Determination of Oversized Vehicle Tracking Patterns by Adjustable Scale Model

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This paper presents a method for determining maneuverability patterns of oversized highway vehicles, and evaluates present methods and formulas used to compute these patterns. It is suggested that an adjustable scale model capable of tracing all points influencing the lateral space requirements of turning highway vehicles may be of use during the establishment of vehicle routing plans, widths of channelized intersections, and critical vehicle dimensions.

It is believed that the scale model described herein may show great savings in both time and money when vehicle characteristics of the sort determined only by the configuration of the vehicle are desired.

• MUCH CONCERN has been given to providing safe, convenient, and economic movement of the automotive vehicle since the advent of this form of transportation. During the past decade, highway transport has become more and more widely used and accepted; vehicles have become larger; and highway facilities have increased accordingly.

Vehicle characteristics are a basic element of highway transportation; therefore, the highway engineer should know the operating characteristics of vehicles using existing highways and of vehicles expected to operate on proposed and future highway networks. Much work has been done in determining optimum vehicle size; the most feasible highway design criteria have been established to meet these vehicle requirements. About 10 years ago, the C-50 design vehicle, a 50-ft tractor-semitrailer combination, was proposed by several competent agencies to establish minimum design standards on high-type roadways. This vehicle was accepted and is now used as the largest vehicle permitted to operate in the majority of states. An increasing need is now arising for moving large and outsized equipment that requires oversized transporters larger than the optimum vehicle, the C-50. When these large transporters are moved over present highway systems, special permission is required from state and local authorities; and, since highways are not designed to accommodate them, special routing must be planned to provide for the safe and convenient flow of traffic. Furthermore, roadway design criteria must be established to facilitate efficient movement in and around such areas as construction sites, missile sites, or various maneuver areas used by the Armed Forces.

TRANSPORTATION CORPS' RESPONSIBILITY

The Army Transportation Corps is responsible for transporting personnel, equipment, and supplies for the Department of the Army and for the Department of Defense, when required. Many of these items require rather large and nonstandard carrier vehicles. Therefore, the Transportation Corps must determine the compatibility of these carriers with existing transportation modes and facilities and the alterations and adjustments that must be made either to the item or to the transportation system, or to both, to allow for adequate, safe, and economical movement. In addition to this basic responsibility, the Department of Defense has designated the Chief of Transportation as its official representative for coordinating the defense transportation interest in public highways and for integrating the foreseen highway needs and operational requirements of the Department of Defense into the highway programs of the United States, its territories, and its possessions. In carrying out this responsibility, the Chief of Transportation must be prepared to advise the Bureau of Public Roads, the American Association of State Highway Officials, and other governmental agencies as to the adequacy of highway design criteria used for proposed highways intended to serve the national defense. This function was delegated to the Assistant Chief of Transportation for Transportation Engineering, who was to find a basis for recommending feasible routing plans, highway design criteria, and vehicle design policy so as to facilitate efficient movement in an emergency or in a peacetime situation. This requirement was put in the form of a project and assigned to the Transportation Engineering Office, U. S. Army Transportation Research Command (USATRECOM), Fort Eustis, Va., a field support agency for the Assistant Chief of Transportation for Transportation Engineering.

PROBLEM AREA

Many unexpected situations arise when large items of equipment are moved over highway networks. Roadways that were not laid out according to any predetermined geometric pattern may have to be used. Therefore, design criteria used by various highway departments will not be sufficient to estimate the size and shape of vehicles these highways will accommodate. In many cases, travel through towns will be unavoidable, and turns that vehicles cannot negotiate without encroaching on opposing traffic lanes may be encountered. Obstructions may be met that will not allow vehicles carrying a load with peculiar overhang to pass in one motion. In this case, traffic will be interrupted with a possible detrimental effect on cargo as well as on approaching traffic. If these conditions could be anticipated, plans could be made to bypass such obstructions, or possibly to arrange for escort and control of traffic by local authorities.

To plan correctly the movement of oversized vehicles over present highway systems, several factors must be analyzed. Two of these factors are most important to the highway engineer: (a) He must know the physical characteristics of the highway on which he wishes to move the item of equipment (this information is normally available from local authorities, or may be obtained by aerial reconnaissance); and (b) He must know the limitations and capabilities of the vehicles he wishes to operate. Some work has been accomplished in this area, but it is believed that considerable research should be done to determine the necessary correlation between highway design criteria and vehicle operating characteristics to provide for more efficient highway transportation.

MANEUVERABILITY ANALYSIS

When the use of oversized vehicles is contemplated, a complete study of the vehicle maneuverability characteristics should be made before routing plans are completed. This study should include such things as minimum turning radius, vehicle off-tracking, and the effect of overhang.

Minimum turning radius is the distance measured from the turning center to the outside edge of the tire scribing the largest circle while the vehicle is executing its sharpest possible turn. This distance is usually given in the performance specification for any vehicle, or it may be computed from wheel base and cramping angle.

