SURFACE VEHICLE RECOMMENDED PRACTICE	J695™	JAN2024
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Turning Ability and Off Tracking - Motor Vehicles

RATIONALE

This document has been updated to correct an inconsistency in Equation 8, which is related to Figure 4. Also, Title of Figure 1, Title of Section 9, and References in Section 2 have been updated to make it more consistent with current SAE Standard formats.

1. SCOPE

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

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest version of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE SP-0374 The Truck Steering System from Hand Wheel to Road Wheel

2.1.2 Other Publications

WHI RCR.3 Western Highway Institute, Research Committee Report No. 3, "Offtracking Characteristics of Trucks and Truck Combinations," San Francisco, CA, 1970.

3. DEFINITIONS

3.1 TURNING CENTER

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 Figure 1).

3.2 TURNING DIAMETER

Twice the turning radius (see Figure 1).

3.3 TURNING DIAMETER - CURB-TO-CURB

3.4 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 Figure 1).

3.5 TURNING DIAMETER - WALL-TO-WALL

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 Figure 1).

3.6 TURNING RADIUS

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 Figure 1).

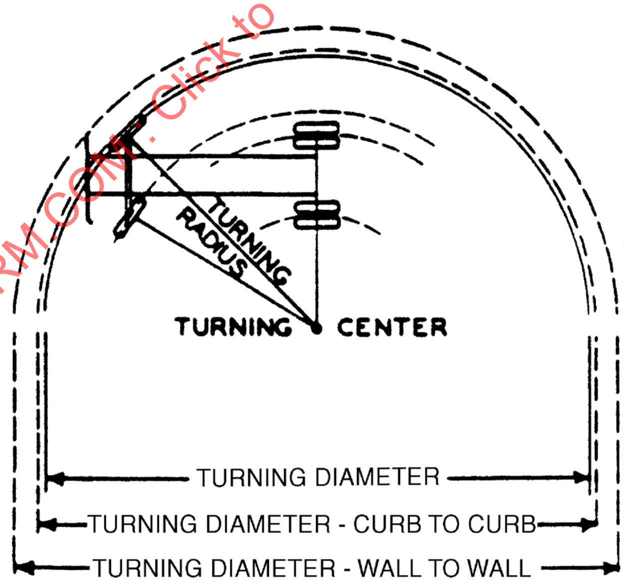

Figure 1 - Diagram illustrating turning diameter of a vehicle

4. DETERMINATIONS

The following determinations, based on Ackerman steering geometry (see Figures 2 and 3), may be made mathematically as explained in detail as follows:

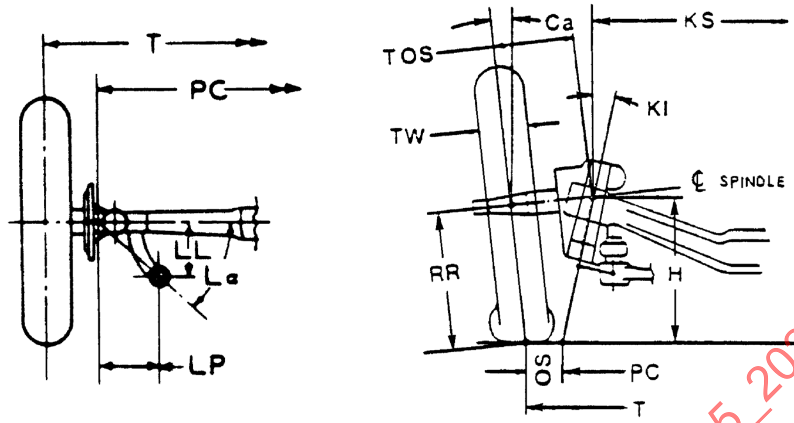

Figure 2 - Diagram illustrating factors of front axle configuration

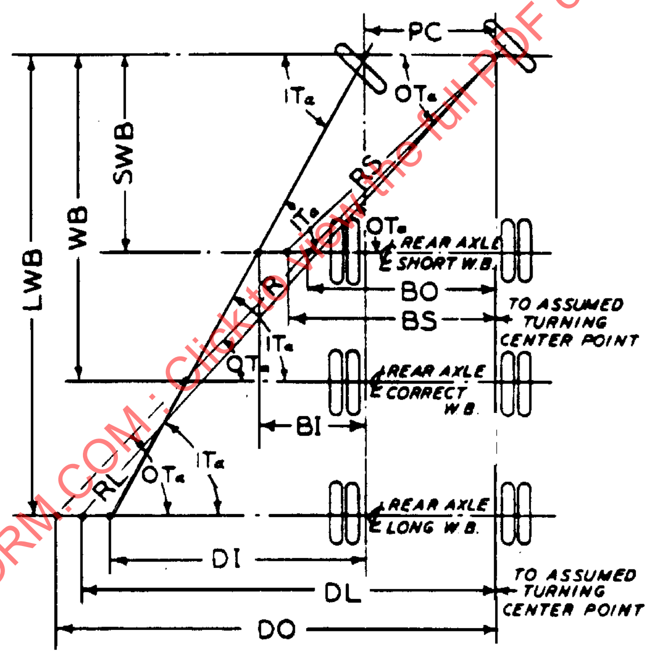

Figure 3 - Diagram illustrating effect of wheelbase on turning radius with a given front axle configuration

