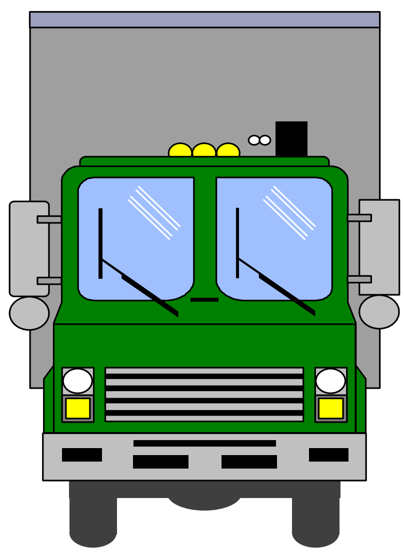
CHAPTER 7



Highway Geometry

INTRODUCTION

Changes in truck size and weight (TS&W) limits impact curve and intersection designs. The costs to adjust these roadway geometric features and provide staging areas to properly accommodate the use of longer combination vehicles (LCVs) are included in this chapter.

BASIC PRINCIPLES

This section provides an overview of the relationship between vehicle turning characteristics and roadway geometry.

TRUCK TURNING CHARACTERISTICS

For this Study, truck turning characteristics, "offtracking," were considered in determining the extent to which roadway geometrics would need to be upgraded to accommodate larger trucks on the roadway. When a vehicle makes a turn, its rear wheels do not follow the same path as its front wheels. The magnitude of this difference in path, known as offtracking, generally increases with the spacing between the axles of the vehicle and decreases for larger radius turns. Off-tracking of passenger cars is negligible because of their relatively short wheelbases; however, many combination trucks offtrack substantially.

LOW-SPEED OFFTRACKING

When a combination vehicle makes a low-speed turn--for example a 90-degree turn at an intersection--the wheels of the rearmost trailer axle follows a path several feet inside the path of the tractor steering axle. This is called low-speed offtracking. Excessive low-speed offtracking may make it necessary for the driver to swing wide into adjacent lanes to execute the turn (that is, to avoid climbing inside curbs or striking curbside fixed objects or other vehicles).

When negotiating exit ramps, excessive offtracking can result in the truck tracking inward onto the shoulder or up over inside curbs. This performance attribute is affected primarily by the distance from the tractor kingpin to the center of the trailer rear axle or axle group (see "Kingpin Setting" box, below). In the case of multitrailer combinations, the effective wheelbase(s) of all the trailers in the combination, along with the tracking characteristics of the converter dollies, dictate this property. In general, longer wheelbases worsen low-speed offtracking. Exhibit 7-1 illustrates low-speed offtracking in a 90-degree turn for a tractor-semitrailer.

The standard double-trailer combination (two 28-foot trailers) and triple-trailer combination (three 28-foot trailers) exhibit better low speed offtracking performance when compared to a standard tractor and 53-foot semitrailer combi-

KINGPIN SETTING

The kingpin, a part of the fifth wheel connection, is the pivot point between the tractor and semitrailer. The kingpin setting is the distance from the center of the fifth wheel connection to the center of the rear axle group.

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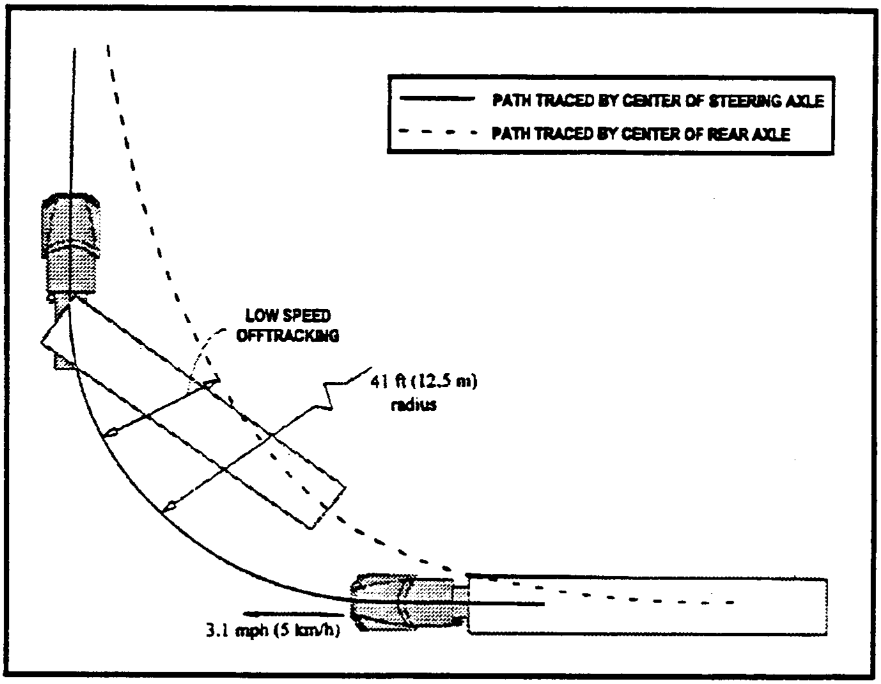
EXHIBIT 7-1
LOW-SPEED OFFTRACKING



