UMTRI–2000-32

Increased Capacity Automobile Transporter — Feasibility Study And Road-Handling Analysis

This report was prepared for the

National Automobile Transporters Association (NATA)

by the University of Michigan Transportation Research Institute (UMTRI)

Final Report

JUNE 2000

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UMTRI-2000-32		

4. Title and Subtitle	5. Report Date
Increased Capacity Automobile Transporter — Feasibility Study And Road-Handling Analysis	June 2000
	6. Performing Organization Code
7. Author(s) Bareket, Z., and Fancher, P.	8. Performing Organization Report No. UMTRI-2000-32
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute 2901 Baxter Road, Ann Arbor, Michigan 48109-2150	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Automobile Transporters Association 902 Buhl Building, 535 Griswold Street Detroit, MI 48226-3602	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The objective of this project was to study the feasibility of developing automobile transporters with a greater carrying capacity without compromising their handling characteristics. In the context of this project, the primary handling characteristic of interest is offtracking. The offtracking analysis was based on (1) actual measurements, and (2) computer simulation based on design drawings provided by three equipment manufacturers.

This report presents results from the offtracking analysis performed using the manufacturers designs, as well as alternative designs that were suggested by UMTRI.

17. Key Words	18. Distribution Statement
Automobile Transporter, Offtracking	Unrestricted

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
None	None		

INTRODUCTION

The objective of this project was to study the feasibility of developing automobile transporters with a greater carrying capacity without compromising their handling characteristics. In the context of this project, the primary handling characteristic of interest is offtracking.

Currently, auto-transporters (formally known as "Stinger-steered combinations") are limited to a total length of 75 ft. The question that is being asked is "can the carrying capacity of the automobile transporter be increased without causing it to offtrack any worse than other two-unit combinations that are legally allowed today?" A long-wheelbase tractor with a 53 ft semitrailer that is currently permitted on many U.S. highways was selected to serve as a benchmark for offtracking performance.

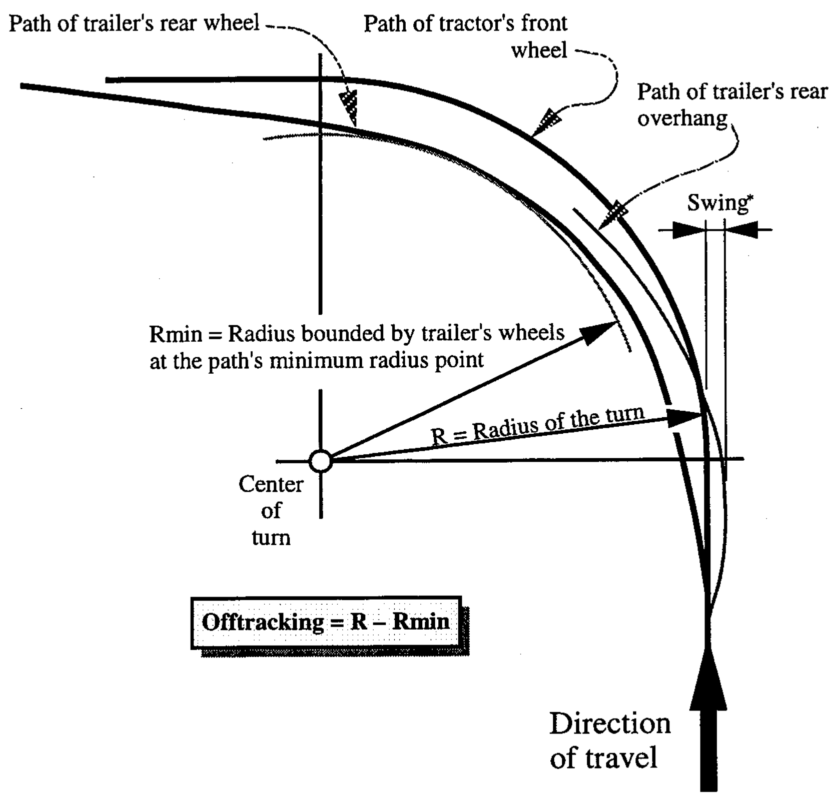
The focus of this study was on performing an offtracking analysis of various auto-transporter configurations. This analysis was based on (1) actual measurements, and (2) design drawings. Several meetings with equipment manufacturers took place, which included a demonstration of loading and unloading of an automobile transporter. Actual offtracking measurements were taken, and schematic layout drawings of both current and suggested configurations were provided to UMTRI. These designs provide those longitudinal dimensions that are sufficient to compute offtracking (length of the individual units, and axle and hitch locations). Three manufacturers provided such design drawings. In this report they are referred to by Mfg. 1, Mfg. 2, and Mfg. 3.

This report presents results from the offtracking analysis performed using the manufacturers designs. It also includes alternative designs that were suggested by UMTRI.

