

Turning Ability and Off Tracking—  
Motor Vehicles —  
SAE J695 SEP82

SAE Recommended Practice  
Last Revised September 1982

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# TURNING ABILITY AND OFF TRACKING— MOTOR VEHICLES—SAE J695 SEP82

## SAE Recommended Practice

Report of the Truck and Bus Technical Committee, approved October 1954, last revised by the Truck and Cab Occupant Committee September 1982.

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 and to which all wheel spindles are normally radial. In the case of two-axled bogies or tandems in which the axles are constrained to parallelism, the interaxle trunnion or its equivalent is assumed to be radial from this point. (See Fig. 1.)

2.2 **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. 7.)

2.3 **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.)

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

2.5 **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.)

2.6 **Turning Diameter—Curb to Curb** is the diameter of the smallest circle within which the vehicle will clear a curb 6 in 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 6 in above the surface on which the tire rests. (See Fig. 1.)

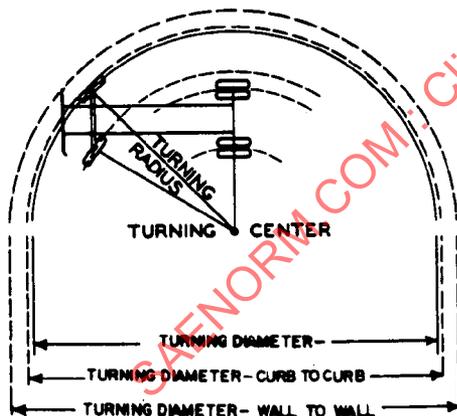


FIG. 1

3. **Determinations**—The following determinations, based on Ackerman steering geometry (see Fig. 1) may be made mathematically as explained in detail hereafter:

3.1 Correct wheelbase for a given axle configuration.

3.2 Turning diameter with a given wheelbase and front axle configuration.

3.3 Configuration required to provide a given turning diameter.

3.4 Correct cross steering lever angles for given wheelbase, pivot centers.

3.5 Curb clearance increment.

4. **Factors of Front Axle Configuration**—Basic to the Ackerman steering system is the assumption that the cross steering levers are at such angle to the centerline of the chassis that, with the front wheels in the straight ahead position, their pivot centers will fall on horizontal lines drawn from the knuckle pivot centers to the center of the rear axle.<sup>1</sup> (See Fig. 3.) We have therefore to deal with the following factors shown in Figs. 2 and 3:

<sup>1</sup> In the case of multi-axled vehicles, the wheelbase is measured to the trunnion or mid-point between axles of a bogie or tandem.

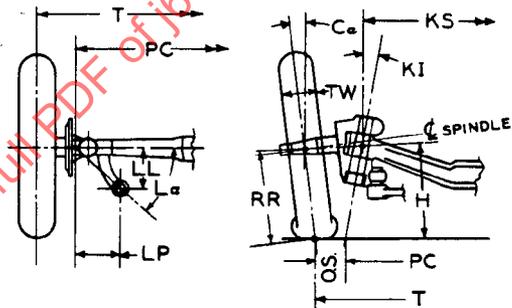


FIG. 2—DIAGRAM ILLUSTRATING FACTORS OF FRONT AXLE CONFIGURATION

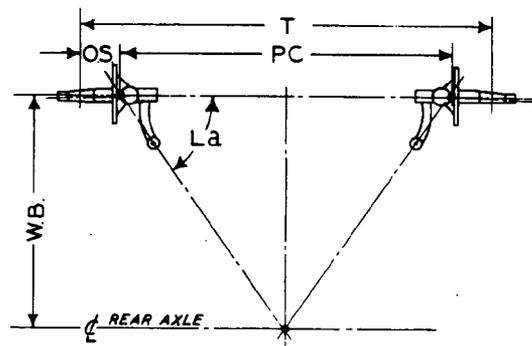


FIG. 3—BASIC ACKERMAN DIAGRAM

The  $\phi$  symbol is for the convenience of the user in locating areas where technical revisions have been made to the previous issue of the report. If the symbol is next to the report title, it indicates a complete revision of the report.