nation. This is because they have more articulation points in the vehicle combination, and use trailers with shorter wheelbases.

HIGH-SPEED OFFTRACKING

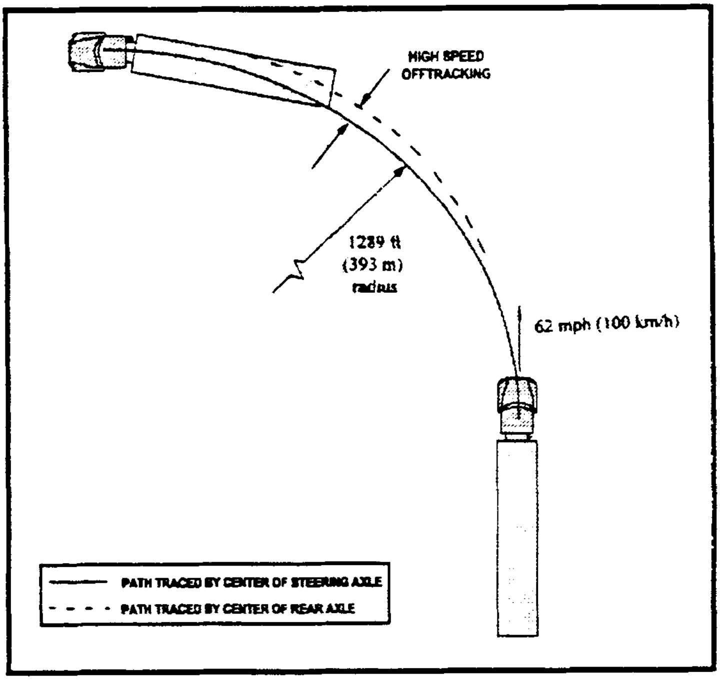
High-speed offtracking, on the other hand, is a dynamic, speed-dependent phenomenon. It results from the tendency of the rear of the truck to move outward due to the lateral acceleration of the vehicle as it makes a turn at higher speeds. As the speed of the truck increases from very slow, the total offtracking decreases until, at some particular speed, the rear trailer axles follow exactly the tractor steering axle. At still higher speeds, the rear trailer axles will track outside of the tractor steering axle. The speed-dependent component of offtracking is primarily a function of the spacing between truck axles, the speed of the truck and the radius of the turn. It is also dependent on the loads carried by the truck axles and the truck suspension characteristics. Exhibit 7-2 illustrates high-speed offtracking for a standard tractor-semitrailer.

ROADWAY GEOMETRY AND TRUCK OPERATIONS

INTERSECTIONS

Most truck combinations turning at intersections encroach on either the roadway shoulder or adjacent lanes. For example, the

EXHIBIT 7-2
HIGH-SPEED OFFTRACKING



turning path of a truck making a right turn is generally controlled by the curb return radius, whereas the turning path in left turns is not constrained by roadway curbs, but may be constrained by median curbs and other traffic lanes. Combination vehicles with long semitrailers are critical in the determination of improvements to intersections required to accommodate offtracking requirements.

It is generally agreed that proper roadway design and vehicle operation requires that no incursion into the path of vehicles traveling in opposing directions of flow be allowed. A higher standard is often used for roadway design in urban areas, where no incursion into any adjacent lane is allowed. This is particularly critical at signalized intersections where heavy traffic is a prevailing condition.

