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16. Abstract

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The research procedure followed was to select five typical, large design vehicles, (WB-50, WB-55, WB-70, WB-100, WB-105), simulate their paths through several degrees of turn at different turning radii, create a table listing their behavior at specific corner curb radii, and develop guidelines specifying conditions where channelization is feasible. Information gathered concerning the turning characteristics of the longer and wider design vehicles and turning templates depicting their minimum turning paths are detailed in the first section of the study results. The second part of the results contains several tables that detail the interaction of each design vehicle with the degree of turn and curb radius. These tables list such things as cross street width occupied, swept path width, conditions where channelization is feasible, and minimum designs for turning roadways.

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CHANNELIZATION GUIDELINES
TO ACCOMMODATE LONGER AND WIDER TRUCKS
AT AT-GRADE INTERSECTIONS

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Study Title: Longer and Wider Trucks on the Texas Highway System

Sponsored by the

Texas State Department of Highways and Public Transportation
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May 1987

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843

METRIC CONVERSION FACTORS

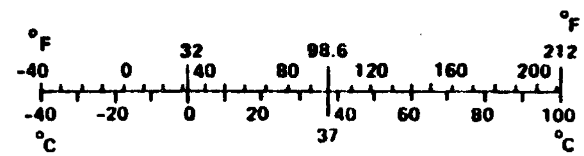
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



ABSTRACT

This report addresses issues concerning the design of at-grade intersections to accommodate the turning characteristics of the various longer and wider truck configurations that were introduced into the traffic stream by 1982 Federal and State legislation. The objectives of this research were to complete a literature review of research concerning truck sizes, turning characteristics, and channelization; determine encroachment and swept path width for various combinations of design vehicle, curb radii, and degree of turn; and develop guidelines for design, operation, and channelization of at-grade intersections to accommodate these larger vehicles.

The research procedure followed was to select five typical, large design vehicles, (WB-50, WB-55, WB-70, WB-100, WB-105), simulate their paths through several degrees of turn at different turning radii, create a table listing their behavior at specific corner curb radii, and develop guidelines specifying conditions where channelization is feasible. Information gathered concerning the turning characteristics of the longer and wider design vehicles and turning templates depicting their minimum turning paths are detailed in the first section of the study results. The second part of the results contains several tables that detail the interaction of each design vehicle with the degree of turn and curb radius. These tables list such things as cross street width occupied, swept path width, conditions where channelization is feasible, and minimum designs for turning roadways.

KEY WORDS: Large Trucks, Intersection Design, Offtracking, Channelization

ACKNOWLEDGEMENTS

The research reported herein was performed as a part of a study entitled "Longer and Wider Trucks on the Texas Highway System" by the Texas Transportation Institute and sponsored by the Texas State Department of Highways and Public Transportation in cooperation with the U.S. Department of Transportation, Federal Highway Administration. Mr. Dock D. Burke of the Texas Transportation Institute served as study supervisor and Mr. Robert R. Guinn and Mr. Robert Harris of the State Department of Highways and Public Transportation served as study contact representatives.

The authors wish to thank Dr. Vergil G. Stover of the Texas Transportation Institute for his technical inputs and constructive suggestions throughout the duration of this project. A special thanks is extended to Mr. Kenneth L. Englander of the College of Engineering's Computer Graphics Facility at Texas A&M University. The assistance of Mr. James C. Cline, Mr. Cesar J. Molina, Mr. Daniel P. Walker, Mr. Muhammad Shah, Ms. Jeanette Arnold, Ms. Maren C. Price, and Ms. Nancy J. Bubert is also gratefully acknowledged.

EXECUTIVE SUMMARY

This study addresses truck tracking problems at intersections due to the increased offtracking of the longer and wider vehicles. The goal was to establish a set of guidelines for intersection channelization to accommodate these larger vehicles. Results of the research include several truck turning templates; tables containing cross street width occupied and swept width for various combinations of design vehicle, curb radii, and degree of turn; and recommendations for the use of channelization when designing for the longer and wider trucks.

This research was needed because although adequate research concerning offtracking had been done on longer and wider truck configurations, information is lacking which relates offtracking to intersection geometry. While the "Green" Book contains information on intersection channelization, the effect of 48-foot trailers and 102-inch wide trucks are not illustrated.

The "Truck Offtracking Model" developed by Caltrans was used in this study. This model was capable of simulating various truck paths in a short time period. The procedure followed can be used for intersection design where there are high volumes of trucks because of its ability to specify any design vehicle, degree of turn, and curb return radius. It might be feasible to design at-grade intersections along Interstate Highways and the Designated System for the larger truck combinations. Concentrations of larger vehicles in other areas, e.g., truck terminals and lumber yards, may also warrant special design consideration. TOM could be used to develop turning templates for special design vehicles. For example, intersections between a logging area and a lumber yard which experience high turning movements could be designed using turning templates of a typical logging truck. The same procedure used in this study could be used in these instances.

Recommendations for further research included the following:

- o Develop additional turning templates at various angles of turn and turning radii.
- o Plot the overhang of the design vehicles as they traverse different angle of the turn at the various radii.
- o Develop tables containing width of pavement information for each of the three cases; one-lane, one-way operation with no provision for passing a stalled vehicle; one-lane, one-way operation with provision for passing a stalled vehicle; and two-lane operation, either one-way or two-way.
- o Develop additional tables for curb radii consisting of three-centered compound curves and simple curves with tapers.
- o Simulate design vehicles making left turn maneuvers. Develop guidelines for these circumstances.
- o Develop step-by-step procedure, similar to steps followed in this study, to be used to evaluate geometry at existing intersections, i.e., step 1 - identify design vehicle. Step 2 - run computer simulation to

obtain plots. Step 3 - compare to existing curb geometry to determine effects of offtracking.

o Prepare computer inputs for several design vehicles in order to make program more "user friendly".