TECHNICAL MODEL

Terminology

The terms and variables associated with modeling and performance evaluation of low-speed offtracking are illustrated in Figure 1 and explained below. Though these terms apply to both high- and low-speed offtracking, the analysis performed in this study addresses only low-speed maneuvers. The dynamic analysis involved with high-speed maneuvers was outside of the scope of this work.



* Note: The swing shown here is exaggerated for demonstration purposes

Figure 1. Low-speed offtracking terminology

For the purpose of offtracking analysis as it was performed in this work, two path trajectories are of interest: the front wheels of the tractor, and the rearmost wheels of the trailer. In this context, the term "wheels" can refer to either the center of the axle, the outside wheel, or the inside wheel. However, it is important to maintain consistency for both path trajectories (i.e., if the path of the front-inside wheel is used, then the path of the rear-inside wheel should also be used, etc.)

While the front wheels of the tractor follow a circular path of radius R, the trailer's rearmost wheels offtrack toward the inside of the turn. At the same time, the rearmost point of the trailer (the overhang, which is further back behind the trailer's rear axle), "swings" outside the prescribed turning radius. With the overhang size of typical trailers, the amount of swing will be almost negligible. However, when the overhang of the trailer approaches half the wheelbase length and more, this measurement of swing becomes an important factor as the trailer's rear end might encroach into the opposing lane. As noted in the figure, the illustrated swing is exaggerated.

Another important term in evaluating offtracking is *swept path*. As the name implies, swept path describes the amount of roadway area "covered" by the turning vehicle. For a truck making a left-hand turn, such as depicted in Figure 1 for example, the swept path is the area bounded by (1) the path of the tractor's front-outside wheel, (2) the path of the trailer's rear-inside wheel, and (3) the swing path of the trailer's right-rearmost point.

Offtracking Performance

Offtracking performance can be assessed in several different ways. The most simple and straightforward way is an experiment where the actual wheel paths are marked, and the appropriate measurements are then taken. While this approach provides the most realistic evaluation, it is also the most time-consuming and complicated to perform. In addition, it is impossible to evaluate truck combinations that are still in the design phase, for which no actual prototype exists.

The purpose of using experimental methods in this work was (1) to extract data, and (2) to validate an example computed result. The experiment that was performed and the results that were obtained, are described under the topic "Measured data" in the next section.

The method of "sum of squares" lies at the other extreme of complexity from the experiment: it is the simplest and quickest to apply. However, the result (a simple numeric value), also provides the lowest level of insight and physical visualization of the actual offtracking scenario.

Steady state offtracking is computed by the following equation: $OT_{ss} = R - \sqrt{R^2 - \sum(wb)^2}$. The term $\sum(wb)^2$ in the equation is commonly referred to as "the sum of squares". To compute it, wheelbases are squared and added; overhang hitches (stingers) are squared and subtracted.

Using the convention of Figure 2, the sum of squares is given by: $\sum(\mathrm{wb})^2 = A^2 + B^2 - S^2$. The sum of squares provides a useful reference value relating to steady-state offtracking. This value is useful as a method for comparison (for example, if combination "X" has a lower sum of squares than combination "Y", it will also demonstrate a better transient offtracking. Nevertheless, the actual transient offtracking value of either "X" or "Y" cannot be determined just by the sum of squares.)

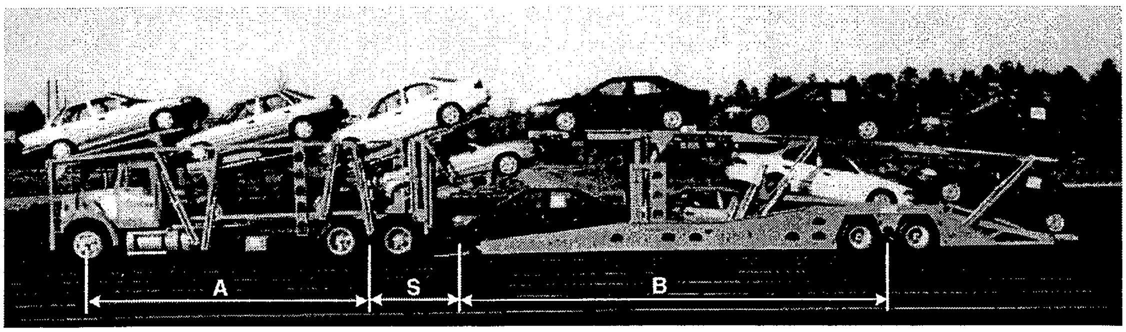


Figure 2. Offtracking and sum-of-squares dimensions

Computer-model simulations present the desired compromise between an experiment and the sum-of-squares simplification. Once the simulation model has been devised, it can provide a good insight to the offtracking problem with only a fraction of the effort required to conduct an actual experiment. Within the framework of this study, all three methods were applied.