However, a substantial number of intersections on the existing highway and street network cannot accommodate even a five-axle tractor semitrailer combination with a 48-foot semitrailer. There are a substantial number of intersections for which improvements for these vehicles are not feasible and controls on vehicles, routing or travel times are required. Examples of common constraints to intersection improvements are bridges, buildings and sensitive environmental or historic plots.

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Interchange Ramps

Access and exit ramps for controlled access highways, such as Interstates, are intended to accommodate certain types of vehicles at design speeds, as well as for high-speed and low-speed offtracking by combination vehicles.

Horizontal Curvature

The rear wheels of trucks and truck combinations traversing horizontal curves generally offtrack to one side or the other of the paths of the wheels on the steering axle. When a truck is traveling at higher speeds the rear wheels can follow a path outside that of the steering axle wheels. This effect is relatively small and virtually never results in the need to make geometric improvements beyond those normally made in the design process. On the other hand, when offtracking is to the inside of the curve at lower speeds and in stop-and-go traffic, it is usually more substantial and must be accommodated. Truck combinations with longer trailers are often prone to producing relatively large amounts of offtracking beyond that provided for in the American Association of State Highway and Transportation Officials (AASHTO) design standards. For roadways not constructed to AASHTO standards, more improvements would be required to accommodate longer combinations where offtracking would exceed normal lane width.

ANALYTICAL APPROACH

The objective of the roadway geometry research conducted for this Study was to examine the impact that the scenario truck configurations would have on the geometric elements (freeway interchanges, at-grade intersections, mainline curves, and lane widths) of the current roadway system, determine what improvements would be needed to accommodate these new trucks, and estimate the costs of these improvements. The focus of this research was to compare the new truck configurations with common, existing large trucks.

Alternative vehicle configurations, including single-unit or straight trucks and single- and multitrailer truck combinations, were analyzed in terms of their interaction with highway infrastructure features. The list of roadway geometry features analyzed includes interchange ramps and intersections.

The baseline trucks used for the Study were the standard tractor-semitrailer combination with 48-foot trailer operating at 80,000 pounds and the Surface Transportation Assistance Act (STAA) double combination with two 28-foot trailers operating at 80,000 pounds. The research analyzed 15 basic truck configurations. Each configuration category includes various body types, specified sets of axle spacings, truck lengths, and trailer lengths, which resulted in 89 specific cases being assessed. Exhibit 7-3 provides the basic configurations examined. For example, tractor semitrailer combinations with trailer lengths up to 57.5 feet were evaluated. All of the STAA twin-trailer combinations considered had two 28-foot trailers. The eight-axle B-train double trailer combination with two trailers

EXHIBIT 7-3
BASIC CONFIGURATIONS
ROADWAY GEOMETRY ANALYSIS

- THREE-AXLE SINGLE UNIT TRUCK (SUT)
- FOUR-AXLE SUT WITH TWIN STEER AXLES
- FOUR-AXLE SUT WITH THREE DRIVE AXLES
- FIVE-AXLE TRACTOR-SEMITRAILER
- SIX-AXLE TRACTOR-SEMITRAILER
- FIVE-AXLE SUT WITH TWO-AXLE FULL TRAILER
- SEVEN-AXLE SUT WITH FOUR-AXLE FULL TRAILER
- FIVE-AXLE STAA DOUBLE
- SIX-AXLE STAA DOUBLE
- SEVEN-AXLE STAA DOUBLE
- SEVEN-AXLE ROCKY MOUNTAIN DOUBLE
- SEVEN-AXLE B-TRAIN DOUBLE
- EIGHT-AXLE B-TRAIN DOUBLE
- NINE-AXLE TURNPIKE DOUBLE
- SEVEN-AXLE TRIPLE

STAGING AREAS

Staging areas are used to break down long multitrailer combinations into single-trailer or shorter multitrailer vehicles for operation on at-grade highways, especially those with only one lane in each direction. The assumption that staging areas will be provided, increases the overall roadway geometry costs of the Longer Combinations Vehicles Nationwide Scenario while reducing the costs to upgrade interchanges somewhat. The Study assumes the breakdown of combinations, which have offtracking greater than the baseline combinations, when they leave a highway designated for their use. This breakdown occurs in either publicly or privately provided staging areas. It is also assumed that carriers would arrange for staging areas not publicly provided when these arrangements provide for more economical operations. Whether provided by the public or privately, the staging areas need to be in place and their costs need to be accounted for.

up to 33 feet in length was evaluated. The maximum size considered for the Rocky Mountain Double (RMD) combination included the first trailer at 53 feet and the second trailer at 28 feet. Turnpike Doubles (TPD) with two trailers up to 53 feet in length were considered.