4.1 Turning diameter[1] with a given wheelbase[2] and front axle configuration.

4.2 Configuration required to provide a given turning diameter[1].

4.3 Curb clearance increment (see Figure 4).

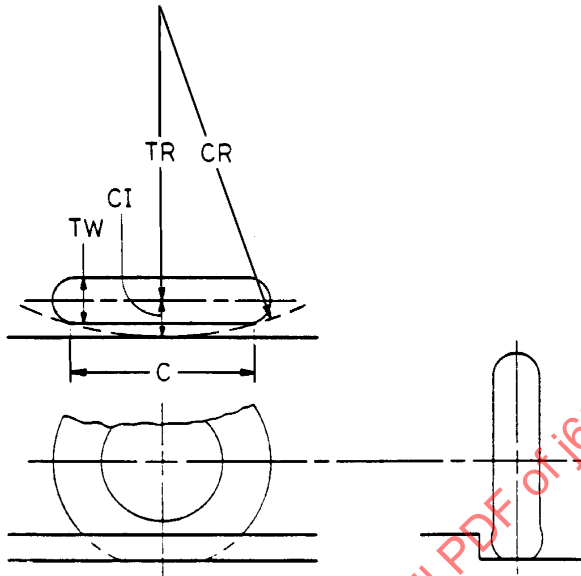

Figure 4 - Curb clearance diagram

5. FACTORS OF FRONT AXLE CONFIGURATION

TR - Turning radius (see Figure 1)

TD - Turning diameter

T - Track of tires at ground (see Figure 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

KS - Kingpin spacing

TW - Tire width

[1] At the maximum turning angle, there is normally Ackerman geometry error between the front wheels that can be described as shown in Equation 4 or Equation 5. 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.

[2] 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 that 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 on 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.

WB - Wheelbase[3]

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 Figure 3)

OTa - Outside wheel turning angle (see Figure 3)

H - Height of center of kingpin from ground (loaded)

R - Radius to pivot center for correct wheelbase (see Figure 3)

RS - Radius to pivot center for shorter than correct wheelbase (see Figure 3)

RL - Radius to pivot center for longer than correct wheelbase (see Figure 3)

C - Curb contact length (see Figure 4)

CR - Curb clearance radius (see Figure 4)

CI - Curb clearance increment (see Figure 4)

TOS - Tire offset measured along spindle centerline

6. FORMULAS

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

$$PC = KS + 2\,(RR\cos Ca + TOS\sin Ca)\;x\tan KI \quad \text{(Eq. 1)}$$

For small measures of camber angle of wheel, loaded, the formula for pivot centers can be simplified with little loss of accuracy to:

$$PC = KS + 2\,RR\;x\tan KI \quad \text{(Eq. 2)}$$

6.2 To determine turning diameter[4] with a given wheelbase[5] and front axle configuration (see Figure 3):

6.2.1 With correct wheelbase[5]:

$$TD = 2\left(\frac{WB}{sinOTa} + OS\right) \quad \text{(Eq. 3)}$$

6.2.2 With wheelbase shorter than correct (SWB):

$$TD = \sqrt{4SWB^2 + \left(\frac{SWB}{tanOTa} + PC + \frac{SWB}{tanITa}\right)^2} + 2OS \quad \text{(Eq.4)}$$

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[3] See Footnote 2.
[4] See Footnote 1.
[5] See Footnote 2.

6.2.3 With wheelbase longer than correct (LWB):

$$TD = \sqrt{4LWB^2 + \left(\frac{LWB}{tanOTa} + PC + \frac{LWB}{tanITa}\right)^2} + 2OS \quad \text{(Eq. 5)}$$

6.3 To determine configuration required to provide a given turning diameter (see Figure 3):

6.3.1 Given pivot centers, offset, and wheelbase[6], to find the turning angle necessary to front wheels:

$$OTa = \arcsin\left(\frac{WB}{\frac{TD}{2} - OS}\right) \quad \text{(Eq. 6)}$$

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

6.3.2 Given offset and turning angle of outside front wheel, to find the necessary wheelbase (see Figure 3):

$$WB = \left(\frac{TD}{2} - OS\right)\sin OTa \quad \text{(Eq. 7)}$$

6.4 To determine curb clearance increment to turning radius (see Figure 4):

$$CI = \sqrt{\left(TR + \frac{TW}{2}\right)^2 + \left(\frac{C}{2}\right)^2} - TR \quad \text{(Eq. 8)}$$

6.5 To determine correct cross steering lever configuration for a given wheelbase[5] and pivot centers (see Figure 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.