Off-tracking is the difference in the path of the inside front wheel and of the inside rear wheel as a vehicle or combination vehicle negotiates a curve. The amount of off-track varies directly with the length of the wheel base of a single-unit vehicle and inversely with the radius of curvature. When a combination unit, such as a tractor-semitrailer or a tractor-full trailer, is used, the off-tracking of the combination unit is a composite that may be less than the sum of the off-tracking of the individual single units. An important advantage of a combination vehicle is that the off-tracking is considerably less than the off-tracking of a single-unit vehicle of the same total wheel base. Ordinarily, off-tracking becomes a problem in connection with combination vehicles. This is the area that is extremely complex and that is of prime importance to the highway engineer as well as to the vehicle designer.

Overhang is any protrusion outside the normal dimension of a vehicle. This protrusion could substantially affect the over-all tracking trace and could therefore influence routing as well as the placement of obstructions, such as signs and fences, during the preliminary layout of facilities.

Of these governing criteria, only the minimum turning radius is available for the majority of vehicles. The remaining critical data may be obtained by one or a combination of actual vehicle tests, mathematical equations, or scale model tests.

FIELD TESTS

To perform efficiently an actual vehicle maneuverability test, it is evident that several basic factors must be present simultaneously: the required vehicle, the technically trained men, and a suitable test area. In many cases, one, or possibly two, of these critical factors may not be available. For instance, routing plans may be submitted for approval to a state highway commission that has no access to either a test area or the required test vehicle. In this case, the commission should send qualified personnel to the vehicle location, or should require that appropriate maneuverability test results be forwarded to them. Either of these alternatives would be very expensive and time consuming.

MATHEMATICAL DETERMINATIONS

It is accepted that certain basic equations exist for determining the trace of points on a single-unit vehicle negotiating critical turns. These equations neglect such variables as tire slip, superelevation of the roadway, tire pressure, and oversteering or understeering, since these factors are largely unpredictable and are of little consequence if low speed and minimum turning radii are used. Vehicles using various types of steering arrangements require equations based on individual linkage systems.

The Ackerman system of steering is by far the most commonly used on highway vehicles. In effect, this system consists of a rigid front axle with pivoting wheels at either end. These wheels are deflected by the rotation of a steering wheel connected to a shaft, which transposes sufficient force through a linkage system to cause a deflection of the front wheels. The minimum turning radius for vehicles using this type of steering may be computed by geometric relationships (Fig. 1) resulting in the following:

$$R=\sqrt{\left(\frac{w}{\sin\alpha}\right)^2+b^2+\left(\frac{2wb}{\tan\alpha}\right)}+d \qquad (1)$$

in which

R = minimum turning radius (measured to outside front wheel);

w = wheel base;

b = distance between knuckle pivot axis;

α = maximum angle through which the inside front wheel can be deflected from the straight-ahead position;

d = distance from the intersection of the front wheel axis with the knuckle pivot axis to the center plane of the front wheels.

Although the Ackerman system of steering is used in practically all vehicles, a so-called "fifth-wheel steering" does exist. This method is employed by the use of an articulating front axle that pivots about a point at the intersection of the axle and the centerline of the vehicle (Fig. 2). The minimum turning radius

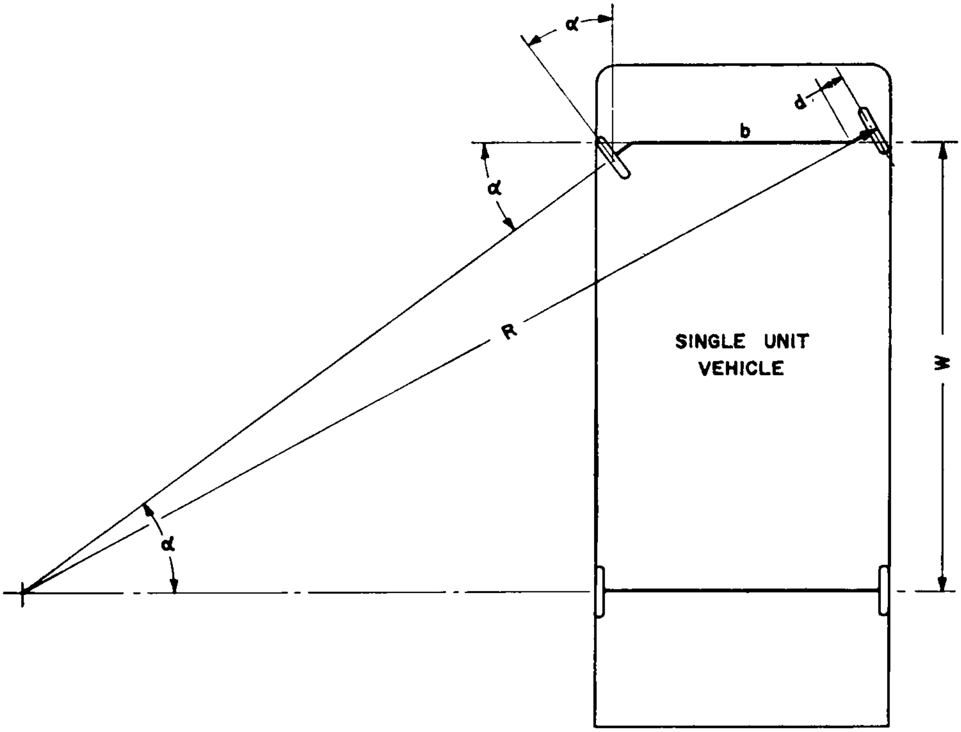

Figure 1. Turning radius diagram.

for vehicles using this type of steering may be computed by geometery and

$$R = r + \tfrac{1}{2}w \qquad (2)$$

$$\cos 90 - \theta = \frac{L}{r} \qquad (3a)$$

$$r = \frac{L}{\cos 90 - \theta} \qquad (3b)$$

$$R = \left(\frac{L}{\cos 90 - \theta}\right) + \tfrac{1}{2}w \qquad (4)$$

in which

R = minimum turning radius;

L = wheel base;

θ = maximum angle through which the front wheels can be deflected from the straight-ahead position;

w = distance between outside points on front wheels;

r = radius of circle traced by center of front axle.