Generally speaking, computer simulations can provide results for (1) steady-state offtracking, or/and (2) transient offtracking. Depending on the truck combination in question, it may need to complete anywhere from about 135° turn up to several 360° turns to reach steady-state offtracking. Transient offtracking describes the instantaneous wheel trajectories and swept paths of the truck during a turning maneuver. Steady-state offtracking is almost never reached during normal operations, even under tight turns. This type of measure is more of a theoretical one, where as the transient offtracking represents a more practical measure. Nevertheless, since it is so easy to compute a "sum of squares" value which serves to scale the maximum offtracking of a given vehicle combination, this measure is presented as a reference value for each vehicle considered here. On the other hand, all final performance evaluations presented in this work, are based solely on transient offtracking values. The computer simulation model that was used provides the values of Rmin, Offtracking, and Swing (see Figure 1) that derive from transient turning.

DATA AND MEASUREMENTS

The analysis that was performed within the framework of this study addressed vehicles having different geometric parameters. The geometric layouts of some of the automobile-transporters were based on actual measurements, and some were based on design drawings. Layouts for baseline tractor-semitrailers that were used as reference combinations were taken from the literature. This section lists pertinent terminology that is associated with vehicle layout configuration and also presents measured data from offtracking tests.

Geometric Data of the Baseline Tractor-Semitrailer

The offtracking analysis carried out in this study entailed a comparison of the performance levels of automobile transporters with those of common two-unit combinations. Three baseline tractor-semitrailer configurations were considered as benchmarks: (1) 48 ft semi, (2) 50 ft semi, and (3) 53 ft semi. All these semitrailers were assumed to be attached to a tractor whose wheelbase is 189 inches. The three baseline tractor-semitrailer configurations are depicted in figure 3 in an aggregate form, listing from top to bottom the respective parameters for the 48, 50, and 53 ft semitrailer versions.

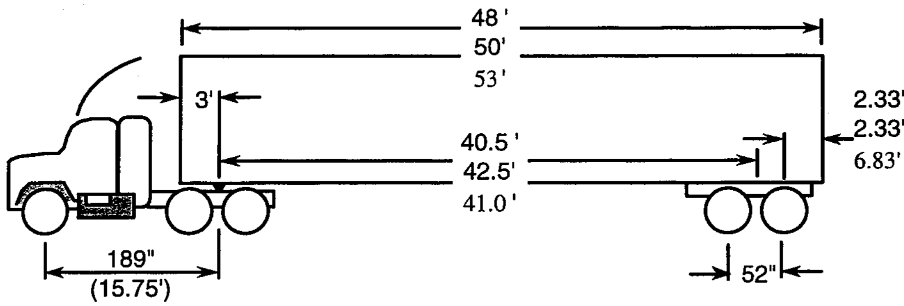


Figure 3. baseline tractor-semitrailer configurations

Some notes and facts regarding the use of the 53 ft semi as a benchmark for offtracking performance are in order. First, unlike the 48 ft semitrailer, the 53 ft semitrailer is <u>not</u> allowed nation-wide. Semitrailers of 50 and 53 ft are allowed in Michigan and in many other states as well. However in Michigan, the 53 ft trailer is allowed **only** on designated routes. It should be noted that there is no such limitation on either the 48 ft trailer, the 50 ft trailer, or the 75 ft auto transporters. Also, from the standpoint of dimensions, the wheelbase of the 53 ft trailer is limited in Michigan and a few other states to 40.5 ± 0.5 ft (that is, the maximum allowable wheelbase for this trailer is 41 ft). Such a wheelbase limitation (or for that matter — a total length limitation) is not imposed on the 50 ft tractor- semitrailer combination. These restrictions are reflected in the dimensions depicted in Figure 3.

The approach of using the 53 ft tractor-semitrailer as a baseline for comparison has two potential shortcomings, namely, (1) they are allowed only on designated routes, and (2) the limited wheelbase is likely to cause less offtracking when compared to a 50 ft tractor-semitrailer. In the following performance analysis all three semitrailers were considered, however, special attention was given to the 50 ft trailer as it might be a better benchmark choice.

Offtracking Responses Measured in Auto Transporters Tests

At a meeting that took place in a loading terminal, the process of loading and unloading of an automobile transporter was demonstrated. In addition, we performed two actual measurements: offtracking, and minimum turning radius. The vehicle used in these tests was a current 75 ft auto transporter with the following dimensions: tractor wheelbase of 21 ft, trailer wheelbase of 30.6 ft, trailer overhang of 13.8 ft, and stinger length of 7.4 ft.

First, the tractor followed a circular curve (R = 50 ft) that was marked on the ground. The path of the trailer's rearmost wheels was marked, so that the swept path of the automobile transporter as it goes through a 90° turn was depicted. Subsequently, the offtracking was measured. From the results that are shown in Figure 4, the offtracking in this case is 12.3 ft.

A calculation using the simulation model for this vehicle resulted in an offtracking value which was 13.3 ft — a deviation of 1 ft. Given the approximations that are involved with such a graphic analysis, it appears that the theoretical model for calculating offtracking represents the problem well.

In a second test, the tractor had its steering wheels turned to the full-lock position, and then it started driving slowly while the paths of the front and rearmost wheels were marked (see Figure 5). Using approximated geometry relations, the reference curve was determined to be of R = 45.25' as the minimum radius of that tractor's inner-front wheel. Figure 5 shows that the offtracking of the minimum offtracking turn is 45.25 – 28.50 = 16.75 ft.