The offtracking characteristics of the Study combination vehicles in relation to curves and intersections, whether on "at-grade" facilities or ramps of freeway (Interstate and non-Interstate) interchanges, were addressed. This was done in terms of offtracking, swept path, shoulder or curb encroachment, and the estimated costs to upgrade the roadways on which each configuration is assumed to operate, such that the offtracking problem is eliminated. The costs of improvements needed to eliminate excessive offtracking was estimated with and without staging areas (see "Stagging Areas" box, left) being provided.

VEHICLE OFFTRACKING PERFORMANCE

The offtracking characteristics of the larger scenario trucks are markedly different from the standard baseline trucks on the road. Research for this Study examined low-speed and high-speed offtracking and swept path width of the LCVs. (See "Swept Path" box, below.)

Exhibit 7-4 presents the offtracking characteristics of the truck combinations evaluated in this Study. The offtracking characteristics of single unit trucks are not presented as they have minimal offtracking; their swept path falls well within current lane width standards. These characteristics are given for an intersection of two-lane roadways with lane widths of 12 feet (current highway design standards call for lanes wider than 12 feet for two-lane roadways). The curb radius is 60 feet.

The exhibit shows that those combinations with two and three short trailers offtrack less than the baseline vehicle, a 48-foot semitrailer combination with a 41-foot kingpin setting. The two semitrailer combinations with lengths of 53 feet and 57.5 feet show the sensitivity of offtracking to the kingpin setting. A 53-foot semitrailer with a 41-foot kingpin setting would offtrack the same as the 48-foot semitrailer combination, but the back of the trailer would swing out a little further due to the

SWEPT PATH

Swept path is the amount of roadway space the truck needs to make the turn without hitting something. The most appropriate descriptor of offtracking for many roadway geometric design applications is the "swept path width." This is shown in the sketch below as the difference in paths between the outside front tractor tire and the inside rear trailer tire(s) of the vehicle.

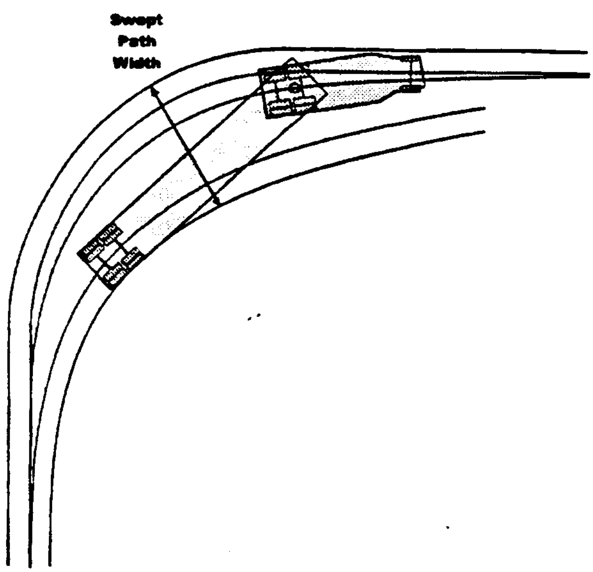

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EXHIBIT 7-4
OFFTRACKING CHARACTERISTICS FOR TRUCKS TURNING RIGHT AT TYPICAL TWO-LANE ROADWAY INTERSECTION
(12-FOOT LANES, 60-FOOT CURB RETURN, 38-FOOT PATH RADIUS)

