Turning Ability and Off Tracking – Motor Vehicles – SAE J695 FEB84

SAE Recommended Practice
Completely Revised February 1984

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PREPRINT

ϕ TURNING ABILITY AND OFF TRACKING—MOTOR VEHICLES—SAE J695 FEB84

SAE Recommended Practice

Report of the Truck and Bus Technical Committee, approved October 1984, completely revised by the Truck and Bus Chassis Committee February 1984.

1. Scope—This SAE Recommended Practice sets forth a method by which the turning ability and off tracking of motor vehicles can be determined.

TURNING ABILITY

2. Definitions

2.1 Turning Center is that point about which all parts of a vehicle or combination of vehicles revolve in describing a turn of constant radius. For ideal steering, free of tire scrubbing, the extended axis of all wheel spindles passes through this center. In the case of two-axled bogies or tandems in which the axles are constrained to parallelism, the turning center is assumed to fall on a line parallel to and midway between these axle centerlines. (See Fig. 1.)

2.2 Turning Radius is the distance from the turning center to the center of tire contact with the road of the wheel describing the largest circle, while the vehicle is executing its sharpest practicable turn (usually to the outside front wheel). (See Fig. 1.)

2.3 Turning Diameter is twice the turning radius. (See Fig. 1.)

2.4 Turning Diameter—Wall to Wall is the diameter of the smallest circle which will enclose the outermost points of projection of the vehicle while executing its sharpest practicable turn. This is equal to the minimum turning diameter plus twice the radial overhang beyond the turning radius. (See Fig. 1.)

2.5 Turning Diameter—Curb to Curb is the diameter of the smallest circle within which the vehicle will clear a curb 150 mm high, while the vehicle is executing its sharpest practicable turn. This is equal to the turning diameter plus twice the horizontal distance from the center of tire contact with the road to the arc subtended by a chord drawn between the points of intersection of the outermost projection of the tire shoulder on a horizontal plane 150 mm above the surface on which the tire rests. (See Fig. 1.)

3. Determinations—The following determinations, based on Ackerman steering geometry (see Fig. 3), may be made mathematically as explained in detail hereafter:

3.1 Turning diameter[2] (TD) with a given wheelbase[1] (WB) and front axle configuration.

3.2 Configuration required to provide a given turning diameter[2] (TD).

3.3 Curb clearance increment (CI). (See Fig. 4.)

4. Factors of Front Axle Configuration

TR–Turning radius (see Fig. 1)
TD–Turning diameter
T–Track of tires at ground (See Fig. 2)
PC–Distance between knuckle pivot centers at ground
OS–Offset, pivot center to track of tire at ground
Ca–Camber angle of wheel, loaded
KI–Kingpin inclination from vertical

[1] To determine the turning ability of a three-axled vehicle, it is customary to measure the wheelbase from the front axle center to a point midway between the two rear axles and to consider a transverse line through this point as the equivalent of the center of the rear axle of a two-axled vehicle. Since these rear axles are constrained to parallelism, a moment is created during a turn which must be overcome by the front tires. This moment increases the front tire slip angle or tire scrub, and results in a larger turning diameter or a turning diameter equivalent to a vehicle with a longer wheelbase. Tests have shown that the true location of the turning center is somewhat further to the rear than midway between the axles. The actual location of the turning center depends upon whether the tire equipment is single or dual, whether the tires are radial or biased ply construction, the load distribution between the two rear axles, the load on the front axle, and the Ackerman error in the tie rod linkage. Calculations to accurately predict the effects of these various factors would be quite complex.

[2] At the maximum turning angle, there is normally Ackerman geometry error between the front wheels that can be described as shown in the equation in paragraph 5.2.2 or 5.2.3. This error will result in tire scrub of both front tires. If equal slippage of both front wheels is assumed, the theoretical turning center will lie midway between the intersections of the turning angle lines of outside and inside front wheels with the centerline of the rear axle. Due to the centrifugal force, the greater pressure on the outer wheel due to this centrifugal force, and other influences, the true turning center will actually lie closer to the outer intersection than to the inner.