IMPLEMENTATION STATEMENT

The material and procedure presented in this report will provide guidance to engineers designing at-grade intersections to accommodate the longer and wider vehicles legalized by the STAA of 1982. The results, with slight modifications, are applicable for inclusion in future updated versions of both the AASHTO and SDHPT design policies. Towards this objective, copies of this report will be provided to the appropriate personnel in both organizations. Consideration of these results will ensure the safest, most-efficient intersection design possible.

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I. INTRODUCTION

The introduction of larger and heavier trucks into the traffic stream by recent Federal and State legislation has prompted research interest by the Texas State Department of Highways and Public Transportation (SDHPT) on how to accommodate these vehicles on their highway system. As a result of this interest, the Texas Transportation Institute (TTI) and the Center for Transportation Research (CTR) studied the impacts of these larger vehicles on geometric design, traffic operations, and highway safety. The first objective of this study, an annotated bibliography summarizing research concerning operational characteristics and geometric design implications of longer and wider trucks, has been completed and published as TTI Research Report 397-1 (1). Another objective, which is the subject of this report, involved the development of channelization guidelines to accommodate longer and wider trucks at at-grade intersections. Additional objectives and their results are documented in subsequent reports (2,3,4).

PROBLEM STATEMENT

Turning characteristics of large trucks such as offtracking and swept path width require special consideration in the design of at-grade intersections. If the curb radius is large enough so that trucks can make right turns without encroaching on adjacent lanes, the paved area at the intersection can become large so that through drivers may not understand where to position their vehicle. In such instances, it becomes necessary to construct a channelizing island to properly control traffic. If the curb radius is small so that trucks cannot make right turns without encroaching, the truck either encroaches and interferes with adjacent traffic or it does not encroach and its rear wheels run over and possibly damage the curb and/or shoulder. In addition, the truck's front overhang may strike those traffic control devices located near the outside of its turning path in the encroachment alternative, or the trailer's right rear tire may strike those devices located near the inside of its turning path in the non-encroachment alternative (offtracking).

Turning characteristics of large trucks in a left-turn maneuver must also be considered in the design process. As with right turns, the decision to be made is whether or not to allow left-turning trucks to encroach on adjacent lanes. If the decision is to allow encroachment, a secondary decision is how much to allow. These decisions dictate the required set-back of median islands, and in their absence, stop bars on both the major and minor streets at the intersection. A combination of the set-back, and the median island's width and nose design can add to or subtract from the available left-turning radius. All of these issues should be addressed when designing the intersection.

Currently, there is limited information on either turning dimensions and characteristics or channelization guidelines, for the new larger vehicles. The American Association of State Highway and Transportation Officials' (AASHTO) A Policy on the Geometric Design of Highways and Streets-- 1984 (5), the "Green Book," contains no information on these larger vehicles because to do so would have delayed its publication. The SDHPT's Highway Design Division Operational and Procedures Manual (6) contains turning templates for one larger vehicles, WB-62TX, but does not contain turning characteristics or design and channelization guidelines for it or any other larger vehicle. Thus, the additional information contained in this report can be used to aid in the design of at-grade intersections serving longer and wider trucks.

RESEARCH OBJECTIVES

The objective of this report is to establish a set of guidelines for intersection channelization so as to accommodate the recently legalized longer and wider trucks on the nation's highways. These guidelines are limited to trucks larger than those covered by current AASHTO policy (5). To accomplish this objective, the following tasks were conducted:

1. Review literature concerning truck size legislation, truck turning characteristics, and intersection channelization;
2. Determine truck turning characteristics for various combinations of large design vehicle and intersection geometry; and
3. Develop guidelines for design, operation, and channelization of at-grade intersections to accommodate these larger vehicles.

Chapters 2 through 4 of this report document these activities. Chapter 5 provides a summary of the study and recommendations for future research.

II. LITERATURE REVIEW

SIZE AND WEIGHT LEGISLATION

Prior to 1956, individual states had exclusive jurisdiction in the regulation of vehicle size and weight. Some of this power was transferred to the federal government with the passage of the Federal-Aid Highway Act of that year. The pertinent sections of that act set maximum width limits of 96 inches and gross weight limits of 73,280 pounds for vehicles operating on the Interstate System; however, if the states' limits in effect at the time were greater than these values, the higher limits were to continue. As a result of subsequent studies and much heated debate (7), the maximum allowable gross vehicle weights were raised to 80,000 pounds in 1974. Not surprisingly, 10 of the states refused to raise their allowable weight limits and were situated such that they effectively blocked cross-country movement of the heavier vehicles.

During this time period, maximum combination vehicle lengths were still being regulated by the states and as with allowable weights, several differences existed. Basically, maximum lengths were less than 55 feet in the eastern third of the country, 55 feet in the middle third, and 65 feet in the western third. In addition, multiple combinations were not permitted in some eastern states, even though double combinations were permitted in most of the rest of the country, and triple combinations were even permitted in some western states. All of these factors led to much confusion and added expense as it required carriers to change vehicle configurations when crossing into states with differing regulations, laws, and policies. Thus, carriers were not able to fully realize the benefits of the larger dimensions allowed in some states.

