis is considerably more complicated than the prediction of the offtracking which occurs in a "zero-speed" steady turn. Although the transient phenomenon is amenable to calculation by computer, given any prescribed path for a leading axle, Jindra [4] has developed a generalized solution for two specific paths of a lead axle, namely, a 90-degree turn and a 180-degree turn. These solutions, as computed for the rear axle of a single-unit vehicle, are shown in Figure 3. Note that the results are given in terms of a nondimensional offtracking, r/R (where r is the turn radius of the rear axle and R is the radius of the prescribed turn being followed by the lead or steering axle), plotted as (1) a function of the angle, θ, traversed by the trailing axle and (2) a function of the nondimensional ratio, $\lambda = \ell/R$, where ℓ is the wheelbase of the vehicle.

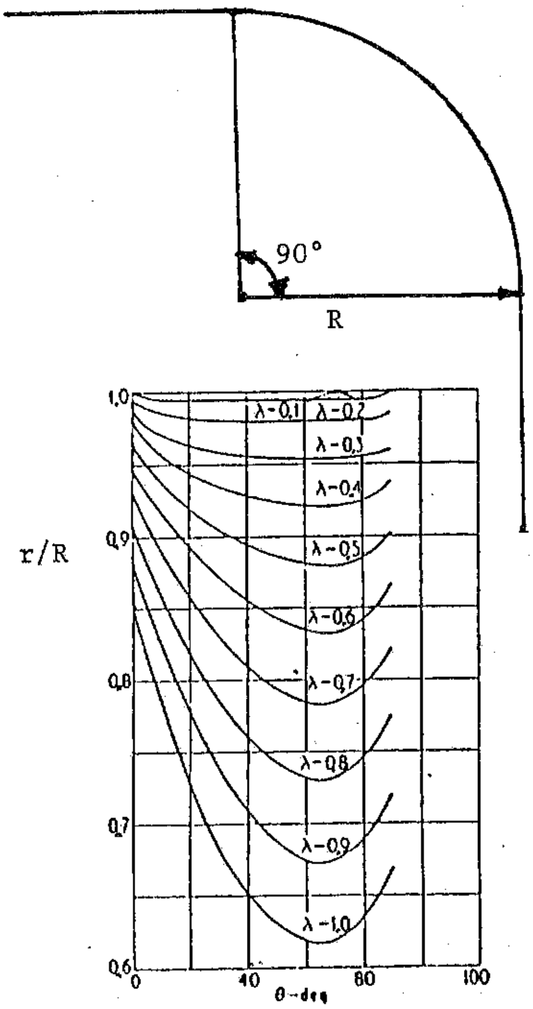

Figure 3a. Offtracking of a single-unit vehicle in a 90° turn [4].

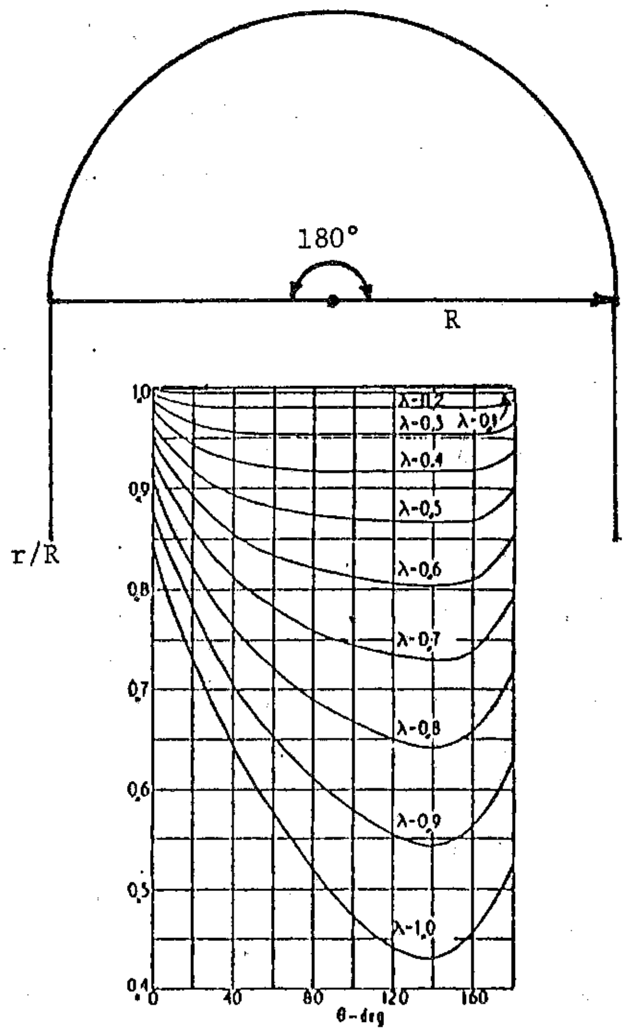

Figure 3b. Offtracking of a single-unit vehicle executing a 180° turn [4].