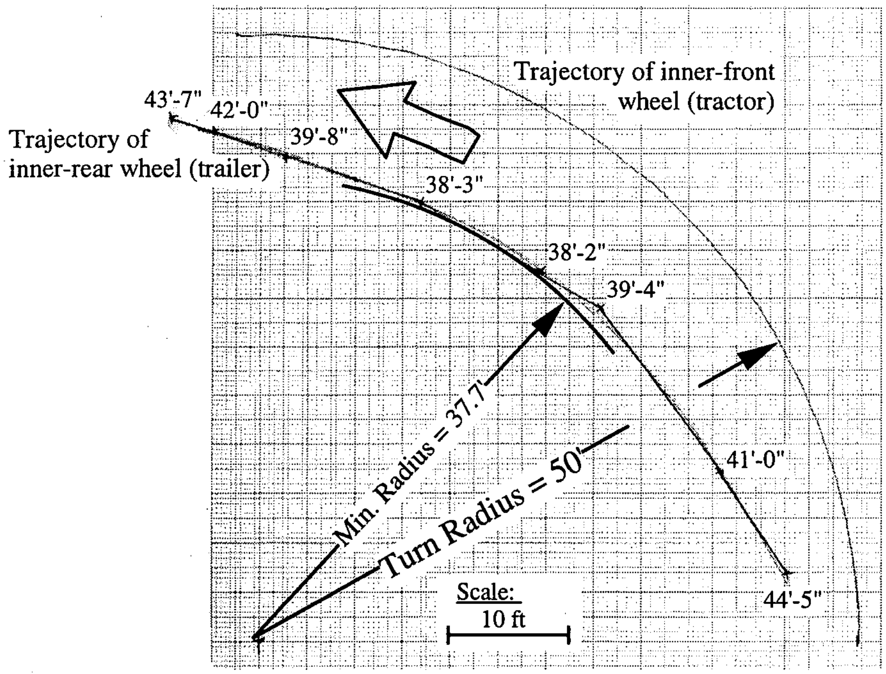


Figure 4. Offtracking experiment — 50 ft turning radius

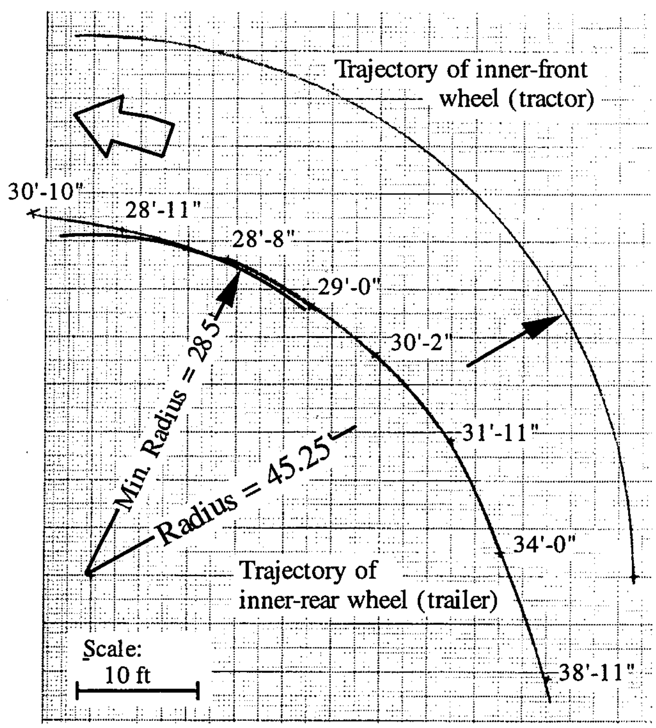


Figure 5. Determining minimum turning radius

Auto Transporter Design Data

Three manufacturers of automobile transporters provided drawings for their primary configurations. These drawings depict those longitudinal dimensions that are required for offtracking analysis. Data were provided for the following configurations:

Manufacturer	Model lengths for which data were provided
Mfg. 1	75’, 85’
Mfg. 2	75’, 80’, 82’, 84’, 85’
Mfg. 3	75’, 82.3’

The pertinent longitudinal dimensions for offtracking are depicted in Figure 6. The needed parameters include tractor or truck wheelbase (A), trailer wheelbase (B), trailer overhang (C), and the effective length of the truck’s stinger (S) (that is, the offset of the low-mounted fifth wheel coupling off of the tractor’s tandem centerline – a stereotypical feature of auto-transporting vehicles that has been termed *stinger steering*.) These dimensions for the various configurations are listed in table 1.