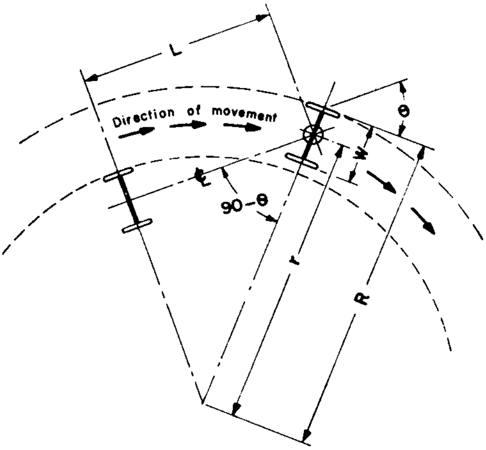

Figure 2. Fifth-wheel steering.

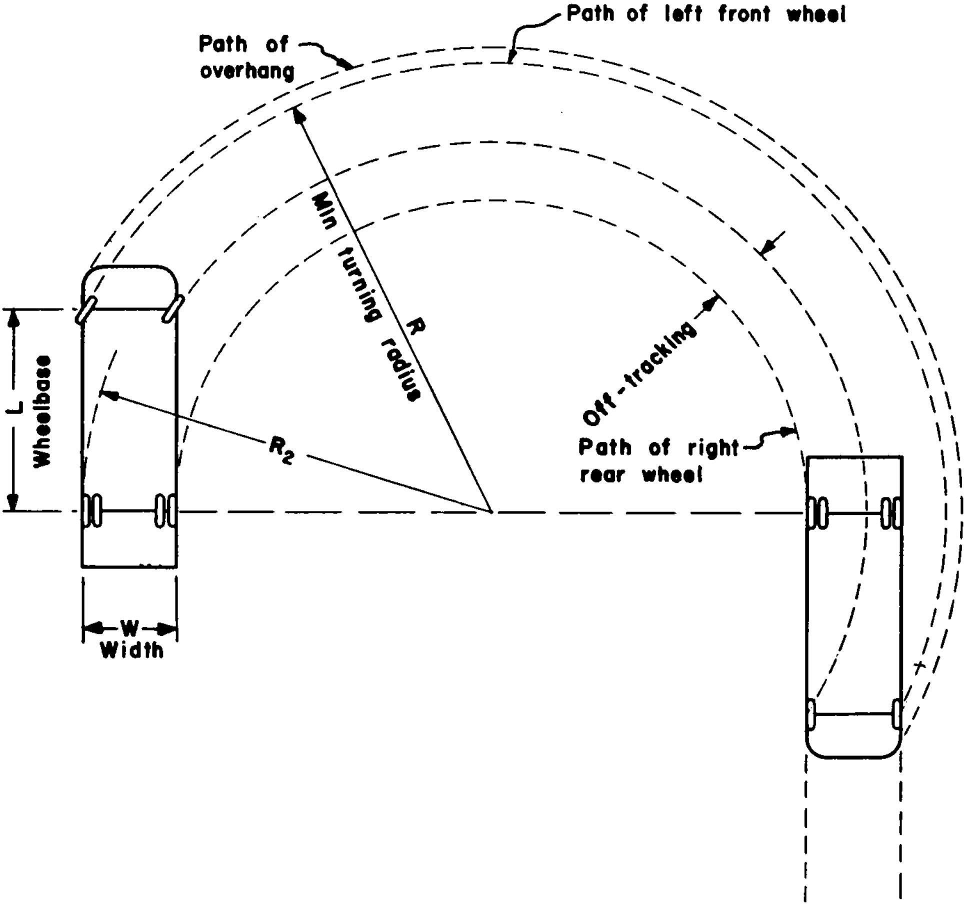

Figure 3. Single unit off-tracking.

Knowing the minimum turning radius, the following was derived for computing the off-tracking (Fig. 3):

$$\text{Off-tracking} = R - R_2 \quad (5)$$

$$R_2 = \sqrt{R^2 - L^2} \quad (6)$$

$$\text{Off-tracking} = R - \sqrt{R^2 - L^2} \quad (7)$$

in which

R = minimum turning radius;

R_2 = radius of circle traced by inside edge of rear wheel;

L = wheel base.