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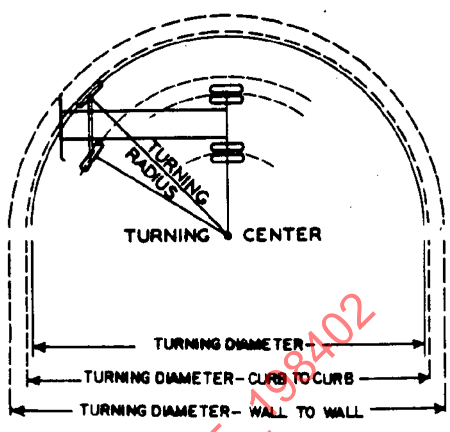


FIG. 1

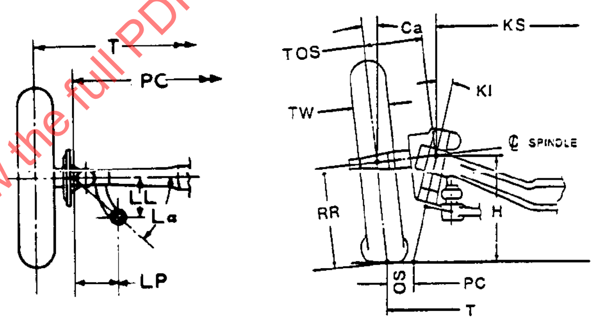


FIG. 2—DIAGRAM ILLUSTRATING FACTORS OF FRONT AXLE CONFIGURATION

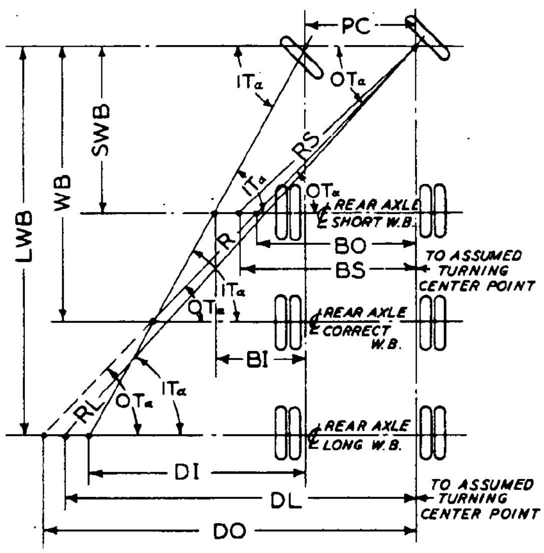


FIG. 3—DIAGRAM ILLUSTRATING EFFECT OF WHEELBASE ON TURNING RADIUS WITH A GIVEN FRONT AXLE CONFIGURATION

KS–Kingpin spacing
TW–Tire width
WB–Wheelbase[1]
LL–Cross steering lever length
LP–Cross steering lever position
La–Cross steering lever angle from axle centerline (true)
RR–Rolling radius of tire
ITa–Inside wheel turning angle (See Fig. 3)
OTa–Outside wheel turning angle (See Fig. 3)
H–Height of center of kingpin from ground (loaded)
R–Radius to pivot center for correct wheelbase (See Fig. 3)
RS–Radius to pivot center for shorter than correct wheelbase (See Fig. 3)
RL–Radius to pivot center for longer than correct wheelbase (See Fig. 3)
C–Curb contact length (See Fig. 4)
CR–Curb clearance radius (See Fig. 4)
CI–Curb clearance increment (See Fig. 4)
TOS–Tire offset measured along spindle centerline

5. Formulas

5.1 Several of the following formulas use the term PC, the distance between knuckle pivot centers measured at the ground. PC can be calculated from given axle dimensions as follows:

$$PC = KS + 2\,(RR \text{ Cos Ca} + TOS \text{ Sin Ca}) \times \tan KI$$

For small measures or camber angle (CA), the formula for PC can be simplified with little loss of accuracy to:

$$PC = KS + 2\ RR \times \tan KI$$

5.2 To determine turning diameter[2] (TD) with a given wheelbase[1] (WB) and front axle configuration (See Fig. 3):

5.2.1 With correct wheelbase[1] (WB):

$$TD = 2\left(\frac{WB}{\sin OTa} + OS\right)$$

5.2.2 With wheelbase shorter than correct (SWB):

$$TD = 2\left[\sqrt{\frac{4\ SWB^2 + \left(\frac{SWB}{\tan OTa} + PC + \frac{SWB}{\tan ITa}\right)^2}{2}} + OS\right]$$

5.2.3 With wheelbase longer than correct (LWB):

$$TD = 2\left[\sqrt{\frac{4\ LWB^2 + \left(\frac{LWB}{\tan OTa} + PC + \frac{LWB}{\tan ITa}\right)^2}{2}} + OS\right]$$