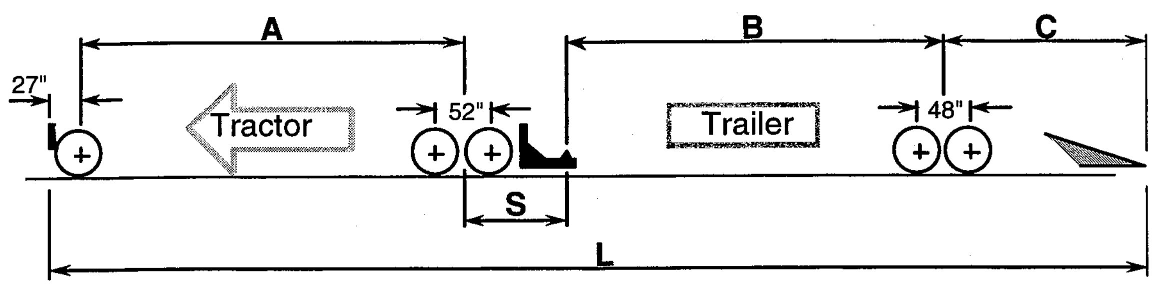


Figure 6. Dimensions template of an automobile transporter

Table 1. Auto transporter design data

Dimension		Mfg. 1		Mfg. 2					Mfg. 3	
Symbol	Description	75’	85’	75’	80’	82’	84’	85’	75’	82.3’
A	Tractor’s wheelbase (ft)	21.2	21.8	21.2	21.2	21.2	21.2	21.2	21.0	21.0
B	Trailer’s wheelbase (ft)	31.7	37.9	30.8	35.8	36.8	38.8	38.8	30.6	38.0
C	Trailer’s overhang (ft)	12.1	14.0	13.6	13.6	13.6	13.6	13.6	13.8	13.7
S	Stinger’s eff. length (ft)	7.2	9.2	7.2	7.2	8.2	8.2	9.2	7.4	7.4

RESULTS FROM SIMULATION AND ANALYSIS

In this section results from simulation and other analyses of offtracking response are presented. In selecting a turning radius for the simulation runs it was first noted that the minimum turning radius of the 50 ft tractor-semitrailer was found to be about 45.5 ft. In the actual offtracking measurements that were performed (see "Measured data" in the previous section), the minimum turning radius for the auto transporter was then noted to be approximately 45.25'. Accordingly, it was determined that for the simulations performed in this analysis of various transporter designs, a turning radius of 46 ft would be an appropriate choice.

Comparison of Offtracking Performance for Manufacturer-Supplied Designs

The configurations provided by the automobile transporter manufacturers were simulated to execute a 90° turn at R = 46 ft. Similarly, the baseline tractor-semitrailers were also simulated. Table 2 lists the results from the computer model and also the sum-of-squares descriptor for each vehicle.

Table 2. Offtracking and sum-of-squares results

	Mfg. 1		**Mfg. 2**					**Mfg. 3**		**Baseline Tractor-semitrailer**		
Measure	75'	85'	75'	80'	82'	84'	85'	75'	82.3'	53 ft trailer	50 ft trailer	48 ft trailer
Offtrack (ft)	13.7	16.7	13.2	15.6	16.0	17.0	16.9	13.1	16.6	17.0	17.8	16.7
Rmin (ft)	32.3	29.3	32.8	30.4	30.0	29.0	29.1	32.9	29.4	29.0	28.2	29.3
Swing (ft)	0.40	0.64	0.57	0.52	0.55	0.53	0.59	0.61	0.52	0.10	0.01	0.01
$\sum(wb)^2$ (ft^2)	1402	1827	1346	1679	1736	1888	1870	1323	1830	1929	2054	1888

All the 75-ft-long automobile transporters that are currently manufactured demonstrate similar offtracking performance levels that lie between 13.1 ft and 13.7 ft. The longest of the configurations suggested by each manufacturer also do not differ greatly in offtracking response, spanning a range of values between 16.6 ft and 16.9 ft. At a total length of 85 ft, these configurations demonstrate an offtracking level which is comparable to that of the 48 ft semitrailer — namely 16.7 ft. The offtracking of the 53-ft semitrailer is almost the same at 17.0

ft. On the other hand, due to its longer wheelbase (see Figure 3), the 50-ft semitrailer demonstrates the worst offtracking — 17.8 ft.

The 85 ft automobile transporter designs all incorporated stinger lengths between 7 ft and 9 ft. We studied additional 85 ft combinations which incorporated a common 8 ft length for the stinger, but without any noticeable improvement. In order to significantly improve the offtracking performance of these automobile transporter designs, a longer stinger (and correspondingly – a shortened semitrailer wheelbase dimension) is required.

However, increasing the length of the stinger involves structural strength challenges, and tends toward greater loading on the tractor's rear axle. Since the semitrailer load is applied to the stinger-mounted fifth wheel which is outside the tractor's wheelbase, it causes the tractor front axle to be unloaded. In order to maintain steering capability, the only way to restore load over the front axle is by placing more payload on the truck ahead of its rear axle. As a result, the rear axle of the tractor can quickly become overloaded as stinger length is increased.