By using the previous assumptions and simple geometric relationships, any point on a single-unit vehicle may be traced on any degree of turn. Many problems encountered during movement may be analyzed by the above determinations; but where movement of combination vehicles is concerned, these basic equations have limited applicability. When longer wheel bases are required, a single-unit truck may not be practical, since maneuverability decreases with an increase in wheel base. However, combination units such as tractor-trailers or tractor-semitrailers may be used with considerable increase in maneuverability. This type of vehicle presents an off-tracking problem that cannot

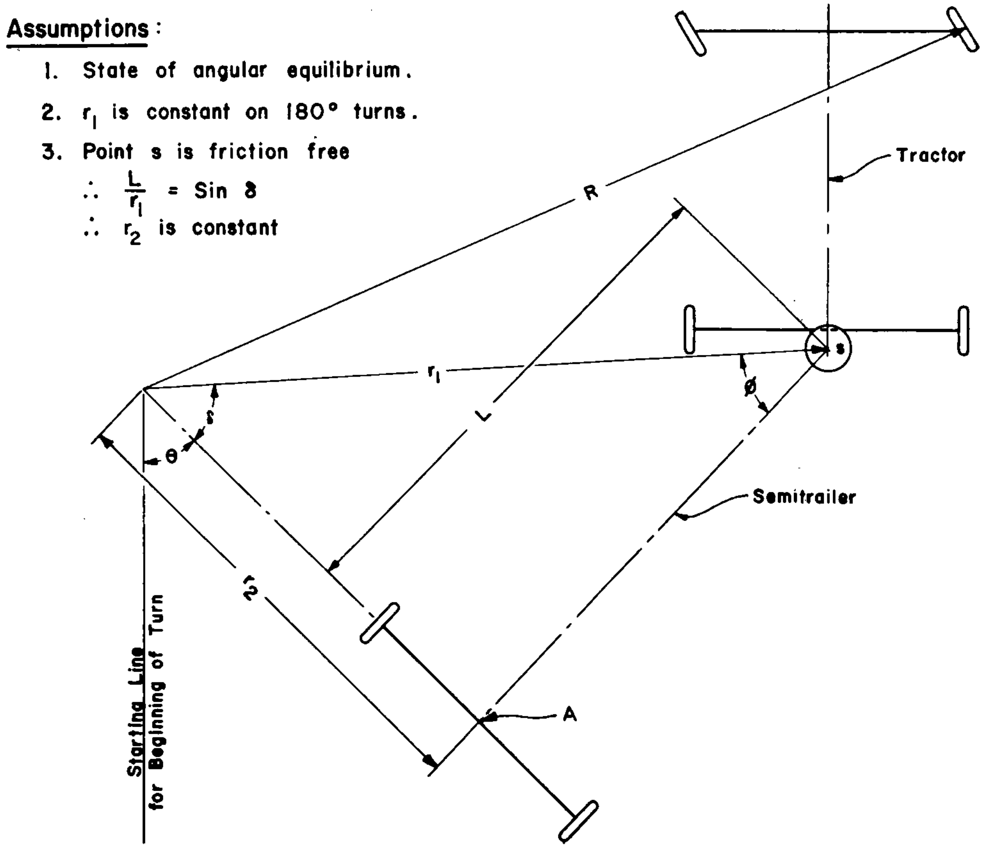

Figure 4. Diagram for analysis.

be analyzed by the methods previously described.

Semitrailers and full trailers pivot about a fifth wheel or kingpin, thereby producing a peculiar off-tracking pattern. Some conclusions have been reached in an attempt to solve this off-tracking trace mathematically. These conclusions may be best shown by Figure 4 and the following explanation.

Figure 4 is only good after the point of equilibrium or maximum off-track has been reached. At this time, the center point of the trailer's rear axle revolves about the same center as does the center point of the rear axle of the prime mover. However, the traces up to the point of equilibrium are of primary concern in the majority of instances. These traces are very difficult to determine, since r_2 will vary at a changing rate and will make an arc with varying centers. The angle ϕ will also vary the amount δ, which is the angle shown at the point of equilibrium. Since point A swings toward the center more at the beginning of the turn than it does as it approaches equilibrium, θ and ϕ do not vary at the same rate. Therefore, the equation of this arc is extremely complex and cannot be determined by simple geometric relationships.

Several purely mathematical approaches have been attempted by the Transportation Engineering Office, USATRECOM, and the Army Mathematics Research Center. The Transpor-