Truck Configuration	Trailer Length(s) (feet)	Kingpin Setting(s) (feet)	Offtracking		Swept Path		Encroachment to Inside of Track	
			feet	percent	feet	percent	feet	percent
Five-Axle Semitrailer	48.0 (Base Line Vehicle)	41.0	14.2	100	21.8	100	10.4	100
	53.0	46.0	16.5	116	24.2	111	12.8	123
	57.5	50.5	18.7	132	26.4	121	15.0	144
Six-Axle Semitrailer	53	44.0	15.6	110	23.2	106	11.8	113
Five-Axle Double	28, 28	21.9 21.9	8.4	59	16.1	74	4.7	45
Seven-Axle Rocky Mountain Double	53, 28	46.0 23.0	18.9	133	26.6	122	15.2	146
Eight-Axle B-Train Double	33,33	32.2 27.1	14.2	100	21.9	100	10.4	100
Nine-Axle Turnpike Double	53, 53	46.0 46.0	27.0	190	34.7	159	23.2	223
Seven-Axle Triple	28, 28, 28	23.0 23.0 23.0	12.7	89	20.4	94	9.0	87

additional 5 feet from the center of its trailer axle group to the back of the trailer.

The effect of articulation, dividing one unit (in this case, the trailer) into one or more units, can be seen by comparing the offtracking of the 57.5-foot semitrailer with the RMD. Their offtracking characteristics are virtually the same, but the RMD, a combination with 53-foot trailer, and a 28-foot trailer

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has an additional 23.5 feet in cargo box length. The combination with the worst offtracking characteristics is the TPD with two 53-foot trailers.

IMPACTS

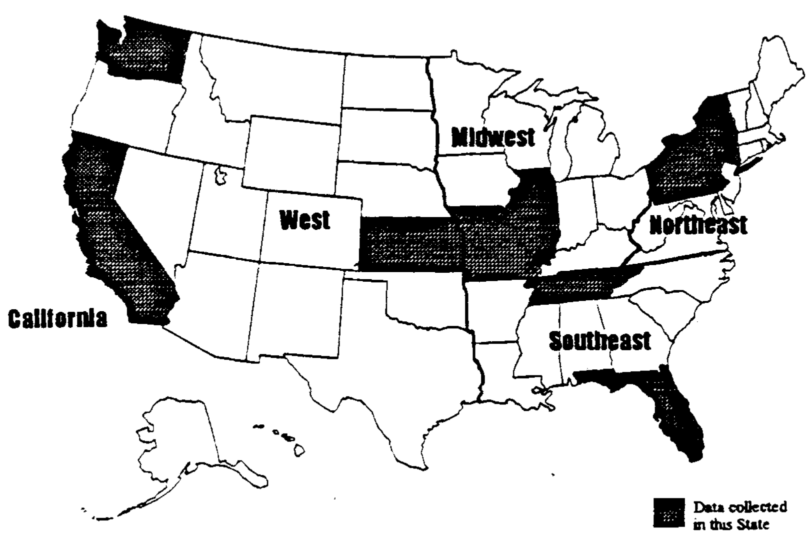
GEOMETRIC

The four roadway geometric elements critical to accommodating truck offtracking are mainline horizontal curves, horizontal curves on ramps, curb return radii for at-grade ramp terminals, and curb return radii for at-grade intersections. Data on the dimensions of these elements were collected for a sample of roadways in nine States, selected from the five regions: Northeast (New York and Pennsylvania), Southeast (Florida and Tennessee), Midwest (Illinois and Missouri), West (Kansas and Washington), and California (see Exhibit 7-5). Looking at the five highway types in the sample States, researchers determined the mainline curve radii based on the Highway Performance Monitoring System (HPMS) data. Where HPMS data were not available, the sample States provided existing aerial photographs and as-built plans on ramp curve and curb return radii at ramp terminals and intersections.

Roughly 25 rural interchanges, 25 urban interchanges, 25 rural at-grade intersections in each of the sample States were examined. The locations were selected because they carried substantial truck traffic.

The feasibility of widening each curve radius was rated as: minor difficulty (just add a little more pavement), moderately difficult, or extremely difficult (requiring major construction or demolition of existing structures). The sample data was expanded to the National

EXHIBIT 7-5
THE FIVE REGIONS OF THE UNITED STATES



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Network for Large Trucks. Estimates were made for the number of locations or mileage that needed improvement and the amount and cost of widening for each truck that offtracks more than the baseline tractor with a 48-foot semitrailer.