A possible solution can be to introduce a three-axle (i.e., tridem) rear suspension on the tractor. The disadvantages of this solution are primarily (1) increased complexity and cost of the tractor unit, and (2) increased empty weight. The advantages, on the other hand, are (1) the ability to increase the length of the automobile transporter, and therefore the loading space, (2) the ability to carry more payload. Also, unlike the addition of trailer axles, additional axles on the tractor have minimal interference with the payload.

We tried combinations having a tridem rear suspension on the tractor (Figure 7). Details of these tridem combinations and the simulated offtracking results are summarized in Table 3.

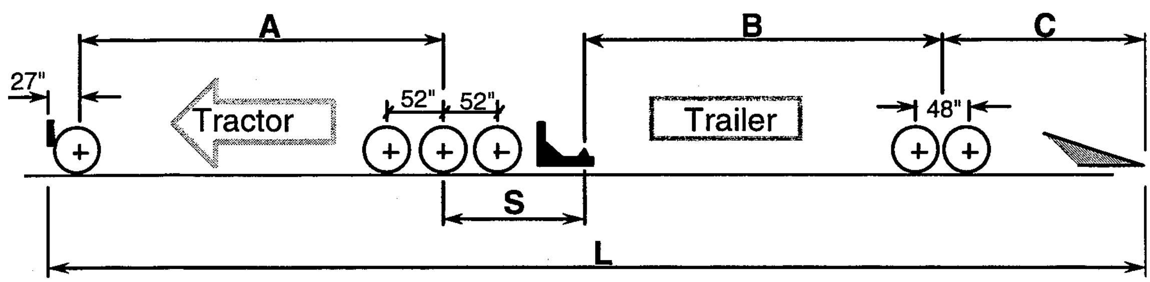


Figure 7. Tridem tractor configuration

Table 3. Transient offtracking results for tridem configurations

Overall Length (ft):	85.00	85.00	85.00	90.00	90.45	92.50	93.00
A (ft)	25.00	28.75	28.00	28.00	30.00	30.00	33.00
B (ft)	35.00	31.00	30.00	35.00	32.00	35.00	33.00
C (ft)	14.75	14.00	13.50	13.75	15.00	15.00	13.75
S (ft)	8.00	9.00	11.20	11.00	11.20	10.20	11.00
Transient offtracking (ft)	16.5	16.1	15.1	17.4	16.8	18.3	18.6

The results in table 3 look rather promising. Compared to results shown earlier for the baseline tractor-semitrailer configurations which gave offtrack values between 16.7 ft (48 ft semitrailer) and 17.8 ft (50 ft semitrailer), the reduced levels of 15.1 to 16.5 ft seen with the tridem-equipped, 85-ft-long automobile transporters show that they outperform the baseline tractor-semitrailers.

Exploring Optimal Parameters for the Industry-Preferred 90 ft Auto Transporter

Next we looked at an analytical way to further optimize the offtracking. A range of parametric values was selected as:

Tractor (truck) wheelbase (A in Figure 5) .... 20 – 30 ft (at 1 ft intervals)
Stinger (S in Figure 5) .... 10 – 15 ft (at 1 ft intervals)
Overhang (C in Figure 5) .... 14 ft
Trailer wheelbase (B in Figure 5) .... calculated to achieve a total length of 90 ft

Using a spreadsheet, all the combinations of the parametric values listed above were organized, and the sum of squares for each was computed. The results are plotted in Figure 8. The figure shows that each "set" has some optimal offtracking point; that is, a point where the sum of squares reaches a minimum.