5.3 To determine configuration required to provide a given turning diameter (TD) (See Fig. 3):

5.3.1 Given pivot centers (PC), offset (OS), and wheelbase[1] (WB), to find the turning angle necessary to front wheels:

$$OTa = \arcsin\left(\frac{WB}{\frac{TD}{2} - OS}\right)$$

$$ITa = \text{arccot}\left(\cot OTa - \frac{PC}{WB}\right)$$

5.3.2 Given offset (OS) and turning angle of outside front wheel (OTa), to find the necessary wheelbase (See Fig. 3):

$$WB = \left(\frac{TD}{2} - OS\right) \sin OTA$$

5.4 To determine curb clearance increment to turning radius (See Fig. 4):

$$CI = \sqrt{\left(TR + \frac{TW}{2}\right)^2 + \left(\frac{C}{2}\right)^2} - TR$$

5.5 To determine correct cross steering lever configuration for a given wheelbase[1] and pivot centers (See Fig. 3).

The conventional tie rod linkage cannot provide perfect Ackerman geometry for all turn angles. In addition, it is often necessary to use one linkage configuration for several different wheelbases. The solution is therefore not a simple answer to a set of equations. It is a cut and try iterative process of examining various alternatives with respect to all wheelbases. Most engineering organizations use computer programs to compare the proposed design to perfect Ackerman geometry and then choose the best available design.

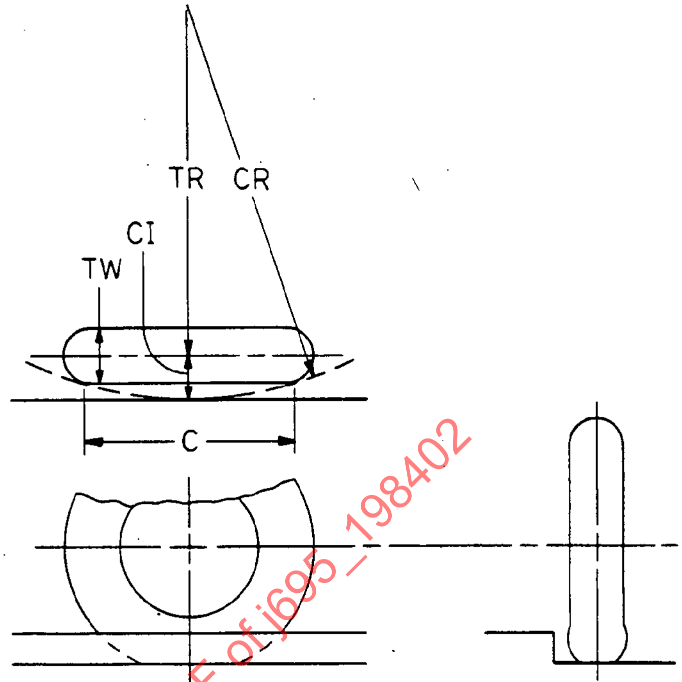


FIG. 4—CURB CLEARANCE DIAGRAM

A detailed graphical method may be found in Appendix I of SAE publication SP-374, The Truck Steering System from Hand Wheel to Road Wheel. SP-374 is available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096.

6. Field Test Procedure

6.1 Check steering geometry alignment and correct, if necessary.

6.2 Check the front wheel cut angles to manufacturers' recommendations. Wheel stops should be so set that the minimum clearance between the tire and the nearest point of interference is 20 mm; or, so that with the wheel stops in contact, a margin of a quarter turn of the steering wheel is left before the maximum travel of the steering gear is reached. In some cases, tire interference will be the limiting factor and in others, the steering gear travel will limit the maximum cut angle.

6.3 Load the vehicle to the maximum recommended gross weight.

6.4 Run the vehicle on a dry, flat apron, making turns in both directions in low gear at engine idle speed. The wheels should be turned to the maximum cut angle. At least two complete circles should be made before making measurements. The path of the outside wheel is marked on the pavement by pouring water on the tire while making the complete circle.

6.5 To determine the turning diameter, measure from the midpoint of tire contact trace on the pavement to a similar point across the diameter of the trace. Turning radius will be half this distance, and the turning center will be at the midpoint of the diameter.