PC—Distance between knuckle pivot centers (true)  
 T—Track of tires at ground  
 OS—Offset, pivot center to track of tire on ground  
 Ca—Camber angle of wheel, loaded  
 KI—Kingpin inclination from vertical  
 KS—Kingpin spacing  
 TW—Tire width  
 WB—Wheelbase<sup>1</sup>  
 LL—Cross steering lever length  
 LP—Cross steering lever position  
 La—Cross steering lever angle from axle centerline (true)  
 RR—Rolling radius of tire  
 Ta—Turning angle (see Fig. 4)  
 ITa—Inside wheel turning angle (see Fig. 4)  
 OTa—Outside wheel turning angle (see Fig. 4)  
 H—Height of center of kingpin from ground, loaded  
 C—Curb contact length (see Fig. 5)

from which to determine:

TR—Turning radius (Fig. 1)  
 R—Radius to pivot center for correct wheelbase<sup>1</sup> (Fig. 4)  
 RS—Radius to pivot center for shorter than correct wheelbase<sup>1</sup> (Fig. 4)  
 RL—Radius to pivot center for longer than correct wheelbase<sup>1</sup> (Fig. 4)  
 CR—Radius to curb (Fig. 5)  
 CI—Curb clearance increment (Fig. 5)

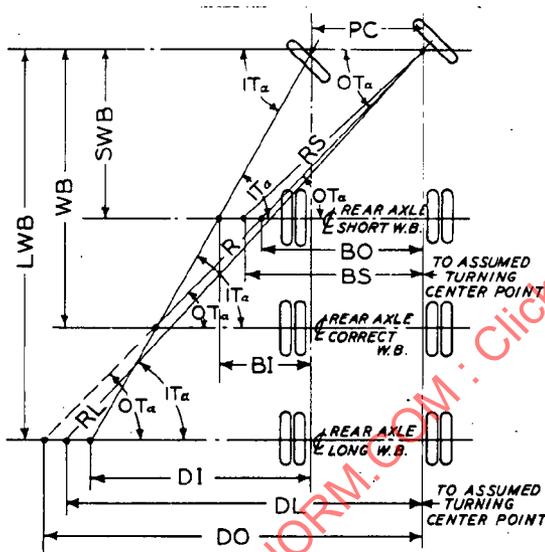


FIG. 4—DIAGRAM ILLUSTRATING EFFECT OF WHEELBASE ON TURNING RADIUS WITH A GIVEN FRONT AXLE CONFIGURATION

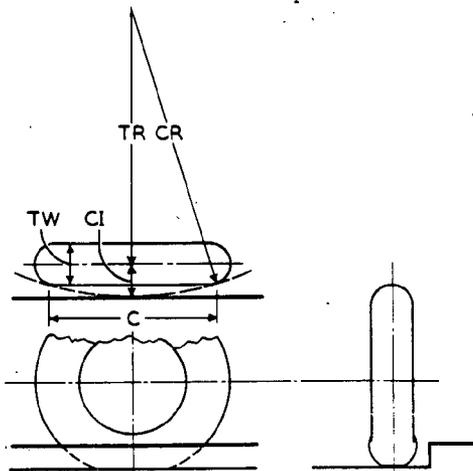


FIG. 5—CURB CLEARANCE DIAGRAM

## 5. Formulas

5.1 To determine the correct wheelbase<sup>1</sup> for a given front axle configuration:

5.1.1 From front axle layout (see Figs. 2 and 3) establish PC and La.

$$5.1.2 \quad WB = \frac{PC \times \tan La}{2}$$

5.2 To determine turning diameter with a given wheelbase and front axle configuration (see Fig. 4):

5.2.1 With correct wheelbase<sup>1</sup>:

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

5.2.2 With wheelbase<sup>1</sup> shorter than correct:

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

5.2.3 With wheelbase<sup>1</sup> longer than correct:

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

6. To determine configuration required to provide a given turning diameter (see Fig. 4).

6.1 Given pivot centers (PC), offset (OS), and wheelbase<sup>1</sup> (WB), to find the turning angle necessary to outside front wheels:

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

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

6.2 Given offset (OS) and turning angle (Ta) of outside front wheel, to find the necessary wheelbase<sup>1</sup> (see Fig. 4):

$$WB = \left( \frac{TC}{2} - OS \right) \sin OTa$$

7. To determine correct cross steering lever angles for a given wheelbase<sup>1</sup> and pivot-centers (see Fig. 4):

Given wheelbase<sup>1</sup> (WB) and pivot centers (PC), to find the correct cross steering lever angle (La):

$$La = \arctan \left( \frac{2 WB}{PC} \right)$$

Cross steering lever ball studs should fall on the angle lines drawn from the pivot center points to the center of the rear axle.

