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Simulation of Truck Turns with a Computer Model

KENNETH T. FONG AND D. CHARLES CHENU

Recent federal legislation allowing the use of longer and wider trucks will have a significant impact on California's existing roadway system. Many freeway ramps, for example, were designed over a decade ago to accommodate only the largest trucks legally in use at that time. Some of the larger trucks legalized by the new legislation are expected to encounter problems maneuvering through these interchanges. Local governments are also concerned because urban intersections designed many years ago simply cannot accommodate the offtracking of the new larger trucks. To assess the ability of the larger trucks to operate on California's existing roadway system, their offtracking characteristics must be carefully evaluated. In the past, engineers at the California Department of Transportation traditionally used a graphic instrument known as the Tractrix Integrator for simulating truck turns supplemented with a mathematical calculation of the maximum amount of offtracking. A computer model developed for analyzing and evaluating truck offtracking is described. Offtracking results from the computer simulation model are first compared with results derived from the Tractrix Integrator, field observations, and mathematical formulas. The computer model is then used to analyze the offtracking characteristics for several of the new, longer trucks. Finally, applications of the computer model to evaluate some special offtracking situations or problems are discussed.

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The 1982 Surface Transportation Assistance Act (STAA) allowed wider and longer trucks on the Interstate system and portions of the primary system. In 1983 California enacted conforming legislation (Assembly Bill 866). As a result of these legislative changes, a new generation of larger trucks has emerged. The evaluation of the maneuverability of these longer, wider trucks and their ability to operate safely on the roadway system is of prime importance.

PREVIOUS METHODS

Offtracking may be described as "the amount of variation between the path traversed by a following wheel as compared to the path of the preceding wheel" *(1)*. In this paper the center of the axles, rather than the wheels, is used as the reference point for measuring offtracking. Offtracking and related terms are shown in Figure 1.

In California, two methods—the Tractrix Integrator and mathematical formulas—have been used to analyze and evaluate offtracking. The Tractrix Integrator was used to produce

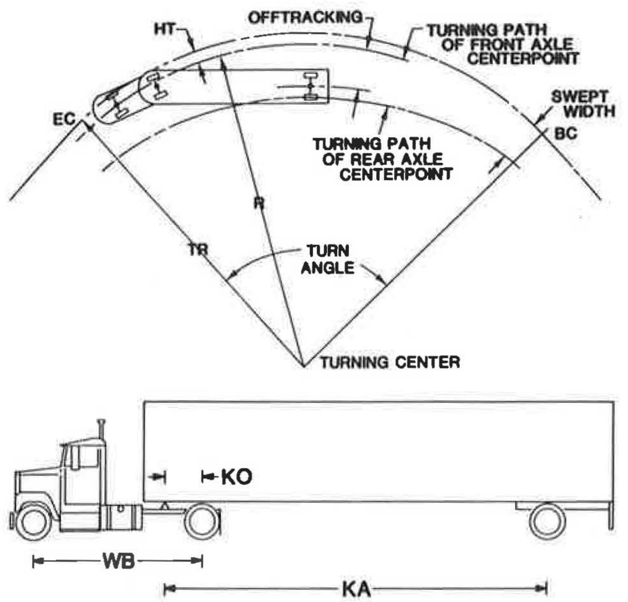

FIGURE 1 Vehicle and offtracking geometries.

offtracking traces and truck turn templates. Mathematical formulas—were used to estimate directly the maximum amount of offtracking.

Tractrix Integrator

Traditionally, highway engineers at the California Department of Transportation (Caltrans) have used a graphic instrument, the Tractrix Integrator, for simulating truck turns (Figure 2). This instrument produces traces of a truck's path that allow the measurement of the amount of offtracking. Thus, one of its main features is that it provides an immediate plot of the truck's path. It is especially well suited for many roadway design situations. Nevertheless, the Tractrix Integrator has several disadvantages. Among them are the following:

- The scale bar cannot be adjusted to accommodate values of less than about 5 ft. Thus, for example, the kingpin is generally assumed to be located directly over the center of the rear tractor axles, and rear overhangs are generally ignored.
- Its use is slow and tedious. To obtain the offtracking path of the first unit of a combination, the pointer of the scale bar first is manually moved carefully along a curve representing the path followed by the center of the front steering axle. Subsequent passes for each unit must be made in order to obtain the path of the center of the rear axle of the rear unit, the pointer in each case following the trace of the previous unit.
- The Tractrix Integrator traces only centerline paths. Consequently, special points of interest (e.g., outside wheels, corners of long rear overhangs, and wide loads) cannot be obtained directly. Artificial lines representing paths of the user-specified point and track widths of the outside front wheel and inside rear wheel, for example, must be manually added to the curves produced from the Tractrix Integrator.
- The Tractrix Integrator used by Caltrans has a bias, probably caused by inexact machining or excessive wear, that causes slightly greater offtracking for right turns than for left turns. To compensate for this bias it is necessary to average the right- and left-turn offtracking of each unit.