As a result of these and other factors, the Surface Transportation Assistance Act (STAA) of 1982 was passed and became law on January 6, 1983. In one of its sections, it required states to permit the operation of larger and heavier trucks (up to 102-inch widths, 48-foot trailers, and 80,000 pound gross vehicle weights) on what would be known as the Designated System. All Interstate highways would be included in the Designated System along with other highways constructed to similar design standards, i.e., four or more lanes, divided, full control of access, etc. States were requested to add additional highways to the system in order to meet the Congressional intent of providing a national network of highways to serve interstate commerce. In effect, it forced state size and weight limits to equal the federal limits on the Designated System, thus promoting uniformity in regulations.

The Texas State Legislature enacted House Bills (H.B.) No. 1601 and 1602 so that Texas' policy would be consistent with that contained in the STAA of 1982. H.B. 1601 sets overall length restrictions on truck-tractor combination vehicles at 65 feet. It also states that a semitrailer operated in a truck-tractor semitrailer combination may not exceed a length of 57 feet and semitrailers and trailers operated in a truck-tractor, multiple trailer combination may not exceed a length of 28.5 feet each. A grandfather clause was included to exempt those semitrailers and trailers that were being actually and lawfully operated in Texas on December 1, 1982. H.B. No. 1602 increases the allowable width of vehicles to 102 inches on the Interstate System.

LARGE TRUCK OPERATIONS

Several key words need clarification at this point: truck, tractor, semitrailer, and trailer. A truck is a self-powered vehicle that supports its full weight. It can either be operated alone or in combination with a trailer. A tractor is a self-powered vehicle made expressly for towing a semitrailer. It supports not only its own weight but also part of the semitrailer's weight. Trucks and tractors may be described further as either cab-over or cab-behind-engine depending on the placement of the cab. A semitrailer is made to be towed behind a tractor. It places its weight partly on the tractor and partly on its own wheels. A trailer is a vehicle that supports its own load entirely and is towed by attaching it to a truck, a semitrailer, or to another trailer. These terms are illustrated in Figure 1.

A 1979 study reported that the trend since World War I had been towards longer tractor-semitrailer combinations and tractor-semitrailer combinations towing one or more additional trailers (8). No federal legislation had been imposed on length or combination types for vehicles using the Interstate System. Other findings were that tractor-semitrailer combinations were the only type of combination vehicle currently permitted in every state. Twenty western states had generally permitted overall lengths of 60 feet or more, while the standard length in eastern states had been 55 feet. Even though there did not appear to be any significant changes in overall length limits during the 15 to 20 years prior to the study, the length of the trailer within the tractor-semitrailer combination had been increasing steadily. This was possible because more widespread use of the cab-over-engine-type tractor enabled the trailer lengths to increase by the amount of decrease in tractor lengths and yet still keep within overall length limits.

Multiple-trailer combinations were growing in popularity during the time period that the 1979 study (8) was made. The most common was a tractor towing two trailers, usually known as "doubles" or "twins". Each trailer was usually no longer than 30 feet with an overall combination length of 65 feet. Another version of the doubles combination was the longer "turnpike double". It typically had a tractor towing two 40-foot trailers with an overall combination length of 98 feet. These combinations had been permitted on the Kansas Turnpike for 22 years, and on the toll roads of Indiana, Ohio, New York, and Massachusetts for 10 to 15 years (8). As of 1977, there had been pressure on western states to allow "triples", a tractor towing three trailers, each less than 30 feet in length. The overall combination length limit usually ranged from 98 feet to 105 feet. These combinations were permitted in four western states and were being tested in six other states.

Multiple-trailer combinations offer the advantage of increased volume capacity and the potential for added operating efficiency. Two 28-ft. trailers have about 15 percent greater cubic feet of space than the 48-ft. semitrailers making them ideal for transporting low density high volume products (9). Doubles are also advantageous to truck operators who regularly deliver less than full truckloads, enabling them to decrease the amount of handling necessary and therefore decrease cost. Another advantage of doubles is that the smaller trailer is easier to maneuver in urban areas than the typically longer single trailer. The regulations permitting the longer trailers, which might seem to increase the axle load unfavorably, are actually advantageous to carriers who frequently carry less dense cargo. Those carriers are not