8. To determine curb clearance increment to turning radius or turning circle (see Fig. 5):

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

## NOTES:

1. It is customary to measure the wheelbase of three-axled vehicles from the front axle center to a point midway between the two rear axles, or the trunnion of the bogie or tandem or its equivalent and to consider the center of a transverse line through this point as the equivalent of the center of the rear axle of a two-axled vehicle.

However, tests have shown that the true location of a radius tangent to the turning diameter, equivalent to the centerline of a single rear axle, is somewhat further to the rear than midway between the axles, depending upon whether the tire equipment be single or dual and upon the load distribution between the two rear axles.

2. Equal slippage of both front wheels is assumed, so that 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.

Owing to vagaries in other geometric influences and the greater ground pressure on the outer wheel, due to centrifugal force, the true turning center will actually lie closer to the outer intersection than to the inner.

9. **Field Test Procedure**—Physical testing of vehicles to determine actual turning radius or turning diameter procedure is as follows:

9.1 Check steering geometry and correct, if necessary.

9.2 Check the front wheel cut angles to manufacturer's recommendations. Wheel stops should be so set that the minimum clearance between

the tire and the nearest point of interference is  $\frac{3}{4}$  in. 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.

9.3 Load the vehicle to the maximum recommended gross weight.

9.4 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.

9.5 For 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.

9.6 For the curb increment, place a straightedge horizontally across the outside face of the tire at an elevation of 6 in above the pavement surface and with a plumb line locate the point on the pavement directly beneath the foremost point of contact between the straightedge 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.

9.7 For 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.

10. **Graphical Determination**—Alternative to the mathematical formulas and field test procedures above, determinations may be made by the graphical or draftsman's method in accordance with the following procedure. Results secured by this method, like those by the mathematical method, are theoretical. They may also be somewhat less exact; but the error will be minute. The graphical method is somewhat easier and more rapid.

In Fig. 6, 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):

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

10.2 Draw a perpendicular to this line, representing the centerline of the front axle.

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

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

10.5 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.

10.6 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).

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

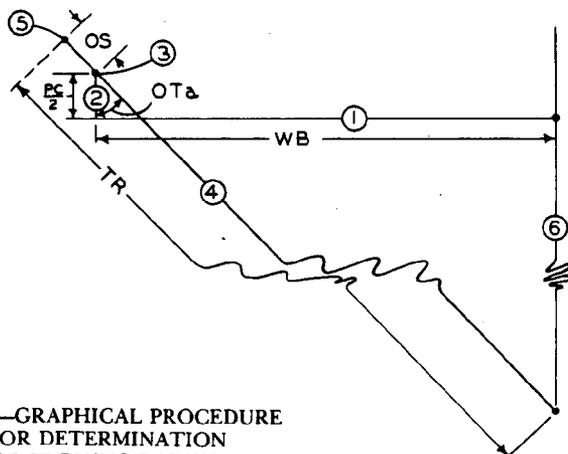


FIG. 6—GRAPHICAL PROCEDURE FOR DETERMINATION OF TURNING RADIUS

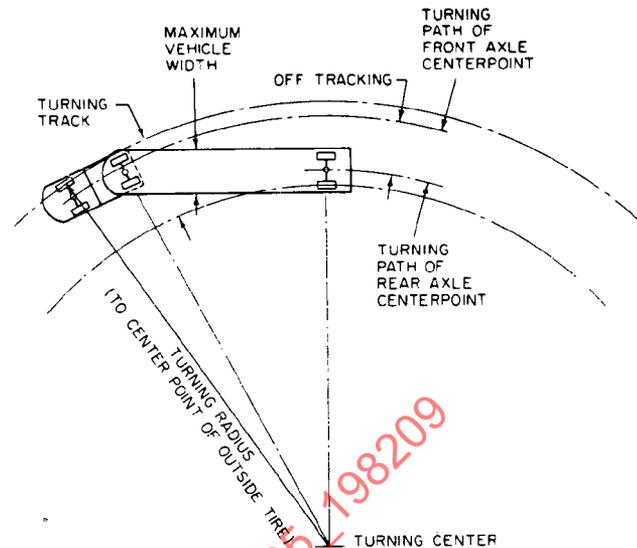


FIG. 7—TYPICAL OFF TRACKING SITUATION

## OFF TRACKING

11. **Definitions**—See paragraph 2.

11.1 **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. 7.)

From a practical standpoint, off tracking determinations are used principally in connection with highway curves and turns of known radius or tangent, such as to be encountered in a projected operation or in the design of roadways of various kinds.