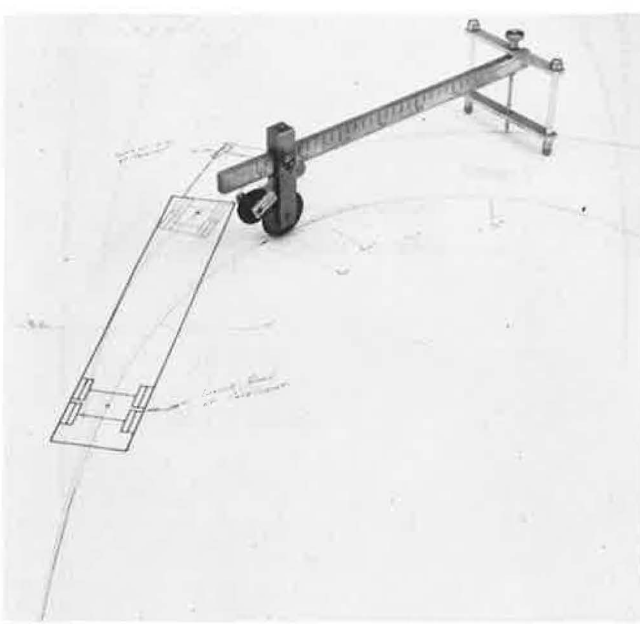

FIGURE 2 Tractrix Integrator.

Mathematical Formulas

Mathematical formulas for estimating maximum truck offtracking were developed by the Society of Automotive Engineers (SAE) in the 1960s. Because these formulas were often very complex and unwieldy, the Western Highway Institute (WHI) in the late 1960s developed simpler but similar equations. The SAE and WHI formulas are widely used by highway engineers to calculate the maximum offtracking expected of a vehicle combination for a curve of a given radius. Although these formulas are widely used, they also are not without shortcomings. They cannot, for example, determine the shape of the spiral path, the amount of offtracking at any point, the location along the path at which maximum offtracking occurs, or whether the maximum value calculated will be reached for a particular curve. Because the location of the maximum offtracking cannot be determined, these formulas are inappropriate in situations where a vehicle pulls out of the turn before the maximum is attained. Both formulas also become indeterminate if the rearmost axle tracks to the inside of the center of the curve, such as on short-radius curves.

A NEW METHOD: COMPUTER MODEL

Anticipating that computer models could provide faster and better solutions to truck offtracking problems, Caltrans started to develop an offtracking model. A literature search indicated a similar project at the University of Michigan. Through contact with FHWA, it was learned that the University of Michigan Transportation Research Institute (UMTRI), as part of a contract with FHWA, had developed a vehicle offtracking computer model, one that in fact simulated the action of the Tractrix Integrator. A detailed description of the nature of the model is presented in the UMTRI report *(2)*.

UMTRI Model

The UMTRI computer model for offtracking simulation is written for the Apple Personal Computer. It is menu driven and easy to use. The program performs the vehicle offtracking simulation by using path and vehicle information supplied by the user and plots selected paths after the simulation. The size of the plot, however, limited by the desktop Apple X-Y Plotter, is relatively small. Also, given a multiunit vehicle or a long path to follow or both, the program will often run out of floppy disk space for storage of the simulation results.

Caltrans Version

Because of the inherent size and capacity limitations of personal computers, Caltrans decided to adapt the simulation portion of the UMTRI model for implementation on the state's IBM mainframe computer and to enhance the program to better meet Caltrans needs. One model has been developed for simple circular curves and a second one for complex compound curves. Three versions (Calcomp drum, Zeta drum, and Xynetics flat-bed plotters) are available for each model. The plots (optional) are the same except that the Calcomp and Zeta plotters have a maximum paper width of 34 in. and virtually unlimited length, whereas the Xynetics plotter has a maximum plotting area of 42 × 88 in. In addition, the Caltrans computer model produces several printed reports.

Supported by IBM's MVS Operating System, the Caltrans offtracking model runs extremely quickly. Only a fraction of a second in computer-processing-unit time is required to execute a simulation run. If the job is submitted via a time-sharing system from a video display terminal, the user can preview the printed output in a matter of minutes. Processing costs vary from less than $0.25 to about $3.00 if a plot tape is generated.

COMPARISON OF COMPUTER MODEL RESULTS

A 48-ft test semitrailer (tractor-semitrailer combination) was used in the comparison of the results from the Caltrans computer model with centerline traces obtained by using the Tractrix Integrator, swept widths observed from an actual field test, and maximum offtracking values calculated from mathematical formulas. Figure 3 shows the 48-ft test semitrailer configuration and key dimensions.

Caltrans Model Versus Tractrix Integrator

The 48-ft test semitrailer was simulated and centerline axle traces were plotted for a 180-degree turn with a 50-ft radius at a scale of 1 in. = 5 ft. Tractrix centerline traces (for right turns and mirror images of left turns) were superimposed on the computer plot. The two sets of traces (computer generated and average Tractrix) were almost identical (Figure 4).