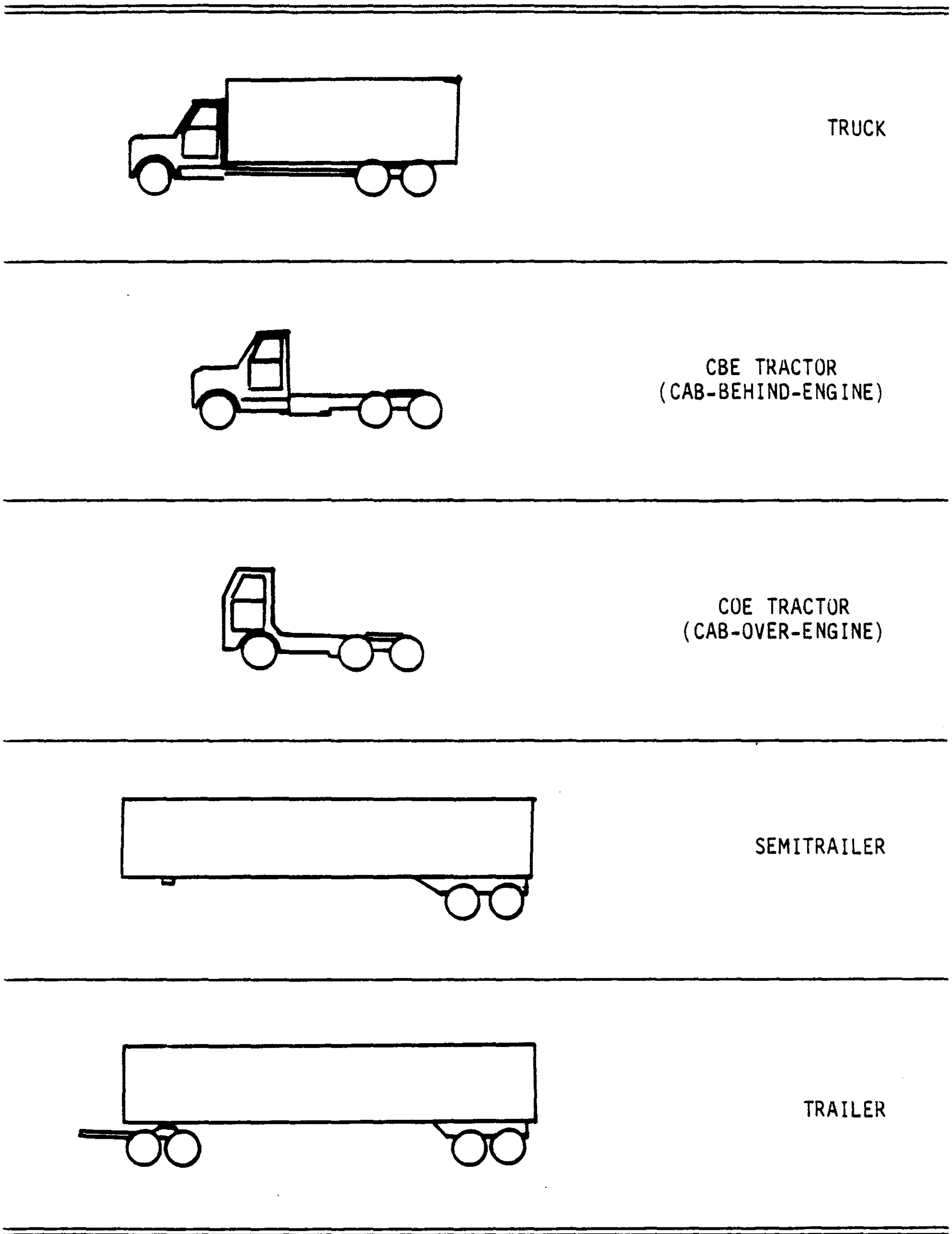


Figure 1. Truck-Combination Vehicle Definitions.

particularly worried about the gross weight per axle limitations as their loads are limited by the volume rather than the weight.

TURNING CHARACTERISTICS

Because of a truck's long wheelbase, its rear wheels do not follow the same path as its front wheels when making a turn. The difference in these paths is defined by the terms "offtracking" and "swept path." Offtracking is generally defined as the difference in paths of the front-most inside wheel and rear-most inside wheel of a vehicle as it negotiates a turn (10). Alternately, the distance may be measured between the tracking of the front and rear outside wheels, or the center of the front and rear axles, but its value will be the same. Offtracking is known to vary directly with the wheelbase of a unit and inversely with the radius of turn. "Its magnitude is affected in combination by the number and location of articulation points, by the length of the arc and the type of curve, and by the speed and turnability of the wheels" (11).

Swept path width may be defined as the amount of offtracking plus the width of the truck. It can also be defined as the difference in paths of the front-most outside wheel and the rear-most inside wheel of the vehicle as it negotiates the turn; however, this is only true for low-speed turns. At higher speeds, "negative offtracking" may occur, i.e., because of side slippage, the rear-most wheels may actually travel outside the path of the front- most wheels and swept path would be defined as the difference in paths of the front-most inside wheel and rear-most outside wheel of the vehicle as it negotiates the turn. With the exception of "negative offtracking,", these terms are illustrated in Figure 2.

Full-Scale Tests and Formulas. Full-scale tests done on test-track curves of known radius were the first method used to determine offtracking. They are extremely accurate because they involve professional drivers and an actual vehicle traversing a measured turn. However, one assumption is that other drivers can repeat this "optimum" performance in the real world. Unfortunately, this method is expensive and the number of truck-turn combinations that would have to be tested made it feasible to develop less expensive, yet equally reliable methods.

Mathematical formulas for determining offtracking were developed by the Society of Automotive Engineers (SAE) and the Western Highway Institute (WHI). SAE's general formula for a single vehicle is based on the solution of the triangle formed by the turning radius of the front and rear wheels and the vehicle's wheelbase when the combination is in a circular turn (12). It is calculated as follows:

$$OT = \sqrt{WB^2 + (\sqrt{TR^2 - WB^2} - HT)^2} - \sqrt{TR^2 - WB^2 + HT}$$

where:

OT = offtracking;
WB = wheelbase;
HT = 1/2 front wheel track; and
TR = turning radius.