6.6 To determine the curb clearance increment, place a straight edge horizontally across the outside face of the tire at an elevation of 150 mm above the pavement surface, and with a plumb line, locate the point on the pavement directly beneath the foremost point of contact between the straight edge and the tire shoulder. The distance from this point to the turning center is the curb clearance radius, and the difference between it and the turning radius is the curb clearance increment.

6.7 To determine the turning diameter wall to wall, drop a plumb line from the extreme outside radial extension of the vehicle and locate the point on the pavement directly beneath it. The distance thence to the turning center is the vehicle clearance radius, twice which is the turning diameter, wall to wall.

7. Graphical Determination—Alternative to the mathematical formulas and field test procedures above, determinations may be made by the graphical or draftman's method in accordance with the following procedures. Results secured by this method, like those by the mathematical method, are theoretical and may be somewhat less exact. The following graphical method is somewhat easier and more rapid.

In Fig. 5, dimensions are defined and the sequence of operations indicated by the circled numerals:

Given pivot centers (PC), offset (OS), outside wheel turning angle (OTa), and wheelbase (WB):

7.1 Draw a horizontal line representing the longitudinal centerline of the chassis.

7.2 Draw a second line perpendicular to the first line, representing the centerline of the front axle.

7.3 Locate a point on the second line a distance above the chassis centerline equal to half the distance between pivot centers (PC).

7.4 Through this point, draw a line at an angle to the front axle centerline equal to the outside front wheel turning angle (OTa).

7.5 Locate a point on this line a distance above the pivot center equal to the offset of the center of tire track (OS) from the pivot center. This is the front wheel track.

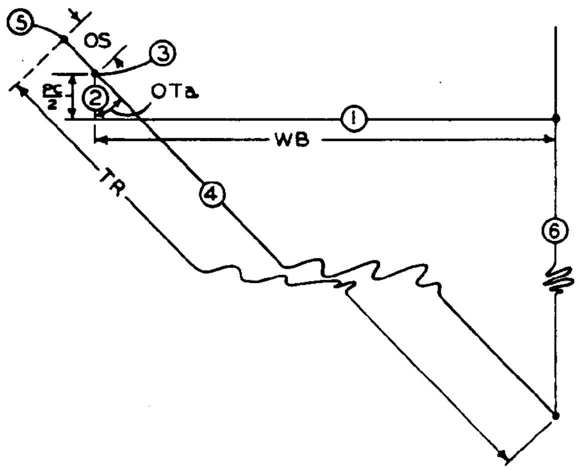


FIG. 5—GRAPHICAL PROCEDURE FOR DETERMINATION OF TURNING RADIUS

7.6 At a point on the chassis centerline, a distance from its intersection with the front axle centerline equal to the wheelbase (WB), drop a perpendicular intersecting the diagonal line from the pivot center (PC). This is the turning center (TC).

7.7 Measure the distance from this center to the point on the diagonal representing the front wheel track. This is the turning radius (TR).

OFF TRACKING

8. Definitions—See Section 2.

8.1 A typical off tracking situation for a tractor semi-trailer, including definitions, is shown in Fig. 6.

8.2 Off tracking is the difference in radii from the turning center to the vehicle centerline at the foremost and rearmost axles of a vehicle or combination and represents the increase beyond the tangent track occasioned by a turn. (See Fig. 6.)

8.3 Turning track is the radial width between centers of road contact of the outermost and innermost tires of a vehicle or combination of vehicles in negotiating a turn. In the case of dual tires, center of road contact is taken to be that midway between those of individual tires. (See Fig. 6.)

8.4 General—In addition to physical trial, there are two methods by which the amount of off tracking may be determined, namely, mathematically and graphically. These two methods were published in J695 approved October 1954 and reaffirmed without change in June 1963. Since these methods required a very good knowledge of mathematics and graphics, many fleet operators and others found these methods too cumbersome and complicated to use. In recent years, data have been developed which are accurate enough to use for all practical purposes. Therefore, the old mathematical and graphical methods have been deleted from this publication. The new method was developed by the Western Highway Institute and a detailed discussion is presented in Research Committee Report No. 3, "Off Tracking Characteristics of Trucks and Truck