The computer plots are in fact better than the Tractrix drawings. As mentioned earlier, the Tractrix Integrator produces traces only for vehicle centerlines and requires rear-wheel paths, for example, to be manually constructed. The computer model, on the other hand, can plot any user-specified vehicle reference points. In addition, as also mentioned earlier, the California Tractrix Integrator has an offtracking bias that is not in the computer model.

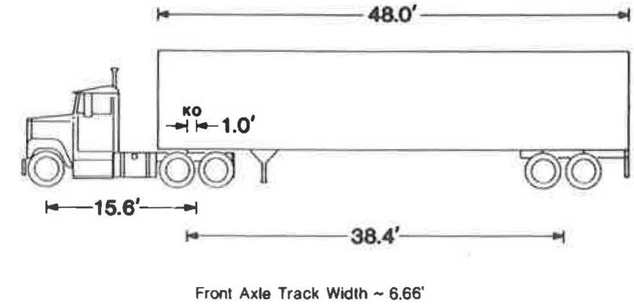

FIGURE 3 Test semitrailer with 48-ft trailer.

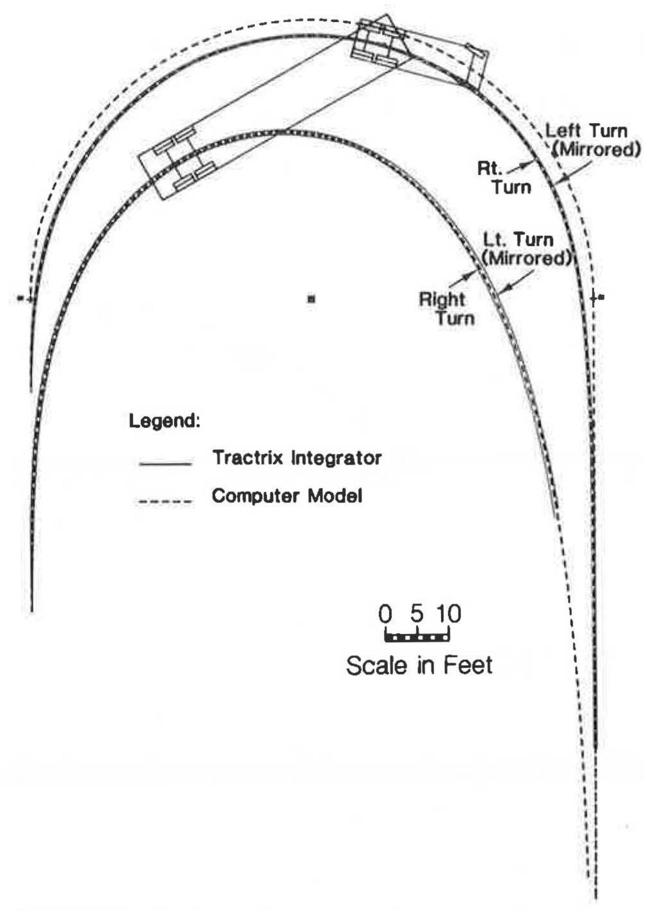

FIGURE 4 Centerline traces.

TABLE 1 RESULTS FROM FIELD TESTS COMPARED WITH COMPUTER MODEL FOR SWEPT WIDTH (FT): 48-FT TEST SEMITRAILER NEGOTIATING A 180-DEGREE 50-FT-RADIUS CURVE

	Angle Ahead of BC (Degrees)						
	0	30	60	90	120	150	180
Field Test	13.5	20.1	23.8	26.2	27.9	27.8	24.0
Computer Model	13.7	20.2	24.1	26.7	28.3	28.1	23.9
Difference	0.2	0.1	0.3	0.5	0.4	0.3	-0.1
% Error	1.5	0.5	1.3	1.9	1.4	1.1	-0.4

Caltrans Model Versus Actual Field Test

In 1984 Caltrans conducted an actual field test of the 48-ft test semitrailer *(3)*. It was driven around a 50-ft-radius, 180-degree curve in a parking area, and the amount of swept distance was recorded at 30-degree increments from the beginning of the curve (BC). Field test results are compared with those from the computer model in Table 1. It may be seen that the results are close. The maximum difference is only 0.5 ft, an error of less than 2 percent.

Caltrans Model Versus Mathematical Formulas

A summary of the offtracking results from the computer model for the 48-ft test semitrailer negotiating a 50-ft radius curve is given in Table 2, which shows the amount of offtracking (in feet) at the beginning and the end of a curve, the maximum offtracking value reached, and where along the path the maximum occurred.