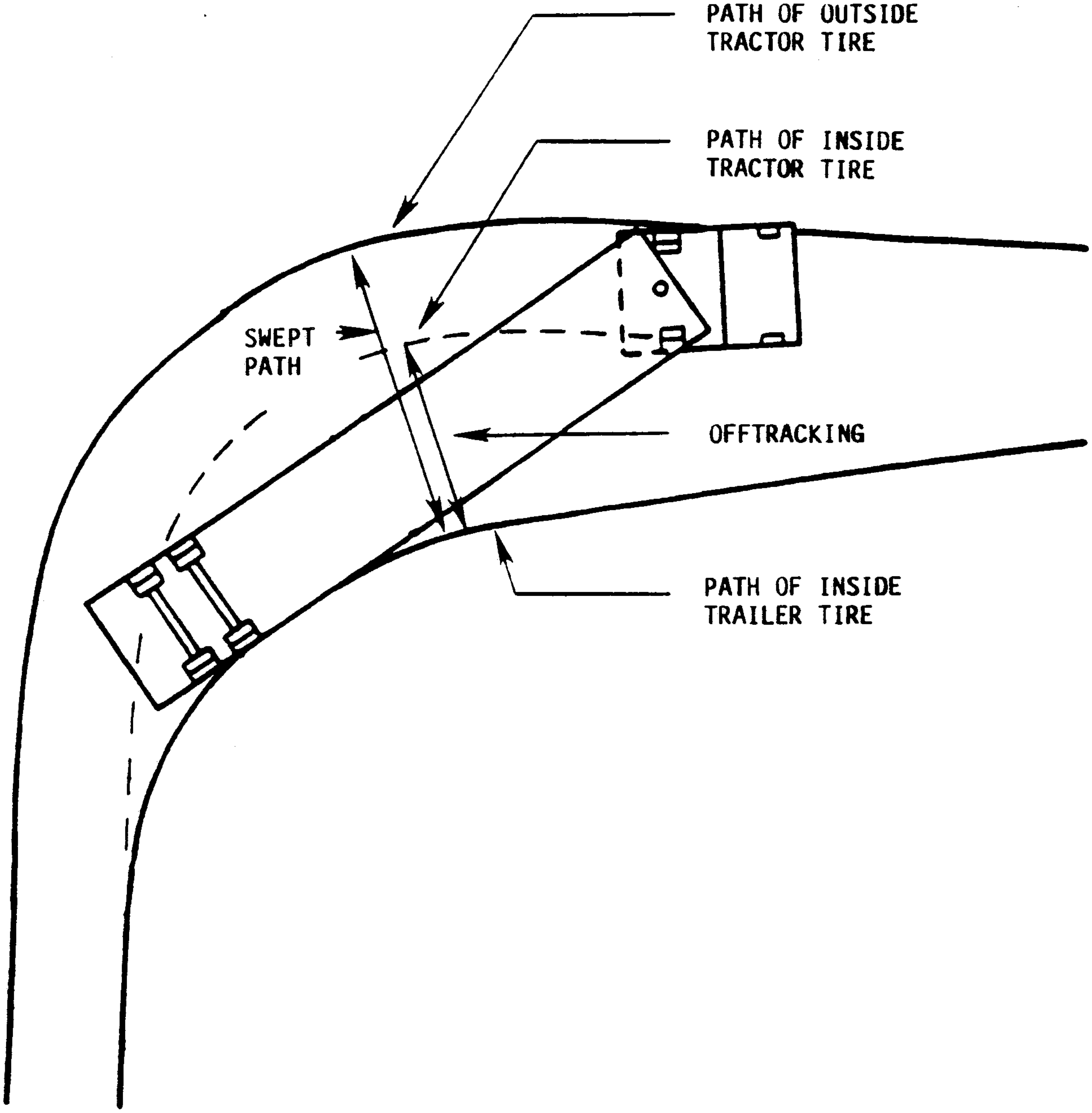


Figure 2. Swept Path Width and Offtracking of a Truck Negotiating a 90 Degree Intersection Turn (6).

This equation is difficult to apply to compound curves and the value of the maximum offtracking is not readily apparent. WHI developed a short form of the equation which eliminates the variable for one-half of the front wheel track (13). Their formula is shown below:

$$MOT = R_1 - \sqrt{R1^2 - (L_1^2 + L_2^2 - L_3^2 + L_4^2 + L_5^2 + \ldots)}$$

where:

MOT = maximum offtracking;
R_1 = turning radius of outside front wheel;
L_1 = wheelbase of tractor;
L_2 = wheelbase of first trailer or semitrailer;
L_3 = distance between rear axle and articulation
L_4 = distance between articulation point and front axle of next trailer; and
L_5 = wheelbase of trailer.

A further simplification is as follows:

$$MOT = R_1 - \sqrt{R_1^2 - \sum(L_i)^2}$$

One shortcoming of using mathematical equations for computing maximum offtracking is that they consider the wheel tracks and not any problems which may result from vehicle overhangs and projections outside of the wheel tread (11).

Scale Modeling. Scale modeling was found to be much more efficient than working with the actual vehicles. The Tractix Integrator, an instrument used to simulate actual vehicle offtracking characteristics, has been used to develop turning templates for a number of different design vehicles (10). The Tractix Integrator has several advantages, e.g., it provides an immediate plot of the truck's path and is especially well-suited for many roadway design situations. It also has several disadvantages. These are:

1. "The scale bar cannot be adjusted to accommodate values of less than about 5 ft. Thus, the kingpin is generally assumed to be located directly over the center of the rear tractor axles, and rear overhangs are generally ignored.

2. 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 very 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.

3. The Tractix Integrator traces only centerline paths. Consequently, special points of interest, for example outside wheels, corners of long rear overhangs and wide loads, cannot be obtained directly.

Artificial lines representing paths of the user specified point, truck widths of the outside front wheel and inside rear wheel for example, must be manually added to the curves produced from the Tractix Integrator (14)."

Perhaps the most widely used methods for design of intersection curve geometry are the turning templates developed by Jack Leisch (15). These templates represent the turning paths of the 1965 AASHTO design vehicles; passenger car, SU-30, B-40, WB-40, and the WB-50. The abbreviation SU represents a single unit vehicle, B represents a bus, and WB represents a truck combination with a 40 or 50 ft. wheelbase from the front-most to rear- most axle. The templates are normally drawn on 8 1/2 by 11 inch sheets of transparent plastic at standard scales of 1" = 20', 1" = 30', 1" = 40', and 1" = 50'. A copy of the turning templates for the WB-50 design at a scale of 1" = 20' vehicle is shown in Figure 3; however, it should be noted that it has been reduced for inclusion in this report.