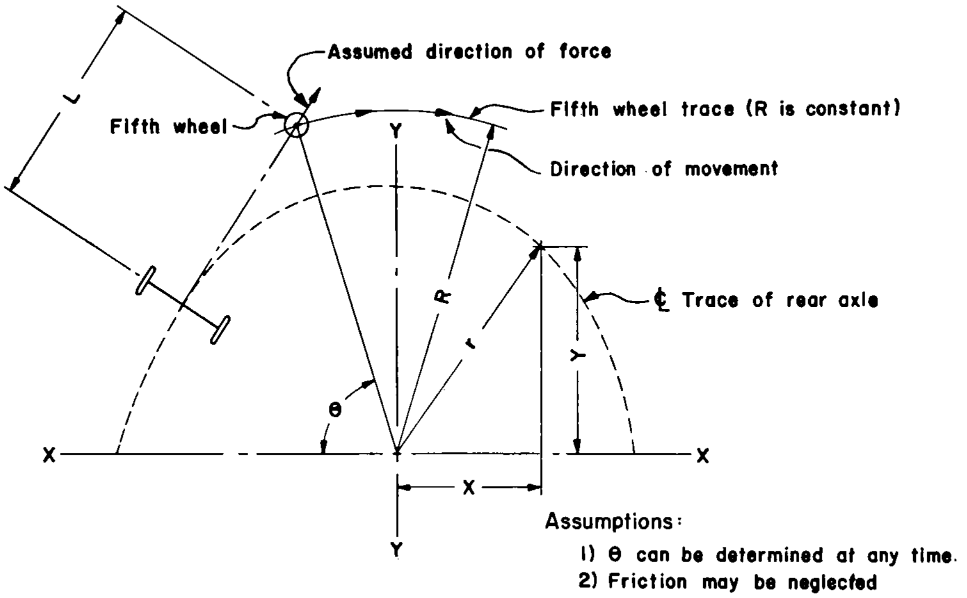

Figure 5. Mathematical approach.

tation Engineering Office, by using polar coordinates (see Fig. 5) and operational calculus, obtained the following:

$$Y=\left[1+\left(\frac{R}{L}\right)^2\right]^{-1}\left\{-L\exp\left[\left(-\frac{R}{L}\right)(\Theta)\right]+\frac{R^3}{L^2}\sin\Theta-\frac{R^2}{L}\cos\Theta\right\} \quad (8)$$

$$X=\left[1+\left(\frac{R}{L}\right)^2\right]^{-1}\left\{R\exp\left[\left(-\frac{R}{L}\right)(\Theta)\right]+\frac{R^2}{L}\sin\Theta+\frac{R^3}{L^2}\cos\Theta\right\} \quad (9)$$

$$r=\sqrt{X^2+Y^2} \quad (10)$$

in which

Y = distance on Y axis of centerline of rear axle;

X = distance on X axis of centerline of rear axle;

R = radius of 5th wheel;

e = 2.71

θ = angle of 5th wheel with respect to X axis at any point during the turn;

L = distance from 5th wheel to rear axle;

r = radius traced by center of rear axle.

This equation was found to be within acceptable accuracy for semitrailers having up to a 24-ft wheel base; above this point, the accuracy decreased with an increase in wheel-base length. This is evidently due to incorrect assumptions and varying quantities at a changing rate.

This problem, using a tractor-full trailer as the vehicle in question, was submitted to the Army Mathematics Research Center, which used a pursuit curve method in approaching a solution. It was concluded that a purely mathematical approach would not be feasible, since the

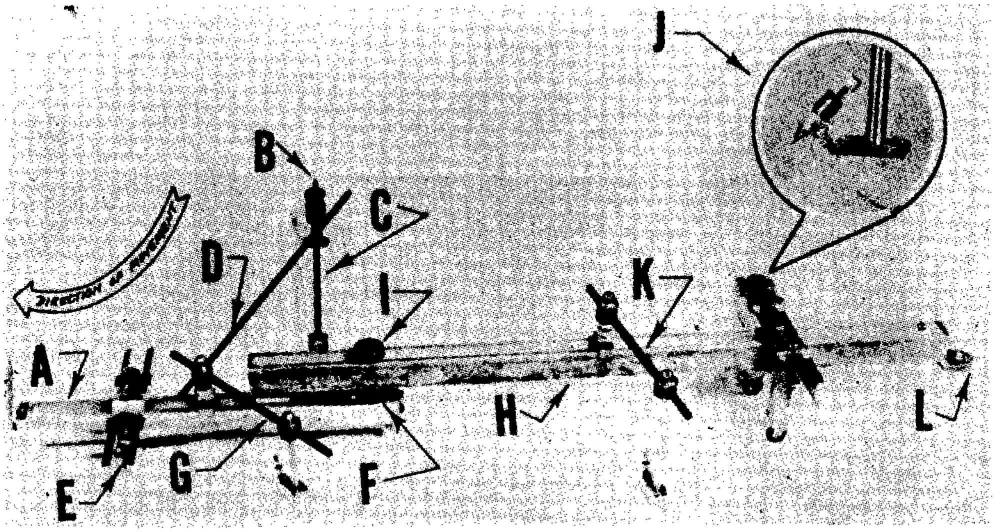

Figure 6. Model of prime mover.

solution would involve continuous calculations requiring the use of an automatic electronic computer. It was also concluded that this approach would involve the use of extraneous mathematics, which would make the calculations extremely complex and highly impractical.

SCALE-MODEL TESTS

Neoperman (*5*) used a variety of scale models for determining track widths of design vehicles. These track widths corresponded with the results of actual field tests conducted by Young (*7*). It is believed that where vehicle characteristics of the sort determined only by the configuration of the vehicle are desired, scale-model tests will show great savings in both time and money. The Transportation Engineering Office, USATRECOM, is of the opinion that an adjustable scale model, which may be used to determine critical traces on any questionable vehicle regardless of size or shape, is the most practical and economical solution to the problem. This opinion was concurred in by the Office of the Chief of Transportation, and action was initiated to design and construct the required model.

A model was designed and constructed to determine the feasibility of using a scale-model approach to the tracking problem. This experimental model is adjustable in all dimensions and consists of four basic components: a prime mover, a semitrailer, a full trailer and a dolly converter.