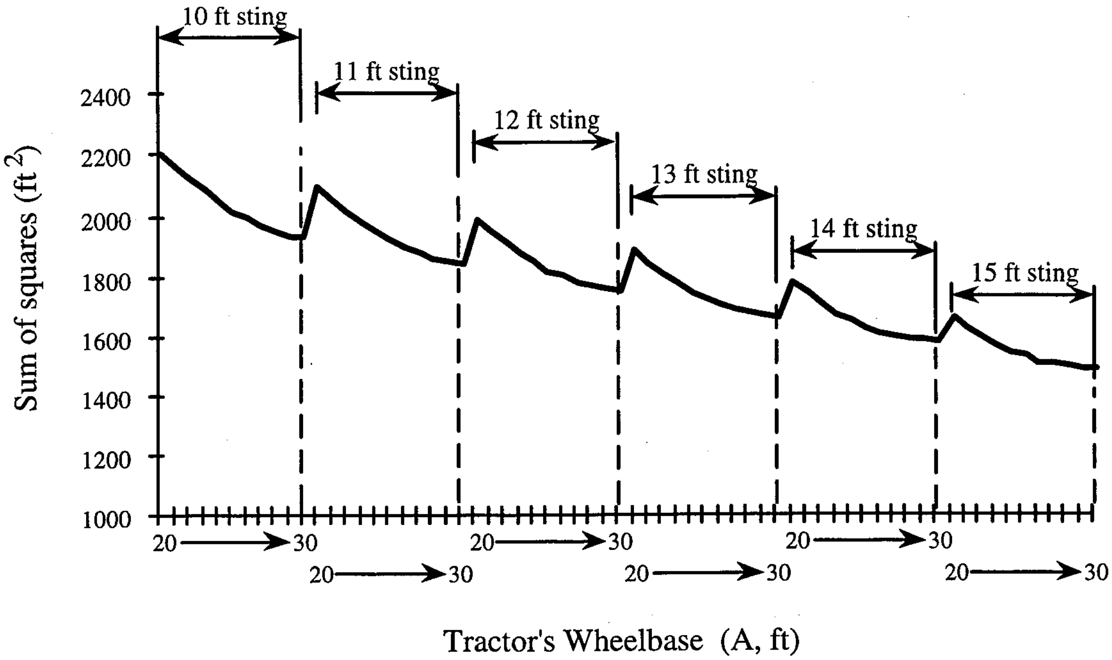


Figure 8. Optimization by sum of squares

For the combinations that comprised the "best" three sets (sting lengths of 13, 14, and 15 ft), the actual offtracking response values were then computed by simulation. The results are illustrated in Figure 9. It appears that even though the sum-of-squares measure is primarily associated with steady-state offtracking, it can also serve as a good comparative predictor of differences in transient offtracking performance.

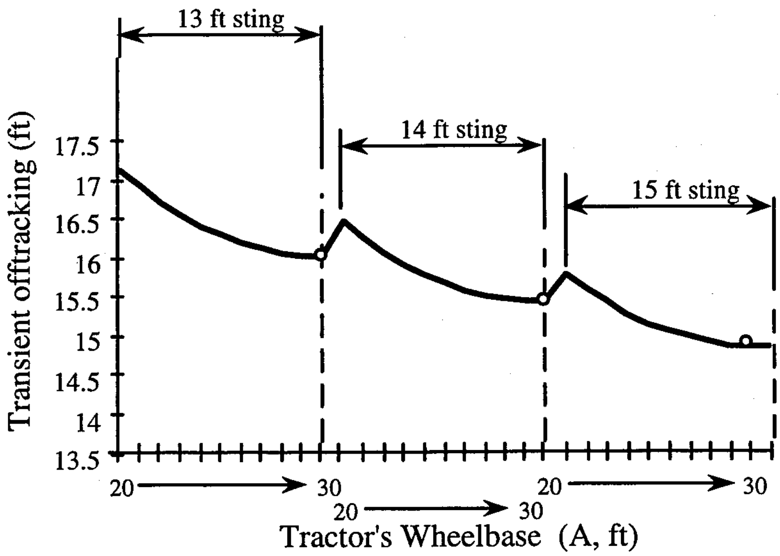


Figure 9. Best configuration by sum of squares

On the plot in Figure 9, the circled points represent those at which the offtracking reaches minimum values. The results for these points are provided in table 4.

Table 4. Offtracking of configurations with minimum sum of squares

Total length (ft)		90.0	
Overhang (ft)		14.0	
Sting length (ft)	13.0	14.0	15.0
Tractor wheelbase (ft)	30.0	30.0	29.0
Trailer wheelbase (ft)	30.8	29.8	29.8
Transient offtracking (ft)	16.0	15.5	14.9

These data show that any of the combinations depicted in the table above, even though they all have a total length of 90 ft, will exhibit offtracking responses that outperform even the most common, 48-ft-semitrailer combination and even more so, the 50 ft semitrailer.

Analysis of a 90 ft Baseline Auto Transporter

Additional analysis which included several combinations of suspension types (tandem/tridem) for both the truck-tractor and the trailer was performed for auto-transporter combinations having an overall length of 90 ft. The offtracking model that was employed in this analysis lumps multi-axle suspensions to a single axle, located at the geometric center of the more complex suspension. As a result of this simplification, the simulation outputs for the tridem-axle trailer and for the tandem-axle trailer were identical. In other words, from an offtracking standpoint a tridem-axle trailer and a tandem-axle trailer have similar performance.

According to the manufacturers of automobile transporters, acceptable stinger lengths should be taken as 9 ft for a truck-tractor with a tandem axle at the rear, and 11 ft for a truck-tractor having a tridem axle. Since the stinger length is different for a tridem-axle truck and a tandem axle truck, the simulation results for these two configurations were distinct.

Two configurations of automobile transporters were analyzed. Figures 10 and 11 show the two layouts of the automobile-transporter combinations that were studied:

- A tridem-axle truck-tractor with a tandem- or tridem-axle trailer, and
- A tandem axle truck-tractor with a tandem- or tridem-axle trailer.