The amount of widening was based on the offtracking of the scenario trucks. For horizontal curves and ramps, it was decided that no encroachment of shoulders or adjacent lanes would be allowed. For intersections and ramp terminals, trucks were not allowed to encroach upon shoulders, curbs, opposing lanes, or more than one lane in the same direction.

For some facilities, the cost of widening existing highway features is required even for the baseline truck. There are turns and highway curves that cannot accommodate existing trucks. The costs are reported in the Base Case Scenario.

The scenario analyses assume that all of the needed geometric improvements have been made. More realistically, these improvements would have to be scheduled over a number of years, and therefore, the full use of the highways assumed available for them would take many years to occur.

STAGING AREAS

If the worst offtracking trucks — the TPDs and the RMDs — are allowed to go everywhere in the truck network, including urban areas, the costs to widen highways to accommodate them would be incalculable. Staging areas were assumed to exist at key rural interchanges and the fringes of major urban areas.

The research examined how often staging areas would be used, where they would be located, and what they would cost. On rural freeways, staging areas would be needed every 15.6 miles. Trucks with trip origins or destinations in an urban area would use urban fringe staging areas. Through trucks would use the interstate or other freeway systems to their destination.

As with geometric improvements, staging areas must be provided before full use of highways assumed available for long-double combinations can actually be realized. Providing public staging areas is likely to require many years.

COSTS

GEOMETRIC IMPROVEMENTS

A model was developed to estimate geometric improvement costs for a given TS&W scenario based on the offtracking performance of the specified truck configurations, and the mileage and location of the roads on which the vehicles are expected to operate. The model is useful in determining geometric requirements for a large range of vehicle configurations for any specified highway network.

The costs to upgrade the roadways to accommodate excessive offtracking are given in Exhibit 7-6. These include widening the lanes for sharp curves and moving curbs back. In the worst cases, widening includes adding a lane. These costs are summarized by mainline curves, at-grade intersections, and freeway interchanges. For the two long double-trailer configurations, the costs with the staging areas are given in parentheses along with the costs without the staging

Exhibit 7-6
Roadway Geometry Costs by Truck Configuration

Truck Configuration	Trailer Length (feet)	Improvement Costs ($ millions)			
		Mainline Curves	Intersections	Interchanges (with Staging Areas)	Total (with Staging Areas)
Five-Axle Semitrailer	48.0 (Base Line Vehicle)	86.4	37.1	630.7	754.2
	53.0	166.2	128.1	1,171.7	1,466.2
	57.5 (Nationwide)	172.4	183.4	1,331.6	1,466.2
Six-Axle Semitrailer	53	88.5	71.7	694.6	854.8
Five-Axle Double	28, 28	No additional costs are incurred; this vehicle offtracks less than the baseline vehicle.			
Seven-Axle Rocky Mt. Double	53, 28	136.0	173.0	1,255.6 (2,677.1)	1,565.6 (2,977.1)
Eight-Axle B-Train Double	33, 33	No additional costs are incurred; this vehicle offtracks the same as the baseline vehicle.			
Nine-Axle Turnpike Double	53, 53	309.1	727.5	3,042.9 (3,536.7)	4,079.6 (4,573.2)
Seven-Axle Triple	28, 28, 28	No additional costs are incurred; this vehicle offtracks less than the baseline vehicle.			

areas. These costs are for one time only (not annual costs) and are those above the costs to eliminate the offtracking problems of the 48-foot semitrailer combination, the base line vehicle.

The cost of each of the geometric deficiencies for a given scenario was determined and expanded based on the number of interchanges and intersections in each of the nine States that correspond to those in the sample. Next, the average spacing, or occurrence of these features in terms of highway miles by functional class was determined. These cost estimates were applied to the remaining States based on their highway miles in each functional class. This gives a national estimate of the costs to upgrade interchanges and intersections to accommodate vehicles with offtracking greater than a semitrailer combination with a 41-foot kingpin setting, which is typical for a 48-foot semitrailer combination. The cost to upgrade sharp horizontal curves was based on data used in the Federal Highway Administration's HPMS Investment/ Performance Models.