Computer Models. Under an FHWA contract, the University of Michigan Transportation Research Institute (UMTRI) developed the first computer model which simulated vehicle offtracking. This modeling package was quite an advancement in working with vehicle offtracking when compared to the previously described methods for studying turning characteristics. The program was developed for a micro-computer environment and designed to be "user-friendly". The program's output was a scaled plot of the paths followed by the vehicle's tires in a format which could be overlaid on drawings of intersections or other situations involving restrictive geometry. The UMTRI Program required a computer compatible with the Apple II+, 48k of memory, one floppy disk drive, and DOS 3.3. Either a monitor or television screen with the appropriate connector was needed for data entry. In order to obtain scaled drawings of the computed tire paths, a dot matrix printer or an X-Y plotter was necessary.

The UMTRI program simulates any vehicle combination involving powered and towed vehicles such as passenger cars, trucks, full trailers, semitrailers, dollies, busses, etc. Combinations which can be handled by the program are conventional vehicles with non-steered rear axles, but not configurations in which rear axles are steered through linkages. The items which must be specified for the program to work are the description of the vehicle and the "input path". The input path is the term used to identify the path which will be followed by the leading axle of the vehicle combination. The path may be as simple as a 90 degree turn or as complicated as a series of compound curves. Two disadvantages of the UMTRI Model are that the size of the plot is limited by the size of the X-Y Plotter, and sometimes when given a multi-unit vehicle and/or a long path to follow, the program will run out of space on the floppy disk when storing the simulation results (14).

TOM is an acronym for the Truck Offtracking Model developed by the California Department of Transportation (Caltrans) that also simulates the offtracking characteristics of any vehicle combination when making a turn. It is used most frequently for trucks. TOM evolved from the Apple II personal computer offtracking model developed by UMTRI in that the simulation portion of the Apple program was adopted by Caltrans' Division of Transportation Planning and placed on the State's IBM mainframe computer. TOM was not as user-friendly as the Apple version, but its plotting capacity was much greater. In addition, the resulting plot was much improved as it was of larger-scale and higher quality. Specifics of the program are discussed later.

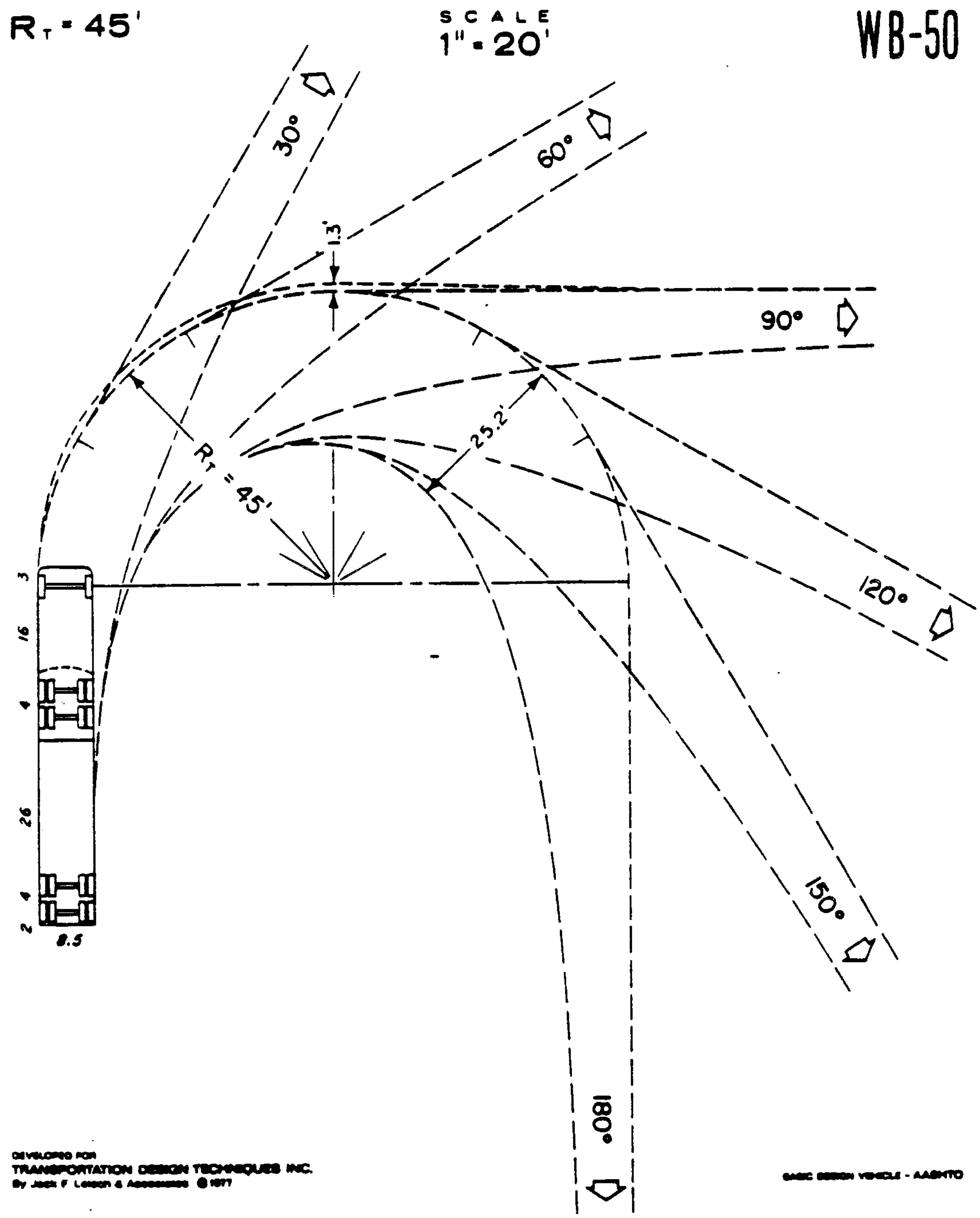


Figure 3. Example WB-50 Turning Template (15).