Jindra shows that the results plotted in Figure 3 are also applicable to a tractor-semitrailer, in that these curves give the offtracking of the axle on a semitrailer, relative to the path prescribed for a kingpin or fifth wheel comparable to the path prescribed for the lead axle of the towing vehicle. Further, by using the concept of an "equivalent wheelbase," Jindra argues that the curves presented in Figure 3 yield the approximate transient offtracking between the leading and last axle of a multiply articulated highway train. To apply Figure 3 to this general case, it is necessary to treat the ratio, λ, as

$$\lambda = Leq/R$$

where Leq is the equivalent wheelbase as defined by

$$Leq = \left[\sum_{i=1}^{n-1} (L_{i1}^2 + L_{i2}^2 - L_{i3}^2) + L_{n1}^2 + L_{n2}^2 \right]^{1/2}$$

Jindra's solution indicates that:

1. The influence of articulation joints is mathematically identical in the low-speed transient response as it is in steady-state response.

2. Smaller intended turn radii (relative to the effective wheelbase) results in longer transients in terms of degrees of turn.

3. For a fixed turn radius, shorter effective wheelbases (smaller λ) result in less offtracking at any point (degrees) in the turn.

The above discussion only applies to vehicles which have single axles, front and rear. For the sake of completeness (although the point is not crucial to the multiple-articulation issue), we should note that tandem axles, as well as dual-wheel assemblies, also affect offtracking, particularly on low-friction roadways, since both generate a turn-resistant yaw moment. Morrison [5] has shown that, in small radii turns on low-friction surfaces, widely spaced tandem axles can significantly increase trailer offtracking.

2.2 High-Speed Offtracking

While low-speed offtracking is characterized by each axle of the vehicle tracking a smaller radius than the axle preceding it, high-speed offtracking has the opposite quality. Generally, it can be expected that articulated commercial vehicles will exhibit an outboard, rather than inboard, offtracking at highway speeds. For multiply articulated vehicles, this offtracking may become sufficiently large that the increase in the width of the vehicle's swept path is significant to safety quality.

Figure 4 shows the general condition of a semitrailer in a high-speed, steady turn [6]. The reference radius (R) is measured to the kingpin of the semitrailer. (Since we have previously designated inboard offtracking as positive, the outboard offtracking shown in the figure is shown as -OT.) From the geometry of the figure, it can be shown that, for small angles:

$$OT = L^2/(2R) - L \cdot \alpha$$

where L is the wheelbase of the trailer and α is the slip angle at the rear axle of the trailer. Given the required static moment balance in yaw and in pitch, it can be shown that:

$$\alpha = a_y \cdot F_z/C_\alpha = (F_z/C_\alpha)(V^2/Rg)$$

where a_y is lateral acceleration in g's, V is forward velocity, F_z is the load on the trailer tires, and C_α is the total cornering stiffness of the tires mounted on the axle of the trailer. Combining these equations yields the following expression for offtracking at speed:

$$OT = L^2/2R - V^2L/Rg \cdot F_z/C_\alpha \qquad (5)$$

where positive values of OT indicate inboard offtracking and negative values indicate outboard offtracking.