TABLE 2 OFFTRACKING RESULTS BY DEGREE OF TURN: 48-FT TEST SEMITRAILER NEGOTIATING A 50-FT-RADIUS CURVE

Degree	Offtracking (in Feet)			Location of
of Turn	BC	EC	Maximum	MOT (deg)
30	5.0	6.2	6.8	19
60	6.1	10.0	11.6	39
90	6.1	12.5	15.2	61
120	6.1	14.2	17.7	85
150	6.1	15.4	19.6	109
180	6.1	16.3	21.0	133
210	6.1	16.9	22.1	159
240	6.1	17.4	22.8	186
270	6.1	17.7	23.4	213
300	6.1	18.0	23.9	241
330	6.1	18.2	24.2	269
360	6.1	18.3	24.4	297

For comparison, the maximum offtracking values computed from the SAE and WHI formulas *(1, 4)* for the 48-ft test semitrailer negotiating a circular curve with a 50-ft radius are as follows:

SAE formula:

$$\begin{aligned} OT &= \{WB^2 + [(TR^2 - WB^2)^{1/2} - HT]^2\}^{1/2} \\ &\quad - \{KO^2 + [(TR^2 - WB^2)^{1/2} - HT]^2 - KA^2\}^{1/2} \\ &= \{15.6^2 + [(50^2 - 15.6^2)^{1/2} - 33]^2\}^{1/2} \\ &\quad - \{1^2 + [(50^2 - 15.6^2)^{1/2} - 3.33]^2 - 38.4^2\}^{1/2} \\ &= 25.0 \text{ ft} \end{aligned} \tag{1}$$

WHI formula:

$$\begin{aligned} MOT &= R - (R^2 - \Sigma L^2)^{1/2} \\ &= 46.67 - [46.67^2 - (15.6^2 - 1^2 + 38.4^2)]^{1/2} \\ &= 25.2 \text{ ft} \end{aligned} \tag{2}$$

where

- OT or MOT = offtracking (maximum or steady-state),
- WB = wheelbase of tractor,
- TR = turning radius of outside front tire,
- HT = half of front-axle track width,
- KO = kingpin offset (fifth wheel) of tractor,
- KA = kingpin to centerline of rear axle group of semitrailer,
- R = $TR - HT$ = radius followed by front-axle center, and
- ΣL^2 = $WB^2 - KO^2 + KA^2$ = sum of square of component lengths between axle spacings.

As mentioned earlier, the mathematical formulas can only give the maximum offtracking value expected; they cannot tell where the maximum will occur. From the computer model, the maximum offtracking attained by the 48-ft test semitrailer making a 90-degree turn is just 15.2 ft, or about 10 ft less than

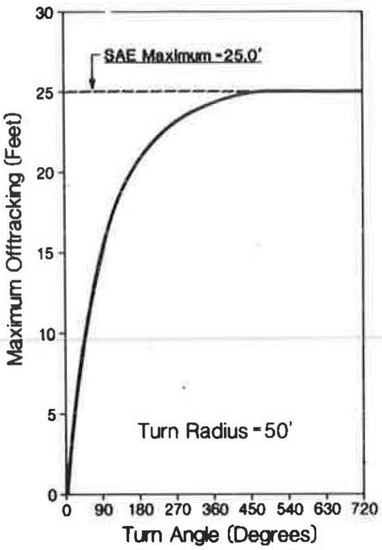

FIGURE 5 Maximum offtracking by turn angle for 48-ft test semitrailer.

the mathematical maximum. On a 180-degree turn, the maximum offtracking value from the computer model is 21.0 ft, or about 4 ft less than the mathematical maximum. And on a 270-degree turn, the maximum is 23.4 ft. This is almost 2.0 ft less than the expected maximum calculated from the mathematical formulas.

Table 2 shows clearly that as the degree of turn increases, the maximum offtracking value also increases, but at a progressively slower rate. It also suggests that if given enough angular rotation, the maximum offtracking value from the computer model will eventually reach the mathematical maximum. This is verified with additional results developed from the computer model. The relationship between maximum offtracking and degree of turn is shown in Figure 5.

OFFTRACKING RESULTS OF LONGER TRUCKS

The computer model was next applied to analyze the offtracking characteristics for the post–1982 STAA California Interstate design vehicle and several of the longer vehicle combinations. These vehicle configurations are shown in Figure 6.

Since enactment of the 1982 STAA, Caltrans designers have been using two design vehicles. The Interstate design vehicle is for use on the Interstate system, non-Interstate freeways, and some conventional highways. The non-Interstate design vehicle (not shown) is used for the remainder of the California highway system.

The first two vehicles in Figure 6, the California Interstate design vehicle and a twin trailer truck with 28-ft twin trailers, are now legal in California. The last three—a Rocky Mountain double, turnpike double, and a triple trailer truck with three 28-ft trailers—are not currently allowed. This latter group of longer combination vehicles is under study as prompted by Section 138/415 of the 1982 STAA.