INTERSECTION CHANNELIZATION

At-grade intersection channelization is defined as the separation or regulation of conflicting traffic movements into definite paths of travel by the use of pavement markings, raised islands, or other suitable means to facilitate the safe and orderly movements of both vehicles and pedestrians (16). Proper channelization increases capacity, improves safety, provides maximum convenience and instills driver confidence. Improper channelization and over-channelization often have the opposite effect and should be avoided because of the confusion they can cause (17). Currently, there are no "guidelines" for intersection channelization when the larger trucks are the design vehicles. The following literature review highlights several references that address channelization at at-grade intersections.

TRB Publications. The Highway Research Board (HRB) sponsored two publications on intersection channelization containing examples and critical analyses so that highway and traffic engineers might benefit from a review of other's work. "HRB Special Report 5--The Design of Intersection at Grade" (17), provided 59 examples of channelized intersections as of 1952. A revision by the same title in 1962 was published as "HRB Special Report 74" (18) and provided more examples of channelization to illustrate design practice as of that date. This report also defined the special objectives of intersection channelization to be to assure orderly movement, increase capacity, improve safety, and provide maximum convenience.

The Highway Research Board Committee on Channelization believed that channelization was generally employed for one or more of the following purposes:

1. Separation of conflicts;
2. Control of angle of conflict;
3. Reduction of excessive pavement areas;
4. Regulation of traffic and indication of proper use of the intersection;
5. Arrangements to favor predominant turning movements;
6. Protection of pedestrians;
7. Protection and storage of turning and crossing vehicles;
8. Location of traffic control devices;
9. Need for reference points;
10. Prohibition of specific movements; and
11. Control of speed.

The most recent publication dealing with channelization is a 1986 version of Special Report 74 (19). It includes illustrative examples of channelization designs and more detailed guidelines than were provided in the earlier reports. In addition, it covers channelization of both new and reconstructed intersections in urban and rural environments. Its contents include typical intersection types such as 4-way, Y, T, oblique, and multileg intersections, as well as freeway ramp intersections with surface streets.

Chapter 5 of the 1986 report provides examples of intersections recently designed and/or constructed. The 37 examples were chosen from over 130 candidate intersection designs submitted by agencies throughout the country.

The examples were grouped according to the following classification: typical intersections, special geometric problems, special operational problems, left turn design treatments, and special case studies in rehabilitation and reconstruction. The group dealing with special operational problems included several examples which highlighted intersections in either urban or rural environments which were designed or redesigned especially for large trucks. The design solutions included increasing right turn radii (for intersections with and without channelization), relocating the median nose for left turns, widening approaches, reducing the size of corner islands, removing parking, and relocating traffic signals to provide more clearance.

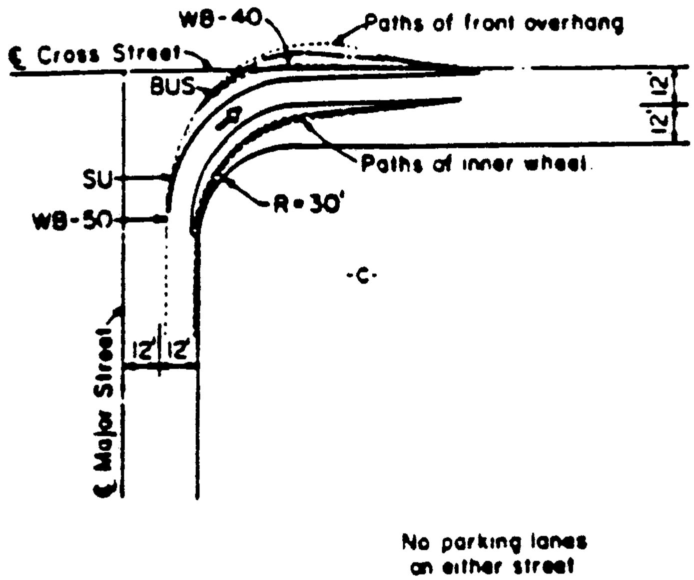
AASHTO Publications. The "Green Book," contains discussions on both offtracking and channelization. It specifies that the larger semitrailer combinations should be used as design vehicles where truck combinations approximating this size will turn repeatedly. Because such designs, particularly when used in two or more quadrants of an at-grade intersection, produce large paved areas that may be difficult to control, it is usually desirable to channelize them, for which somewhat larger radii are needed (6).

Chapter IX of the "Green Book" discusses at-grade intersections. Figure 4 illustrates the effect of curb radii on turning paths of various design vehicles. As shown, larger radii allow the turning vehicles to more nearly stay in their lane. For example, at a 15-foot radius and with 12-foot lanes, a passenger car can turn with no encroachment on an adjacent lane. The SU, WB-40, and WB-50 design vehicles must swing wide and occupy two lanes on both the approach and cross streets in order to make the turn. In fact, the WB-50 must occupy a part of a third lane on the approach street. In contrast, at a 25-foot radius, the passenger car can still turn without encroaching and all trucks can turn within the confines of two lanes on either street.