STAGING AREAS

The cost to provide public staging areas was also estimated. For rural areas, it was estimated that 2,455 staging areas, each sized to accommodate six trucks, would be required. The cost for constructing them was estimated to be $737 million.

For urban areas (137 were considered), it was assumed that each highway route into the urban area that was considered available for long double combinations would have a staging area. This resulted in staging areas from two for many urban areas to as many as 14 for Indianapolis. The total for the country was 830 with six being the most typical number for urban areas. The cost to provide space for 20 trucks for each urban staging area was estimated as $1.2 million, which gives a total cost for urban staging areas of $996 million.

ASSESSMENT OF SCENARIO IMPACTS

This section presents the costs to upgrade the highways that are assumed to be used by the Study vehicles in each TS&W policy scenario. This upgrading improves the mainline curves and intersection and interchange features such that the scenario vehicle with the worst offtracking characteristics would not offtrack excessively, that is, offtrack outside the width of its lane (see Exhibit 7-7).

The costs for each scenario are one time only costs (not annual costs), further, they would require a number of years to complete, given resource constraints and competing priorities in the States.

The Study's overall results are based on the assumptions that the roadway geometry improvements have been made and that the staging areas represented by the above costs are in place. In reality, funds need to be available and even then considerable time is required to make the improvements. Presumably, individual States would restrict the operation of long doubles until the necessary improvements have been made.

EXHIBIT 7-7
SCENARIO ROADWAY GEOMETRY IMPACTS

Analytical Case	Predominate Scenario Vehicle	Trailer Length (Feet)	Improvement Costs ($Million)				
			Main-line Curves	Inter-sections	Inter-changes	Total	Change in Total Costs from Base
1994 Base Case	Baseline Vehicles	48 or 53	86.4	37.1	630.7	754.2	0
2000 Base Case	Baseline Vehicles	48 or 53	86.4	37.1	630.7	754.2	0
SCENARIO							
Uniformity	Baseline Vehicles	48 or 53	86.4	37.1	630.7	754.2	0
North American Trade (51,000-Pound and 44,000-Pound Tridem-Axle Weight Limits)	Six-Axle Semitrailer	48 or 53	88.5	71.7	694.6	854.8	100.6
LCVs Nationwide — No Staging Areas	Nine-Axle Turnpike Double	53 and 53	309.1	1,127.5	3,042.9	4,079.6	3,325.4
LCVs Nationwide — With Staging Areas	Nine-Axle Turnpike Double	53 and 53	309.1	1,127.5	3,536.7	4,573.2	3,819.0
H.R. 551 (Analysis Region 4 only)	Five-Axle Semitrailer	48 or 53	- 50.7	- 89.6	- 181.5	- 321.8	- 170.2
Triples Nationwide	Baseline Vehicles	48 or 53	86.4	37.1	630.7	754.2	0

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UNIFORMITY SCENARIO

The costs shown in Exhibit 7-7 are those for 53-foot semitrailer combinations with 41-foot kingpin settings. Most States require this setting to be 41 feet or less. Given this requirement, the roadway geometry costs for this scenario would be the same as the base case.

NORTH AMERICAN TRADE SCENARIOS

The six-axle semitrailer combination dominates the eight-axle B-train double combination in both of these scenarios, as its offtracking is slightly worse (15.6 feet versus 14.2 feet) than those of the baseline vehicle, whereas the B-train double offtracks the same as the base line vehicle. The scenario's cost for eliminating this impact is $100.6 million over the Base Case improvement costs.

LONGER COMBINATION VEHICLES NATIONWIDE SCENARIO

The nine-axle TPD offtracks more than the other vehicles evaluated in this scenario. Therefore, the cost to eliminate its excessive offtracking is $3,325 million and $3,819 million with public staging areas added.

H.R. 551 SCENARIO

The impact shown in Exhibit 7-7 is actually a savings of $170 million, as semitrailer lengths under this scenario would eventually be no longer than 53 feet. The impact estimate is based on the fact that 57.5-foot semitrailer combinations operate in ten, mostly Western States, and that no curves or intersections had been upgraded to accommodate them.

TRIPLES NATIONWIDE SCENARIO

There are no roadway geometry impacts and costs for this scenario (see Exhibit 7-7) because the triple-trailer combination offtracks less than the typical semitrailer combination that operates on virtually all highways.