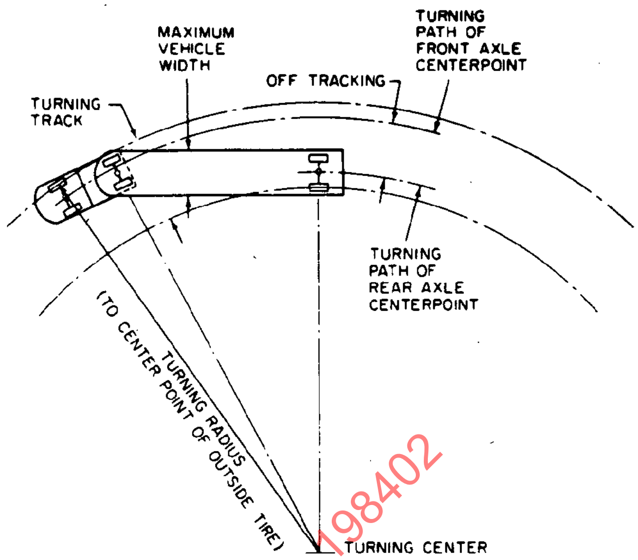


FIG. 6—TYPICAL OFF TRACKING SITUATION

Combinations." An equation in the calculation of maximum off tracking was used as the basis for off tracking distances when the radius of curve is known and the squares of the component wheelbases of a combination have been totalled. Thus, the method has become known as the "sum of the squares." It is this method, easy to calculate and simple to apply, which is recommended as a general practice.

9. Factors of Off Tracking

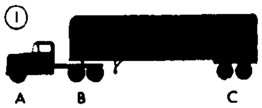
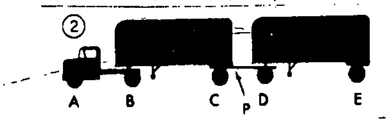
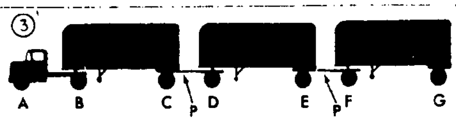
9.1 Amount of Off Tracking—The amount of off tracking varies directly with the wheelbase length of a unit and inversely with the radius of the turn through which the vehicle travels. It also varies with the degree of turn through which a vehicle travels. In this regard, it can be generally stated that the amount of off track will increase up to the point where a vehicle is negotiating a 270 deg turn. Around that point, the maximum off track will occur. The procedure given herein deals only with determining maximum off track. The magnitude of off tracking is also affected by the number and location of articulation points. There are other factors which influence the off tracking, such as the type of curve (simple, compound, reverse), speed and turning ability of the vehicle, inflation and condition of tires, and others. However, the results obtained by the method of the sum of squares are consistently in approximate agreement with results derived from actual field tests.

9.2 Negative Off Tracking—Negative off tracking results from the contra-behavior to the normal tendency on the part of the following wheels to trail inwardly from the foremost wheel as the vehicle performs a turning maneuver. Negative off tracking is the result of: (a) Rear axle overhang (rear axle to pintle hook) of a towing vehicle, or (b) stinger steering, a coupling system that shifts the point of articulation between towing and towed units from the pintle hook position rearward by means of a rod or "stinger" attached to the towing unit.

9.3 Axle Intervals and Hitch Distances—For the determination of off tracking of single or combination units, it is necessary only to measure the spacing between axles or axle groups (wheelbase) and hitch distances. This distance or wheelbase is identified in the case of three-axled vehicles as the distance from the front axle center to a point midway between the two rear axles. For this purpose, the front axle or axle group (either of a single unit or of the towing unit) is identified by the letter A, the second by B, the third by C, etc. The letter P represents hitch points, normally the pintle hook in a combination having two or more cargo units but, alternatively any point of articulation other than the pintle hook. Thus, the component distances for purpose of determining maximum off tracking for a tractor semi-trailer, with a full trailer, shown as vehicle No. 2 in Table 1, are axle distance AB, BC, and DE and the axle-to-pintle-hook distance CP and the pintle-hook-to-axle (or towbar) PD.