Equation 5 shows that offtracking at speed consists of an inboard,

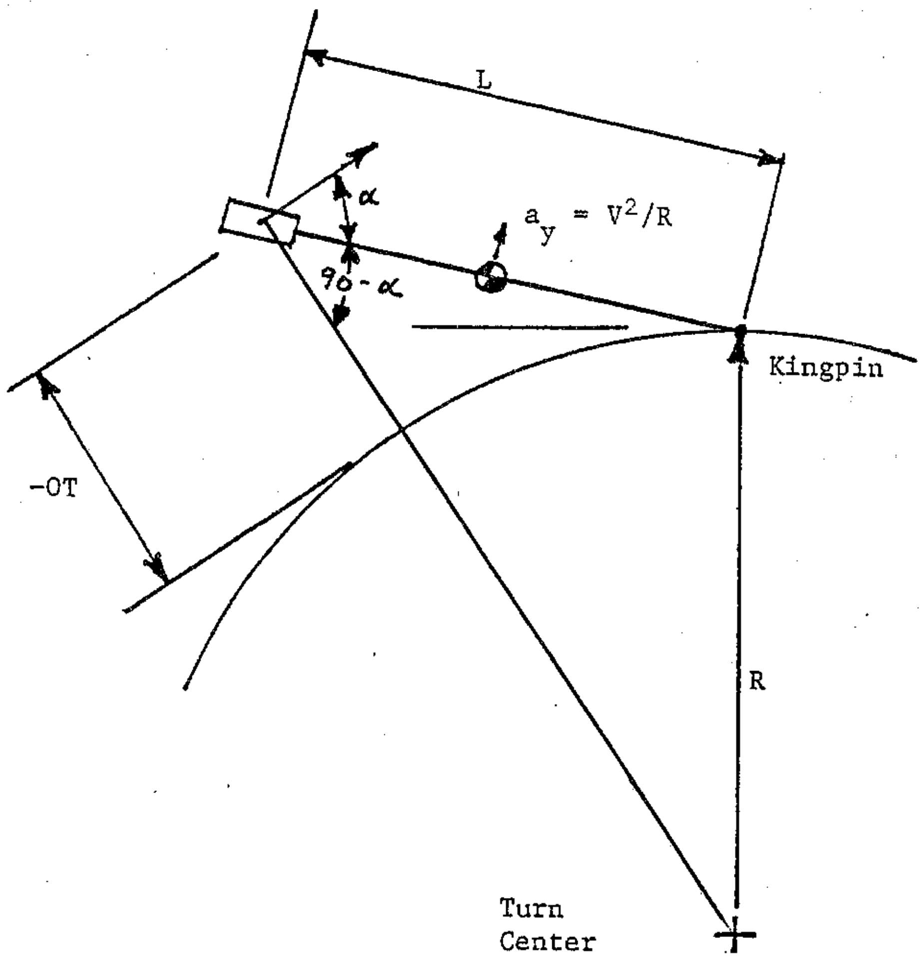

Figure 4. Geometry of the high-speed offtracking of a semitrailer.

zero-speed offtracking component (the first term) and a velocity-related component (second term) with an outboard polarity. For turns at fixed radii, the outboard component increases strongly with speed and is more pronounced for trailers which use lower stiffness tires.

Equation 5 also demonstrates that for a particular speed, load, and cornering stiffness, there is a critical trailer length (L_{cr}) which results in maximum outboard offtracking (minimum OT given the sign convention used herein). Differentiating OT with respect to L and setting the result to zero, we find that:

$$L_{cr} = (F_z/C_\alpha)(V^2/g) \tag{6}$$

Equation (6) shows that there is a trailer wheelbase dimension, L_{cr}, at which high-speed offtracking maximizes for given values of speed and F_z/C_α. (Note that L_{cr} is not a function of either path radius or lateral acceleration, per se.)

All of the preceding discussion has been concerned with the outboard offtracking of a single trailer relative to its lead point (kingpin for a semitrailer). On noting that a dolly can be treated in the same manner (considering its lead point as the pintle hitch), it can be shown that the overall offtracking of a multiply articulated vehicle at speed is approximately as follows:

$$OT = OT_{zero\ speed} - V^2/Rg \cdot (L_1 F_{z1}/C_{\alpha 1} + L_2 F_{z2}/C_{\alpha 2} + L_3 F_{z3}/C_{\alpha 3} + \ldots) \tag{7}$$

On assuming a vehicle which uses the same tires on all axles, each carrying the same load, we find that

$$OT = OT_{zero\ speed} - (V^2/Rg)\ (F_z/C_\alpha)\ (L_1+L_2+L_3+\ldots)$$

where the L's are the "wheelbases" (hitch to axle lengths) of each of the dollies and semitrailers making up the train. It is particularly of interest to note that the sum of all these lengths is approximately equal to the overall length of the trailer train. Thus, we see that the outboard component of offtracking at speed is not a function of the number of articulation joints, but only of overall length. Note, however, that the articulated vehicle will still track further outboard at any given lateral acceleration because of its smaller, inboard component at zero-speed. Figure 5 illustrates this offtracking phenomenon and demonstrates why multiple articulation joints lead to larger outboard offtracking at increased speed.