11.2 **General**—In addition to physical trial, there are two methods by which the amount of off tracking may be determined, namely, mathematically and graphically. Ordinarily, the mathematical and graphical methods require a very good knowledge of mathematics and graphics. These two methods have been published in SAE J695 approved October 1954 and reaffirmed without change in June 1963. However, many fleet operators and others found these methods too cumbersome and complicated to use. In recent years, there have been developed data which are accurate enough to use for all practical purposes. The 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 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 totaled. 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.

## 12. Factors of Off Tracking

12.1 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.

12.2 **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.

φ TABLE 1—INTERIOR DIMENSIONS OF ILLUSTRATIVE VEHICLES AND MAXIMUM OFF TRACKING VALUES FROM FIG. 8 OR TABLE 2

(1) Illustrative Vehicles	(2) Measurement	Wheelbase <sup>a</sup>		(5) Wheel- base Squared	(6) Sum of Squares of Wheel- bases	Maximum Off Tracking (in ft) If Radius of Curve is				
		(3) ft-in	(4) decimal ft			(7) 50 ft	(8) 75 ft	(9) 120 ft	(10) 165 ft	(11) 250 ft
①  OAL = 55 ft	AB	17-0	17.000	289.00	1260	16.6	9.5	5.5	3.9	2.6
	BC	31-2	31.167	971.38						
②  OAL = 65 ft	AB	10-0	10.000	100.00	999	12.6	7.4	4.4	3.1	2.0
	BC	20-2	20.167	406.71						
	CP <sup>b</sup>	-2-6	-2.500	-6.25						
	PD	6-0	6.000	36.00						
	DE	21-6	21.500	462.25						
③  OAL = 95 ft	AB	10-0	10.000	100.00	1491	21.5	11.6	6.7	4.8	3.1
	BC	20-2	20.167	406.71						
	CP <sup>b</sup>	-2-6	-2.500	-6.25						
	PD	6-0	6.000	36.00						
	DE	21-6	21.500	462.25						
	EP <sup>b</sup>	-2-6	-2.500	-6.25						
	PF	6-0	6.000	36.00						
	FG	21-6	21.500	462.25						
④  OAL = 100 ft	AB	17-9	17.75	315.06	2468	c	19.2	11.1	7.8	5
	BC	33-3	33.25	1105.56						
	CP <sup>b</sup>	-4-0	-4.0	-16.00						
	PD	7-1	7.083	50.17						
	DE	31-10	31.833	1013.34						

<sup>a</sup> Wheelbase, rear axle to pintle hook, or pintle hook to front axle or bogie.

<sup>b</sup> P denotes pintle hook.

<sup>c</sup> This value is beyond Fig. 8 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.

**12.3 Axle Intervals and Hitch Distances**—For the determination of off tracking of single or combination units it is necessary only to measure φ the spacing between axles or axle groups 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.

**12.4 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 any other to demonstrate the ease with which Fig. 8 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

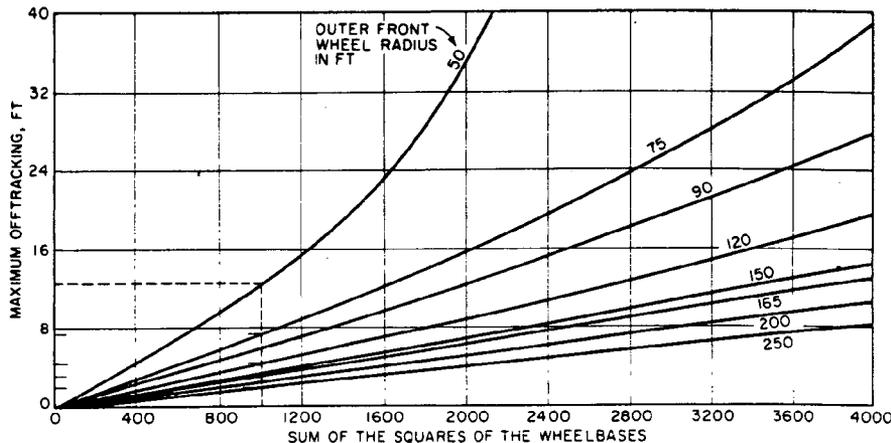


FIG. 8—MAXIMUM OFF TRACKING OF VEHICLES ACCORDING TO SUM OF SQUARES OF THEIR COMPONENT WHEELBASES, FOR VARIOUS SELECTED CURVE RADII