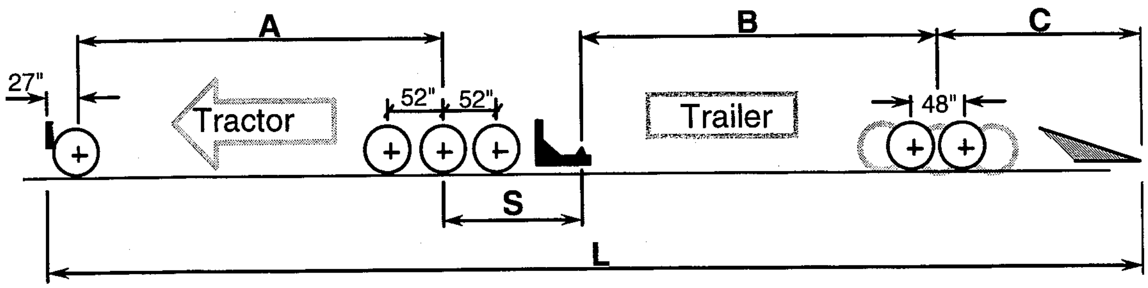


Figure 10. Tridem tractor with a tridem/tandem trailer

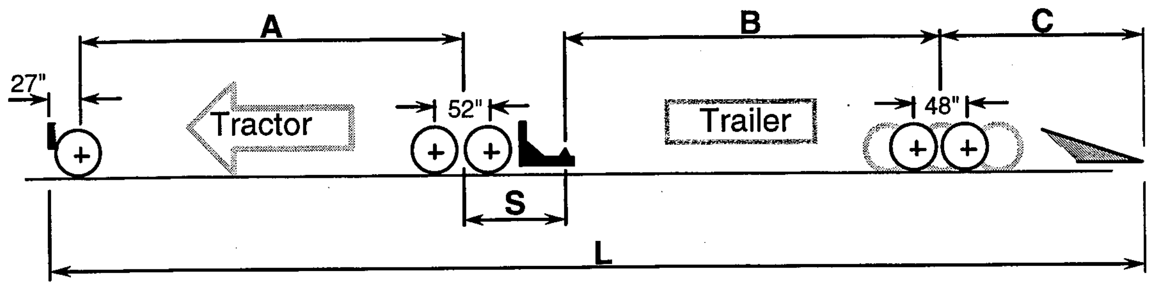


Figure 11. Tandem tractor with a tridem/tandem trailer

The "starting point" for wheelbases was: A = 30 ft, and B = 32 ft. The overall length used in this analysis (common to all configurations) is 90 ft. In addition, as mentioned above, design considerations determined the length of the stinger based on the type of rear suspension used in the truck-tractor. The long rear overhang of the trailer (dimension "C" in the figures) has obvious negative effects that are associated with it (such as the Swing illustrated in figure 1). At the same time, the overhang has a positive effect on loading space. To cover a range of possibilities, two different overhang lengths were simulated (C = 14.75 and 13.75 ft). Another factor considered was the importance of the trailer's wheelbase: dimension "B" can be very crucial for efficient loading. As a result, each of the two layouts was simulated with two different truck wheelbases (A = 30 and 28 ft) to allow longer trailers. A total of four simulations was performed for each configuration layout.

The configurations were simulated to execute a 90° turn around a turning radius of 46 ft. The results of the analysis are summarized in Table 5.

Table 5. Offtracking results for 90 ft configurations

Configuration:	Tridem tractor with a tridem/tandem trailer (Figure 1)				Tandem tractor with a tridem/tandem trailer (Figure 2)			
Overall Length (ft):	90.00							
A (ft)	30.00	28.00	30.00	28.00	30.00	28.00	30.00	28.00
B (ft)	32.00	34.00	33.00	35.00	34.00	36.00	35.00	37.00
C (ft)	14.75	14.75	13.75	13.75	14.75	14.75	13.75	13.75
S (ft)	11.00	11.00	11.00	11.00	9.00	9.00	9.00	9.00
Transient offtracking (ft)	16.8	16.9	17.3	17.4	17.9	18.0	18.4	18.5

Considering the range of offtracking values for the baseline tractor-semitrailers (16.7 to 17.8 ft), we see from the results in table 5 that all 90-ft auto transporters with a tridem-equipped tractor demonstrate offtracking performance that fall within that range. Two of the auto transporters with tandem-equipped tractors (C = 14.75 ft) demonstrate a transient offtracking response that is only 0.1 and 0.2 ft poorer than that of the 50 ft semitrailer.

SUMMARY

In general, the guidelines for designing the best offtracking tractor-trailer combination might be formulated as follows:

- Tractor wheelbase (dimension "A" in the figures) and trailer wheelbase (dimension "B") should be the same (A = B), and at their minimal possible value.
- Stinger length ("S") should be as long as practically reasonable.

The baseline reference used in this study is a 53 ft tractor-trailer. The transient offtracking of that combination (see table 2) is 17.0 ft. It can be argued that unless marginal conditions prevail (either in an actual delivery area, or in a tightly-designed test course), all the auto-transporter combinations of 90 ft overall length listed in table 5 will demonstrate a level of offtracking performance that is within 10% of the response on the 53-ft semitrailer.

It should be noted that this study has restricted its examination of auto transporter design to the issue of offtracking performance only. It is assumed that vehicle configurations that show good offtracking performance can also be made to exhibit acceptable performance in other domains of dynamics and control, as needed to satisfy the broad mission requirements for a highway vehicle.