9.4 Determination of Off Tracking—Table 1 demonstrates the method of determining maximum off tracking for four typical vehicles. Any one of the four vehicles shown in Table 1 would serve as well as

TABLE 1—INTERIOR DIMENSIONS OF ILLUSTRATIVE VEHICLES AND MAXIMUM OFFTRACKING VALUES FROM FIG. 7 OR TABLE 2

(1) Illustrative Vehicles	(2) Measurement	Wheelbase[a] (3) ft-in	Wheelbase[a] (4) Decimal ft (m)	(5) Wheelbase Squared ft²(m²)	(6) Sum of Squares of Wheelbases ft²(m²)	Maximum Off Tracking—ft(m) if Radius of Curve is: (7) 50 ft (15.24) (m)	(8) 75 ft (22.86) (m)	(9) 120 ft (36.58) (m)	(10) 165 ft (50.29) (m)	(11) 250 ft (76.20) (m)
OAL = 55 ft (16.76m) ① 	AB	17—0	17.00 (5.18)	289.00 (26.85)						
	BC	31—2	31.17 (9.50)	971.38 (90.24)	1260 (117.05)	16.6 (5.06)	9.5 (2.90)	5.5 (1.68)	3.9 (1.19)	2.6 (0.79)
OAL = 65 ft (19.81m) ② 	AB	10—0	10.00 (3.05)	100.00 (9.29)						
	BC	20—2	20.17 (6.15)	406.71 (37.78)						
	CP[b]	−2—6	−2.50 (−0.76)	−6.25 (−0.58)						
	PD	6—0	6.00 (1.83)	36.00 (3.34)						
	DE	21—6	21.50 (6.55)	462.25 (42.94)	999 (92.81)	12.6 (3.84)	7.4 (2.26)	4.4 (1.34)	3.1 (0.95)	2.0 (0.61)
OAL = 95 ft (28.96m) ③ 	AB	10—0	10.00 (3.05)	100.00 (9.29)						
	BC	20—2	20.17 (6.15)	406.71 (37.78)						
	CP	−2—6	−2.50 (−0.76)	−6.25 (−0.58)						
	PD	6—0	6.00 (1.83)	36.00 (3.34)						
	DE	21—6	21.50 (6.55)	462.25 (42.94)						
	EP	−2—6	−2.50 (−0.76)	−6.25 (−0.58)						
	PF	6—0	6.00 (1.83)	36.00 (3.34)						
	FG	21—6	21.50 (6.55)	462.25 (42.94)	1491 (138.51)	21.5 (6.55)	11.6 (3.54)	6.7 (2.04)	4.8 (1.46)	3.1 (0.95)
OAL = 100 ft (30.48m) ④ 	AB	17—9	17.75 (5.41)	315.06 (29.27)						
	BC	33—3	33.25 (10.14)	1105.56 (102.71)						
	CP[b]	−4—0	−4.00 (−1.22)	−16.00 (−1.49)						
	PD	7—1	7.08 (2.16)	50.17 (4.66)						
	DE	31—10	31.83 (9.70)	1013.34 (94.14)	2468 (229.28)	[c]	19.2 (5.85)	11.1 (3.38)	7.8 (2.38)	5.0 (1.52)

[a] Wheelbase, rear axle to pintle hook, or pintle hook to front axle or bogie.
[b] P denotes pintle hook.
[c] This value is beyond Fig. 7 and Table 2. Off track of over 60 ft could be expected, indicating the vehicle is pivoting around the rear axle group rather than making a free rolling turn.

any other to demonstrate the ease with which Fig. 7 or Table 2 may be used in obtaining a close estimate of maximum off tracking. For vehicle No. 2, the sum of the squares of the wheelbases and hitch distance is 999, as shown in column 6. This figure is the total of the five entries in column 5 for this vehicle. It is the algebraic sum of the squares of those five entries. The sum is described as algebraic because it includes the negative effect on off tracking produced by the rearward sweep of the pintle hook behind the rear axle of the first trailer. Its effect is the same, in general character, as that produced by location of the kingpin in a position forward of the tractor rear axle. Normally the kingpin offset varies 8–16 in, and its effect on the off tracking result is minimal. For practical purposes, it may be then assumed that the kingpin is centered over the tractor rear axle or trunnion in case of a tandem and no negative off tracking is involved here. Because of that, no point P need be considered when working with a coupling assumed to be directly over an axle or axle group like at a fifth wheel such as is found on a tractor-semitrailer. Whereas column 3 shows the wheelbase in feet and inches, these must be converted to decimal feet shown in column 4. The figures (decimal feet) shown in column 4 are squared and are shown in column 5. when the squares of the wheelbase (column 5) are totaled (column 6), reference is made either to Fig. 7 or Table 2. For vehicle No. 2, the chart is entered at 999 (1000 for all practical purposes) on the horizontal or sum-of-the-square scale on Fig. 7 and the off tracking read on the vertical scale. On a 50 ft radius, the off tracking is 12.6 ft. This same reading is obtained by using Table 2.