The computer model was used to simulate all five vehicle types negotiating simple circular curves of various radii and

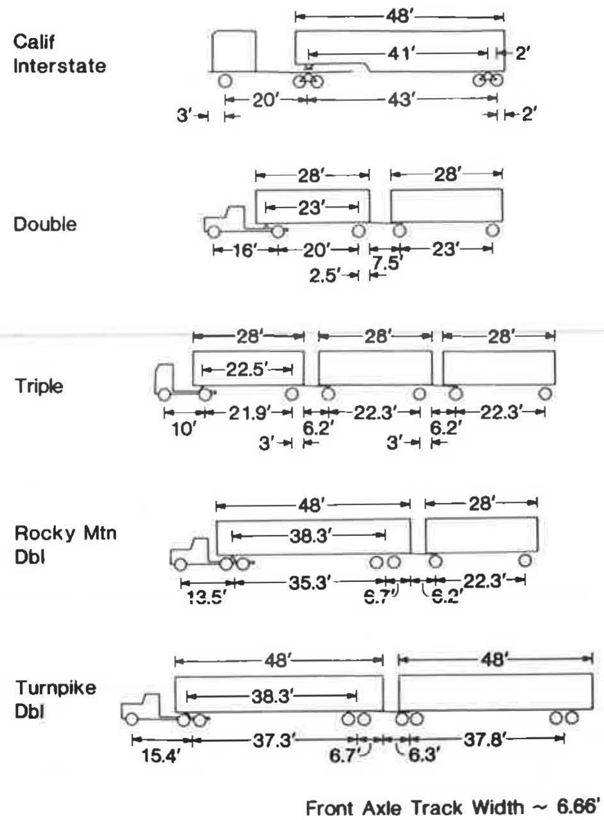

FIGURE 6 Truck configurations.

central angles. The maximum offtracking values for these vehicles on a 180-degree turn with radii of 60, 100, and 150 ft are summarized in Table 3. For comparison, the maximum offtracking values calculated from the SAE and WHI equations are also given.

The following observations may be made from Table 3:

- The maximum offtracking values calculated by using the SAE and WHI formulas differ only slightly and in most cases are identical.
- The maximum offtracking values from the computer model and mathematical formulas are the same for trucks making the longer-radius turns (e.g., ~100 ft). For the shorter-radius turns, the difference in offtracking may be substantial. For example, on a 180-degree turn at a radius of 60 ft, the difference in offtracking is about 14 ft for the turnpike double. It should be pointed out that on an actual field test, the maximum offtracking observed for the turnpike double negotiating a 180-degree turn on a 60-ft-radius was 32.7 ft, with the measured maximum located about 120 degrees from the beginning of the curve *(3)*. This value also confirms the maximum offtracking value from the computer model.
- Amount of offtracking varies inversely with the radius of turn. The shorter the radius, the greater the amount of offtracking. Offtracking is very sensitive at the shorter-radius turns and becomes relatively inelastic for the wider-radius turns.

As indicated earlier, the mathematical equations provide only the theoretical or steady-state maximum value. The simulation

TABLE 3 MAXIMUM OFFTRACKING VALUES (FT) FOR TRUCKS MAKING A 180-DEGREE TURN

	Turn	Maximum Offtracking (in Feet)			
	Radius	Computer Model		Math Formulae	
Vehicle Description	(ft)	Max	@Deg	SAE	WHI
California	60	20.8	134	22.9	23.0
Interstate	100	11.4	147	11.4	11.4
Design Vehicle	150	7.3	157	7.3	7.3
Double 28'	60	13.3	129	13.5	13.6
all state hwys	100	7.3	144	7.3	7.3
after 1983 AB 866	150	4.7	157	4.7	4.7
Triple 28'	60	16.7	124	17.3	17.3
under Federal study	100	9.0	138	9.0	9.0
per 1982 STAA	150	5.8	154	5.8	5.8
Rocky Mountain double	60	21.7	128	23.7	23.8
under Federal study	100	11.7	144	11.7	11.7
per 1982 STAA	150	7.5	156	7.5	7.5
Turnpike double	60	33.0	123	46.9	47.5
under Federal study	100	17.7	136	17.8	17.8
per 1982 STAA	150	11.1	149	11.1	11.1

model, on the other hand, determines the maximum amount of offtracking for a specific degree of turn. The two values (from the equation and simulation model) will be the same only if the degree of turn is sufficient to allow the vehicle to reach its steady-state condition. It is often necessary for a vehicle to travel more than 180 degrees (particularly on short-radius curves) to reach its steady-state condition. In addition, the SAE and WHI formulas cannot determine the shape of the curve going to and from the point of the maximum offtracking or where the maximum value will occur. An important feature of the computer model is that it can keep track of where the truck is at any given instant. The amount of offtracking and its location are routinely reported as the truck moves along its prescribed path. This can be very helpful in the analysis and evaluation of offtracking problems.

The results from the computer model are used in Figure 7 to show the maximum offtracking of the California Interstate design vehicle by turn angle for different turn radii. Similar graphs may be made for the other trucks as well, but only one is presented to illustrate the relationship that offtracking for a particular vehicle configuration is a function of both the turn radius and the turn angle.

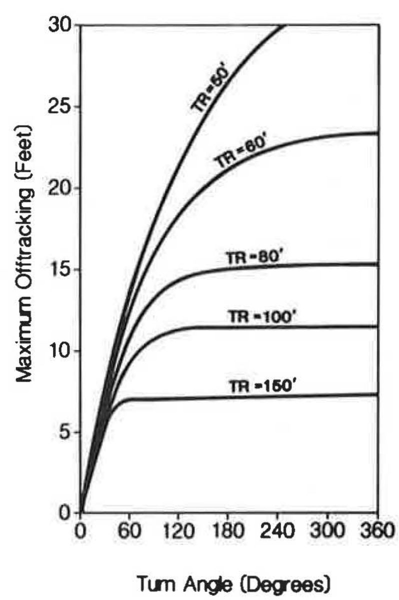

FIGURE 7 Maximum offtracking by turn angle and radius for California Interstate design vehicle.