Prime Mover

The prime mover (A in Fig. 6) is constructed so that its motion is controlled by a point (B in Fig. 6) at the intersection of an adjustable perpendicular rod (C in Fig. 6) that connects the inside edge of the model at the centerline of the rear axle and another rod (D in Fig. 6) that connects a point (E in Fig. 6) at the outside edge of the front bumper or outside front wheel. The length of the latter rod is determined by the minimum turning radius of the vehicle in question. A marking device is installed in this outside point and scribes a trace of the minimum turning radius or front overhang of the vehicle. There is a fifth-wheel connection (F in Fig. 6) on the rear of the prime mover, which can be adjusted independently of any part on the prime

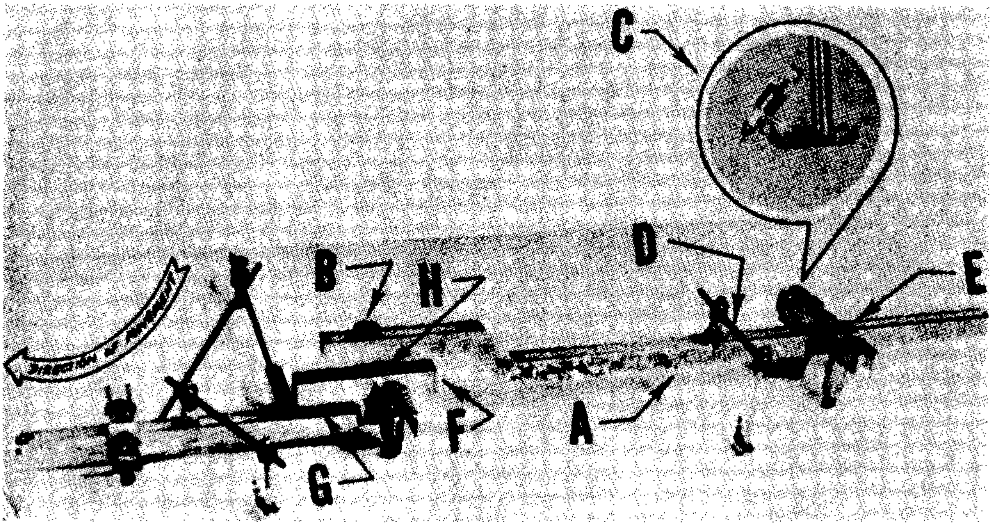

Figure 7. Model of gooseneck semitrailer.

mover. There is also a detachable telescoping rod (G in Fig. 6) that traces any overhang.

Semitrailers

The semitrailers were a standard semitrailer (H in Fig. 6) and a gooseneck semitrailer (A in Fig. 7), both of which have an adjustable fifth-wheel connection (I in Fig. 6 and B in Fig. 7). This connection on the standard semitrailer engages the adjustable connection on the rear of the prime mover, whereas the connection on the gooseneck semitrailer engages a connection on the dolly converter. The width of both units varies from the smallest width known or proposed to the largest. Wheels are adjustable transversely and longitudinally, and adjustable markers are placed as shown in J in Figure 6 and C in Figure 7. The wheels are positioned to simulate the centerline of a single or bogie axle, since the two are the same as far as critical tracking traces are concerned. There is a telescoping rod (K in Fig. 6 and D in Fig. 7) with a marker to trace overhang on any part of the two models. Provision has been made for attachment (L in Fig. 6) of a full trailer or dolly converter to the rear of the standard semitrailer.

Full Trailer

The full trailer (A in Fig. 8) is built on the same order as the semitrailer, except that it has two axles (B and C in Fig. 8). The rear axle is identical to that of the semitrailer, but the front axle is free to rotate about a frictionless pin at the centerline of the vehicle. A tongue (D in Fig. 8) is built as an integral part of the front axle and is adjustable longitudinally.

Dolly Converter

Dolly converters are used in many instances when excessively heavy loads are transported. These converters are designed to reduce axle loads transmitted to the supporting media; thus, a transporter can move heavier items of equipment without exceeding maximum legal axle weight limits. To provide for this movement, an adjustable dolly converter (F in Fig. 7) has been designed and constructed for use with the gooseneck semitrailer. There are two independent, adjustable, fifth-wheel connections: one male member (G in Fig. 7) for connection to the prime-mover's fifth-wheel position, and one female member (H in Fig. 7) for attachment to the gooseneck semi-