A detailed graphical method may be found in Appendix 1 of SAE SP-0374.

7. FIELD TEST PROCEDURE

7.1 Check steering geometry alignment and correct, if necessary.

7.2 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.

7.3 Load the vehicle to the maximum recommended gross weight.

7.4 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] See Footnote 2.

7.5 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. The turning radius will be half this distance, and the turning center will be at the midpoint of the diameter.

7.6 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.

7.7 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.

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

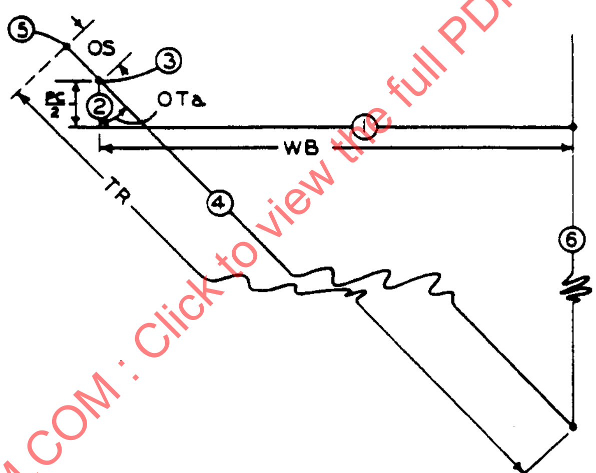

Figure 5 - Graphical procedure for determination of turning radius

Given pivot centers, offset, outside wheel turning angle, and wheelbase:

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

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

8.3 Locate a point on the second line a distance above the chassis centerline equal to half the distance between pivot centers.

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

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

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

8.7 Measure the distance from this center to the point on the diagonal representing the front wheel track. This is the turning radius.

9. DEFINITIONS FOR OFF TRACKING

9.1 A typical off tracking situation for a tractor semitrailer, including definitions, is shown in Figure 6.

9.2 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 Figure 6).

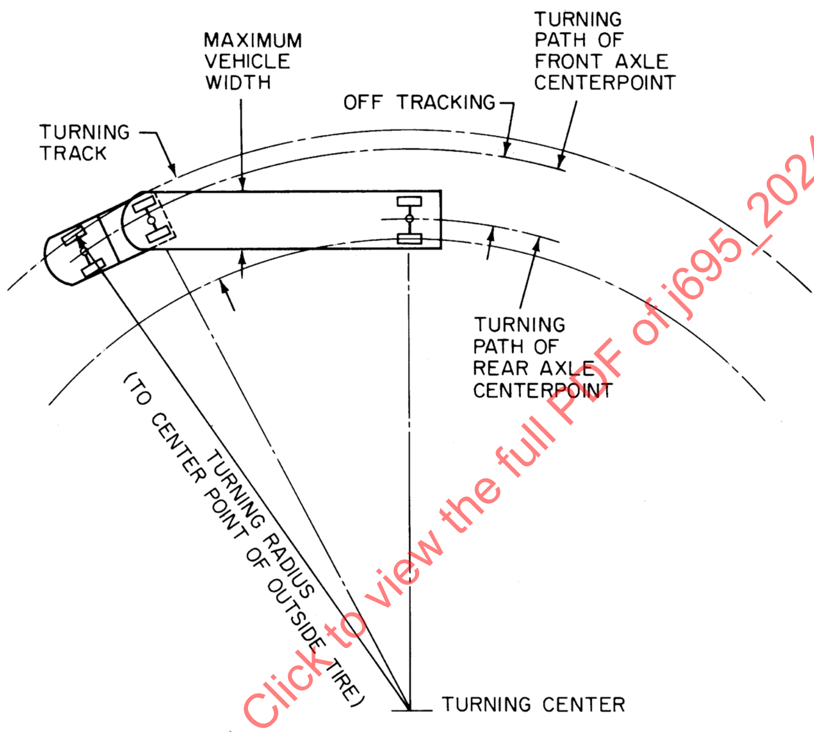

Figure 6 - Typical off tracking situation

9.3 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 Figure 6).

9.4 General

In addition to physical trials, there are two methods by which the amount of off tracking may be determined, namely, mathematically and graphically. These two methods were published in SAE 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 graphic methods have been deleted from this publication. The new method was developed, and a detailed discussion is presented in WHI RCR.3. 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.

10. FACTORS OF OFF TRACKING

10.1 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-degree 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 that influence the off tracking, such as the type of curve (simple, compound, or 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.

10.2 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.

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.

10.3 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 the purpose of determining maximum off tracking for a tractor semitrailer, 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.

10.4 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 Figure 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 to 16 inches, 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, as 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 Figure 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 Figure 7 and the off tracking read on the vertical scale. On a 50-foot radius, the off tracking is 12.6 feet. This same reading is obtained by using Table 2.