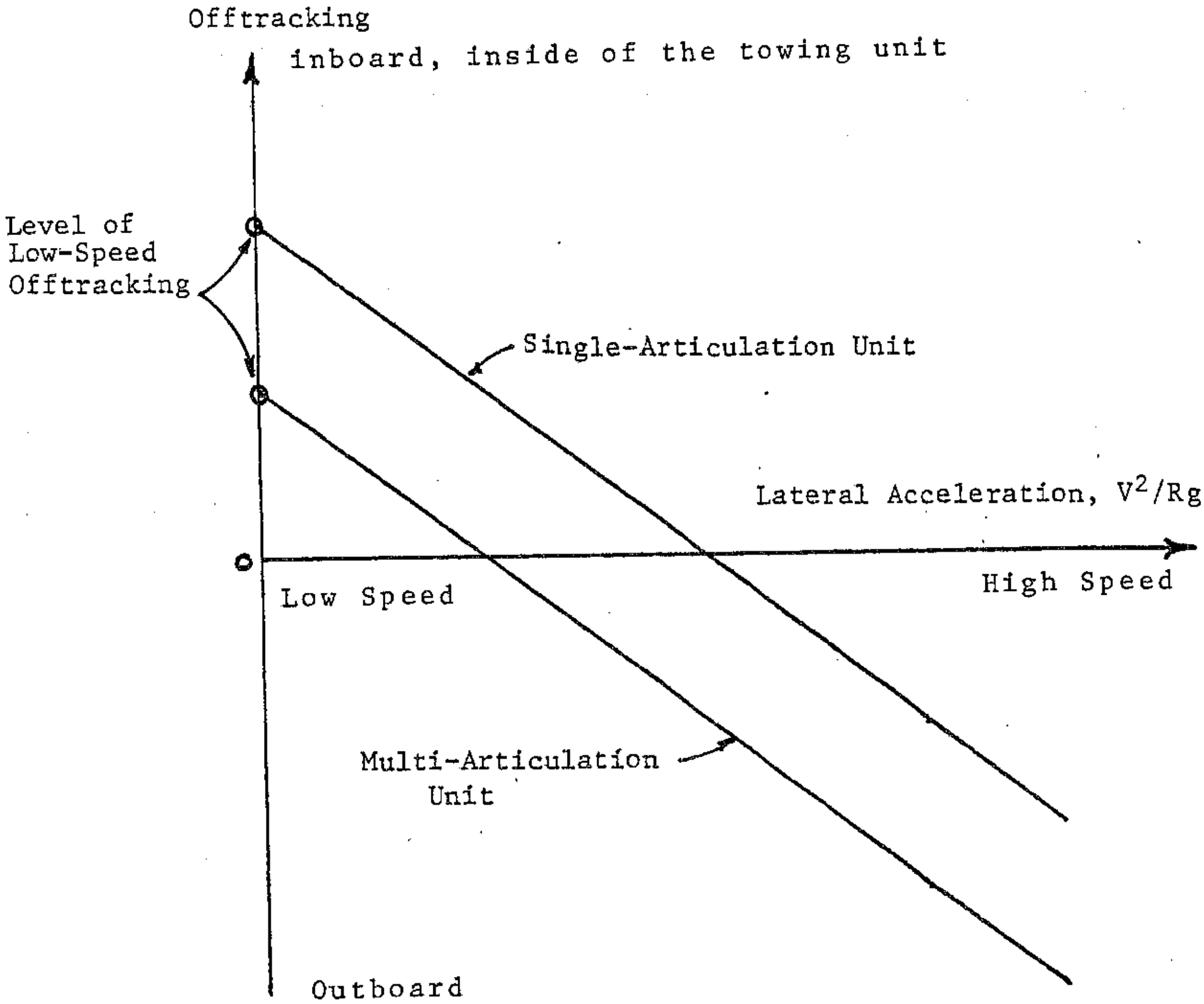

Figure 5. Offtracking of single- and multi-articulated vehicles of similar length.

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