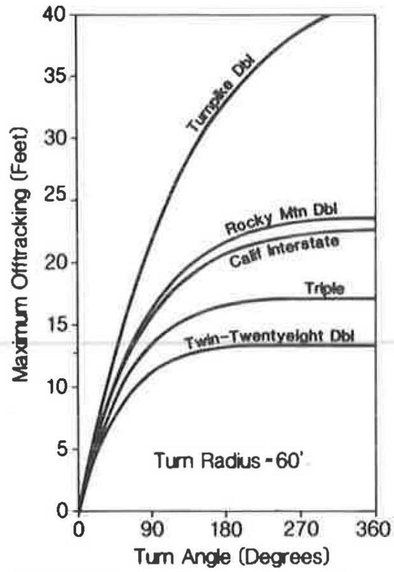

FIGURE 8 Maximum offtracking by turn angle for selected trucks.

Figure 8 is similar to Figure 7, but instead of various turn radii and central angles, offtracking for various vehicle combinations negotiating a common radius curve through various turning angles is shown. From Figure 8 it may be seen that

- The turnpike double offtracks the greatest amount, and the twin with 28-ft trailers offtracks the least. On a 180-degree turn with a 60-ft radius, the turnpike double offtracks almost 20 ft more than the twin.
- The Rocky Mountain double and the California Interstate design vehicle have similar offtracking characteristics, but the Rocky Mountain double offtracks slightly more than the California Interstate design vehicle.
- The amount of offtracking for the triple with 28-ft trailers falls somewhat between that of the California Interstate design vehicle and the twin.
- None of the vehicle combinations would be able to negotiate a 60-ft-radius right-angle turn, such as that found at urban intersections, without tracking outside of a normal 12-ft lane. For example, the twin would require 11.4 ft of offtracking plus 8.5 ft of track width, or about 20 ft of swept width.

SPECIAL OFFTRACKING STUDIES

Applications of the computer model to evaluate special offtracking situations or problems are discussed in the following sections. Some of these special offtracking studies include

- Backtracking and pivoting of rear trailer wheels,
- Effect of kingpin placement,
- Boom carriers, and
- Compound curves.

Backtracking and Pivoting

Backtracking and pivoting is the stopping and backing up, with or without pivoting, of the rear trailer tires while the tractor follows a specified uniform path. This occurs when long vehicle combinations negotiate curves with a very short radius and large central angle. Caltrans has recently begun using the computer simulation model to investigate this problem.

As previously mentioned, mathematical formulas cannot be used in short-radius turns where the rearmost axle tracks to the inside of the radius center. The computer model overcomes this limitation quite easily. To demonstrate this ability, Figure 9 shows a computer plot of the California Interstate design vehicle negotiating a 180-degree turn on a 25-ft-radius curve. The backtracking and pivoting of the semitrailer behind the curve center is readily identified. It should be pointed out, however, that the computer model does not calculate the minimum turn radius, that is, the sharpest curve that can be made by a truck. It is up to the user to determine whether any such short-radius turn is actually possible for a particular type of truck.

Kingpin Placement

The computer model was used to investigate the effect of the placement of the fifth wheel (kingpin offset) on the amount of offtracking.

The offtracking results from the computer model for three types of trucks negotiating a 180-degree turn at radii of 60, 100,

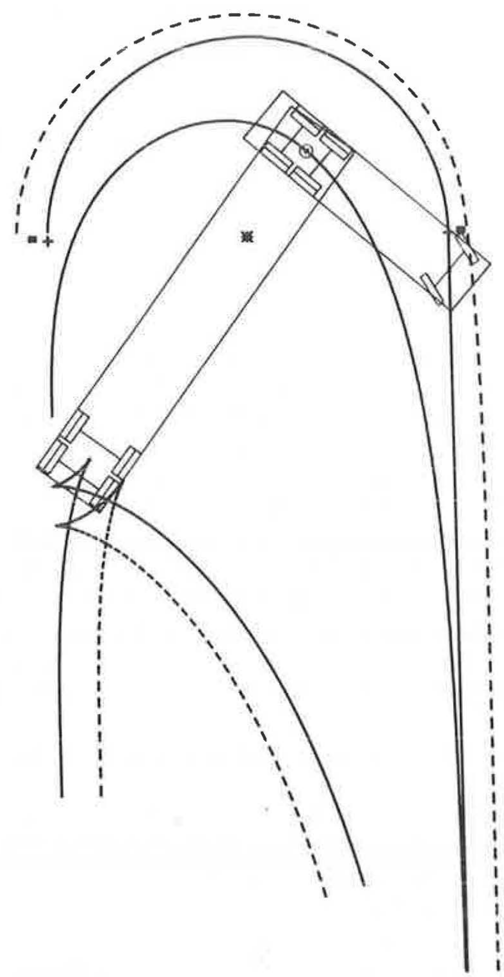

FIGURE 9 Backtracking and pivoting behind the turning radius center.