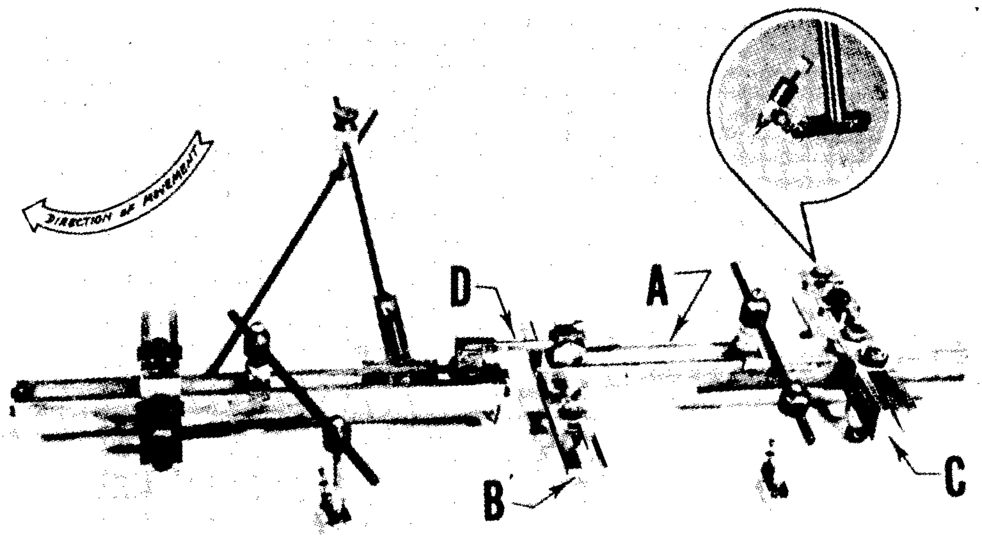

Figure 8. Model of full trailer.

trailer's fifth-wheel position. The axle on the dolly converter is identical to the semitrailer axle except that movement under the female fifth-wheel member is allowed.

The model was constructed to a scale of 1 in. = 5 ft, since this scale is familiar to the majority of people and is commonly found in engineering concerns. This is also the largest practical scale that will permit testing on an average drafting table, as well as the smallest possible scale for precision construction.

During the model tests, certain basic assumptions must be made in order to produce a tracking trace requiring a minimum amount of turning space. These assumptions are also made in order to reduce such variables as the human element, tire scuff or slip, superelevation of the roadway, tire pressure, and oversteering or understeering. It is conceivable that these variables can be estimated empirically and the model results adjusted accordingly. The author has recommended that further study be done to determine what adjustments may be made to the theoretical model results in order to determine vehicle characteristics at higher speeds and with less restrictions imposed upon the driver.

It is assumed that:

1. Tire slip may be ignored.
2. The vehicle is stopped and the front wheels are cramped at the maximum angle prior to entering the turn.
3. The vehicle is stopped and the front wheels are returned to the straight-ahead position prior to leaving the turn.
4. Creep speeds (0 to 5 mph) are used.

Full-size-vehicle tests were conducted to determine the reliability of the model results. The vehicles used were believed to represent a cross-section of typical oversized vehicle types. The vehicles in Figures 9, 10, 11 and 12 were used and checked with the model results. It is felt that this accuracy is sufficient for estimating vehicle routing and for establishing highway design criteria.

Since the correlating vehicle tests have proven the feasibility of a scale-model approach, a more complete and more accurate model has been designed (A in Fig. 13). Although it has many minor modifications, it is basically the same as the experimental model except for the movable center point. This item was designed to facilitate movement when the model is leaving a turn. In appearance,

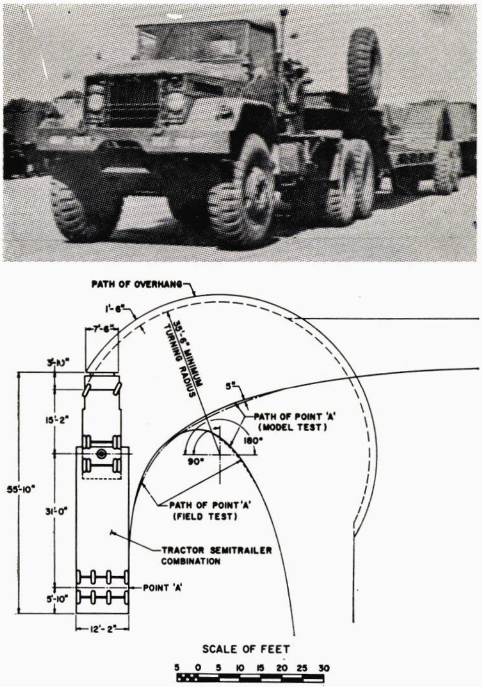

Figure 9. Tank transporter.

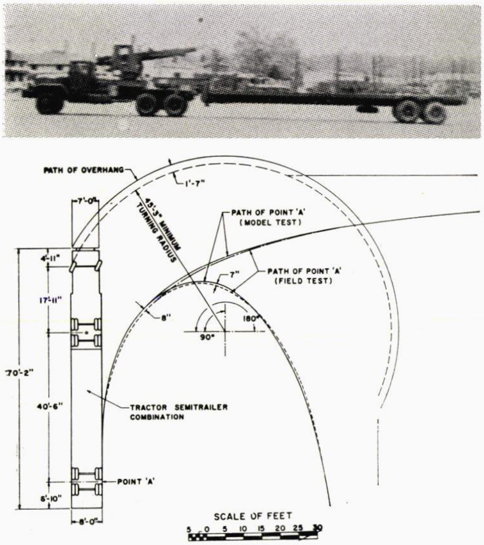

Figure 10. Aircraft transporter.