TABLE 4 MAXIMUM OFFTRACKING (FT) FOR CENTRAL ANGLE OF 180 DEGREES

	Kingpin Offset (Feet)						Max.
	0	±1.0	±2.0	±3.0	±4.0	±5.0	Diff
TR = 60'							
Calif Interstate	20.84	20.83	20.80	20.74	20.67	20.57	.27
Rocky Mtn Dbl	21.81	21.80	21.76	21.71	21.63	21.53	.28
Triple	16.70	16.69	16.65	16.60	16.53	16.42	.28
TR = 100'							
Calif Interstate	11.40	11.40	11.38	11.35	11.31	11.26	.14
Rocky Mtn Dbl	11.77	11.76	11.75	11.72	11.68	11.63	.14
Triple	9.00	9.00	8.98	8.95	8.91	8.86	.14
TR = 150'							
Calif Interstate	7.28	7.28	7.27	7.25	7.22	7.19	.09
Rocky Mtn Dbl	7.50	7.50	7.49	7.47	7.44	7.41	.09
Triple	5.78	5.78	5.77	5.75	5.73	5.69	.09

and 150 ft are given in Table 4. Different placement of the kingpin on the tractor was assumed. These results (and those for a 90-degree central angle, which is not shown) reaffirm the correctness of the mathematical formulas (Equations 1 and 2) and indicate that

- The maximum offtracking occurs when the kingpin is located directly over the rear tractor axle or axles;
- Offtracking decreases as the kingpin is moved away (either ahead of or behind) the rear tractor axle or axles;
- Corresponding kingpin locations ahead of and behind the rear tractor axle or axles cause the same amount of offtracking; and
- The effect of the kingpin placement on offtracking is negligible. Even when the kingpin is offset 5 ft, the maximum offtracking on a 180-degree turn with a 60-ft radius is only 0.28 ft (about 3.5 in.).

Boom Carriers

The use of the computer simulation model to track points selected by the user is shown in Figure 10. The original plot was at a scale of 1 in. = 5 ft. It has been reduced for this paper.

Simulations of various boom lengths for both front and rear boom carriers have been made. In this example an unsupported 32.5-ft front boom carrier is shown on a 90-degree 60-ft-radius curve. Points of interest that were plotted include the corners of the boom overhang and the right carrier overhang. The boom overhang is particularly important because it exhibits consider-

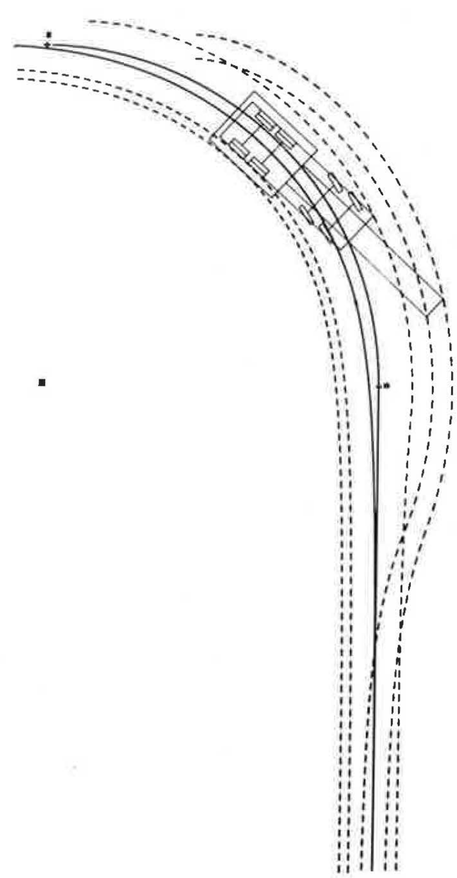

FIGURE 10 Path traces of special points for unsupported front boom carrier.

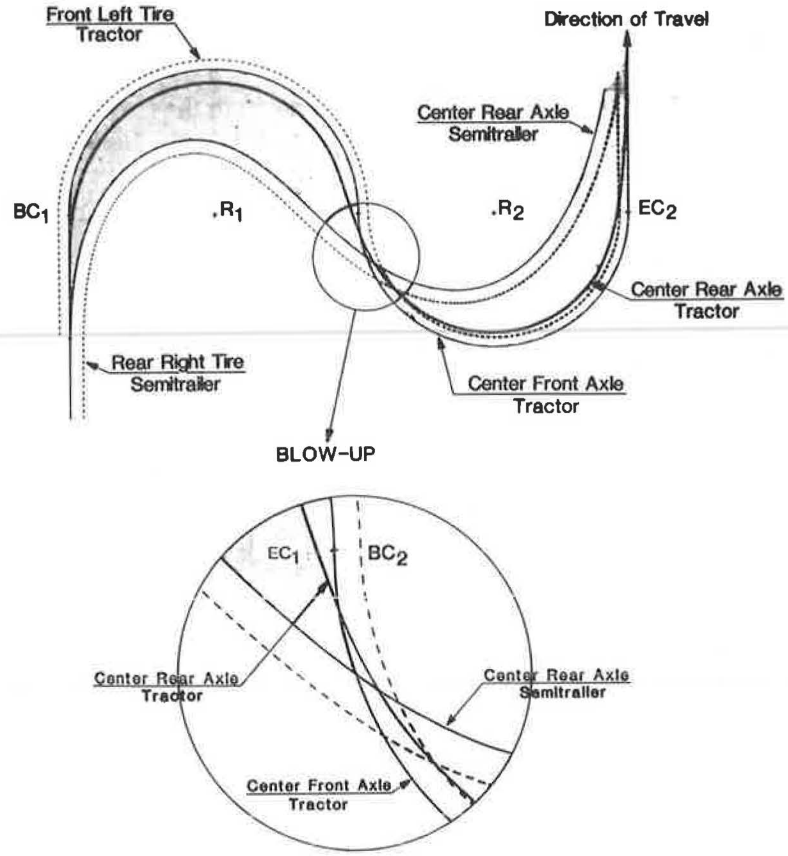

FIGURE 11 Tractor-semitrailer negotiating an S-curve.

able negative offtracking (often overlooked when offtracking is analyzed), which extends well past the end of the curve (EC). Rear boom carriers, on the other hand, generally have an outswing that starts before the beginning of the curve (BC).

Currently only plots of the special point traces may be obtained from the computer simulation model. Calculation of the amount of offtracking for user-specified points is not available at this time. These values will be added in the future to an updated version of the program.

Compound Curves

Offtracking has been defined in several ways, the simplest being "the additional width (over and above the truck width) required by a vehicle when making a turn" *(3)*. Because of the complex paths followed by vehicles negotiating compound curves and because offtracking continues after a vehicle has completed its turn, a definition that is both more flexible and precise is needed. It appears satisfactory (provided the rear axle does not swing inside of the curve center) to define the offtracking as the amount of variation between the path traversed by a point on the steering axle and the path of the corresponding point on the subsequent axle (or axles if the steering axle path is not outermost) that has the greatest variation, when measured normal to the path of the front axle. The formulation of a more universal definition that covers all situations is needed.

In Figure 11 a tractor-semitrailer is shown negotiating a reverse curve or S-curve. In this plot the complex paths and offtracking that result when a vehicle negotiates a sequence of curves of different radii with changes in the direction of travel and the difficulty in defining (much less measuring) the amount of offtracking may be seen. At this time the offtracking (and swept-width) values are not calculated; instead, only the traces are drawn.

SUMMARY

Recent legislation allowing the use of wider and longer trucks will require careful evaluation of the maneuverability of these vehicles. With the rapid increase in the use of computers, highway engineers are turning to computer models for faster and better answers to offtracking problems for a range of new and proposed configurations. Caltrans has recently implemented a computer model that has proved superior to methods used in the past. The computer model has provided new insights into many offtracking problems. It is extremely fast, efficient, and economical to use. Offtracking simulation models are expected to evolve rapidly in the 1980s. This exciting new computerized method will be the chief analytical tool for solving offtracking problems in the future.

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Two-Lane Traffic Simulation: A Field Evaluation of Roadsim

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Roadsim is a traffic simulation model for two-lane rural roads developed in 1980 by FHWA. In the subject study the accuracy of the model was evaluated by comparing its results with observed traffic behavior. The field data were collected on a two-lane rural road in Loudoun County, Virginia. Statistical analyses were performed to compare the measures of effectiveness (MOEs) observed in the field with those obtained from the simulation. The selected MOEs included mean vehicle speed, traffic volume, percent of vehicles following, platoon distribution, and average platoon size. Analysis showed that Roadsim's simulation results compared favorably with those observed in the field. Although this study validates Roadsim under a single geometric and traffic condition, results support its potential usefulness to the transportation engineering community. Further validation under a wide range of traffic and geometric conditions, however, is needed. Researchers are encouraged to use Roadsim to further validate its potential and recommend enhancements.

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Traffic simulation, a tool used by traffic engineers in the analysis of roadway capital investment and traffic control management, provides valuable information to decision makers by predicting the likely effects of traffic or geometric changes on a roadway before the changes actually occur. Simulation results may be used to decide whether to proceed with the change, modify it, or abandon it. Simulation may determine the most effective way to spend available funds.

Initially, traffic simulation was directed to the urban scene. Because urban intersection traffic essentially behaves as a multilane queueing system, traffic may be simulated by using techniques developed for operations research. Simulation of freeway ramp traffic required modeling of traffic behavior by using queueing analogies. Freeway simulation studies were the pioneers of traffic simulation as a research tool.

Simulation of rural traffic on two-lane roads developed at a slower pace because the two-lane flow is complicated by platooning and passing decisions and therefore not easily modeled. Also, the low volumes on rural two-lane roads usually do not make simulation cost-effective. In addition, two-lane traffic simulation requires numerous computations, which require