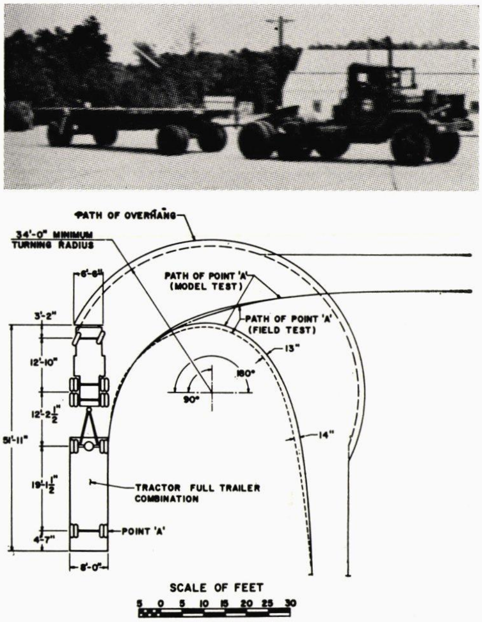

Figure 11. Missile transporter.

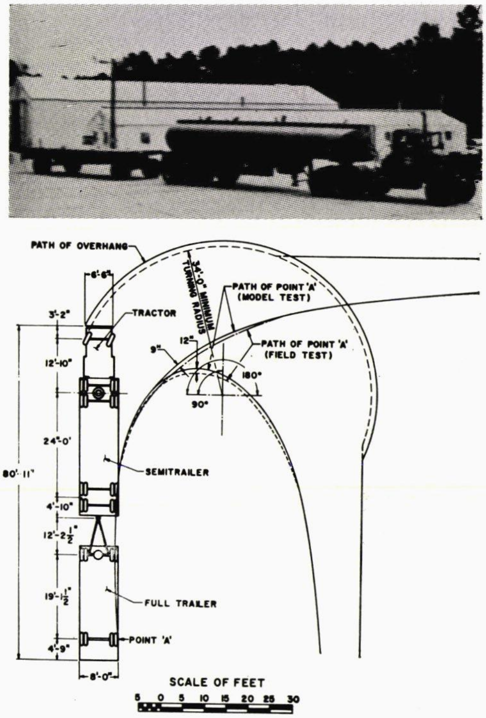

Figure 12. Tractor train.

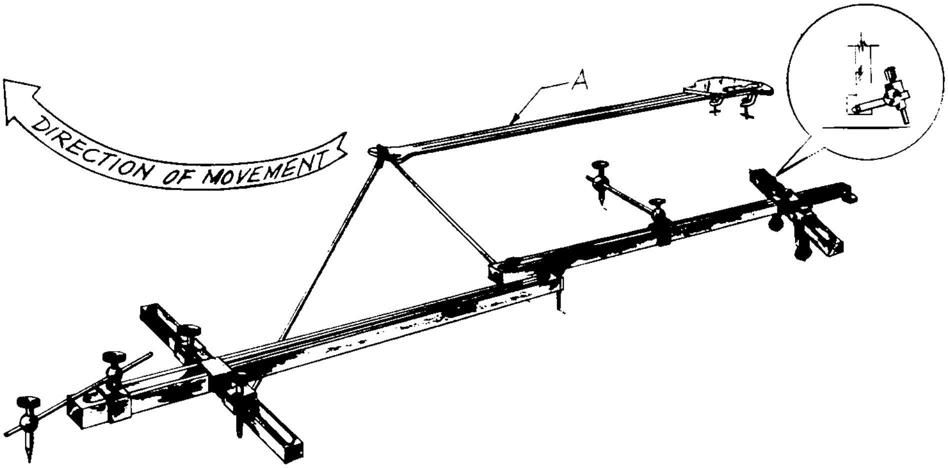

Figure 13. Improved model with movable center point.

it is similar to a steel T-square having the turning center built into the blade. The head of the T-square is fixed while the blade moves through it, pulling the prime mover on a straight line. This operation is performed after the prime mover has completed any degree of turn.

When this final model is constructed, the Transportation Engineering Office, USATRECOM, will be in a position to recommend highway design criteria and critical vehicle dimensions and to foresee restrictive clearances along routes where obstructions or bottlenecks may exist. Department of Defense organizations will be able to obtain maneuverability data by forwarding the physical dimensions of any vehicle in question. Tests will then be performed with the adjustable scale model, and the results will be forwarded to the requesting agency.

SUMMARY

At the present time, vehicle maneuverability data are obtained by testing an actual vehicle or by interpolating between maximum and minimum off-track. In the latter case, it is assumed that a vehicle will reach the maximum off-track on any given turn, but obviously this is not always true. By using a scale-model approach, it is possible to obtain accurate data faster and more economically.

Since results show that, for all practical purposes, tire slip may be ignored when turns are made at minimum radius and creep speed, certain geometric relationships exist for computing the trace of critical points on single-unit vehicles. Although these relationships are good for single-unit vehicles, combination units, such as tractor-trailers or tractor-semitrailers, present an off-tracking problem that may not be analyzed by any straightforward geometric relationship.

To produce the necessary off-tracking trace, an adjustable scale model that simulates the movement of any questionable highway vehicle negotiating restrictive-type turns was developed.

Indications are that a scale-model approach is sufficiently accurate to determine vehicle tracking at low speeds. However, it is felt that much further study is needed to estimate vehicle performance at high speeds.

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