Figure 5 illustrates the details of triangular island design. The lower right corner of each curbed island is designed for approach-end treatment (noses rounded on appropriate radii of 2 to 3 feet), while the merging end only needs minimum rounding (about 1-foot radius). The lower left corner should be rounded with a radius of 2 to 5 feet. The minimum offset from the edge of the curbed island to the through-traffic lanes should be 2 to 3 feet. Such islands are desirable where the curb radius is greater than the minimum required by the design vehicle. Physically islands should be at least 50 square feet in urban areas and 75 square feet in rural areas; however 100 square feet is preferable for both (6).

The "Green Book" also contains guidelines on designing median openings. Figure 6, Table IX-16 from the "Green Book", indicates minimum design of median openings for SU, WB-40, and WB-50 turning paths for a 75-foot control radius. A control radius of 75 feet accommodates WB-40 and WB-50 vehicles with only minor swinging wide at the end of the turn. The median opening and the shape of its nose vary according to median width. There is little or no difference between the two types of median ends for medians around 4 feet wide but once the median is wider than 10 feet, the bullet nose is preferred over the semicircular end as it more nearly approximates the path of the turning vehicle's rear wheel and thus results in a narrower median opening.

FHWA Publications. Part V of the Manual of Uniform Traffic Control Devices, (MUTCD), also contains information on islands. The MUTCD states that the primary function of a channelizing island is to control and direct a



-c-

Angle of intersection equal to 90 degrees

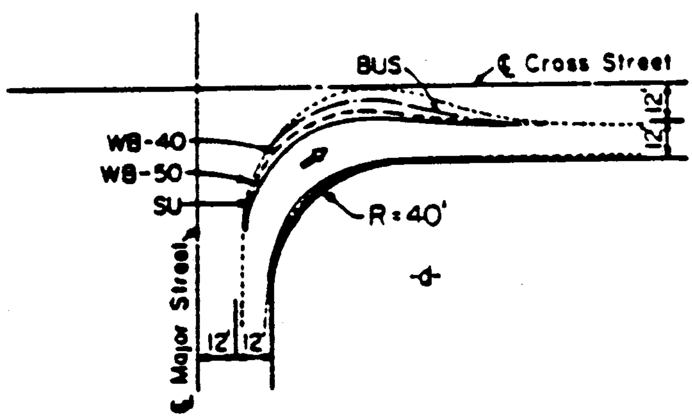


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Figure 4. Effect of Curb Radii on Turning Paths of Various Design Vehicles (6).

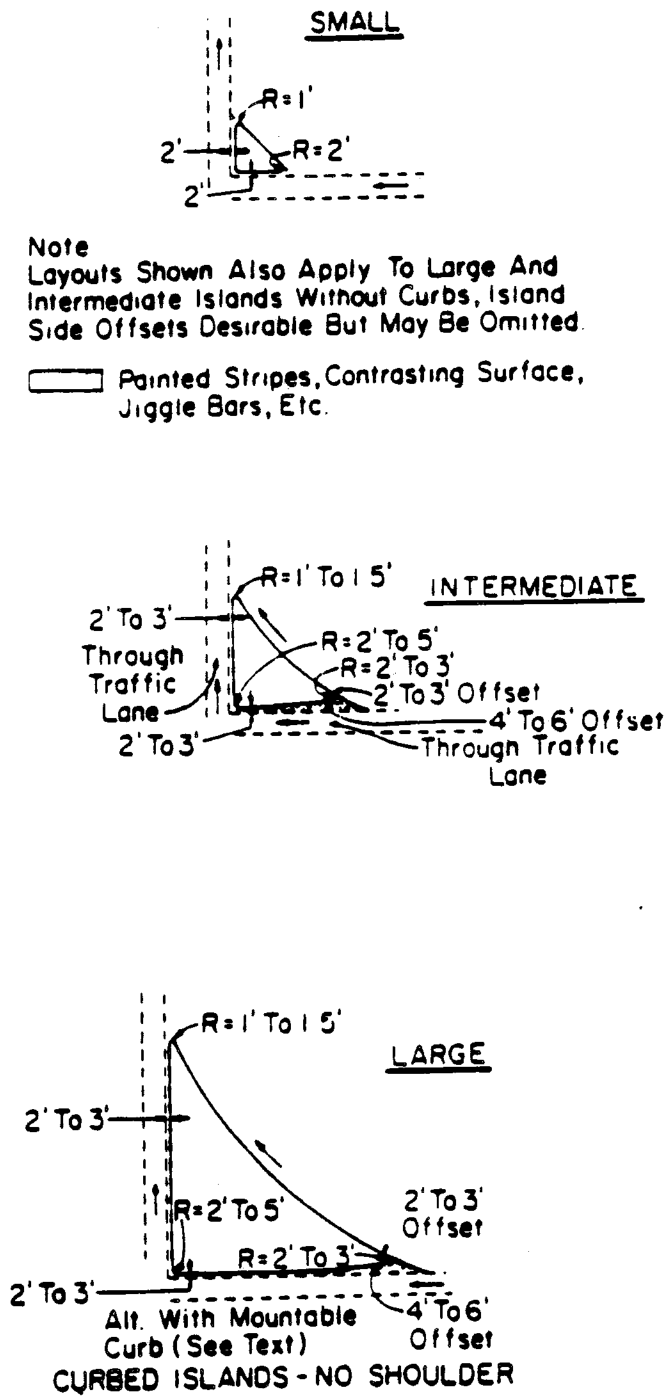
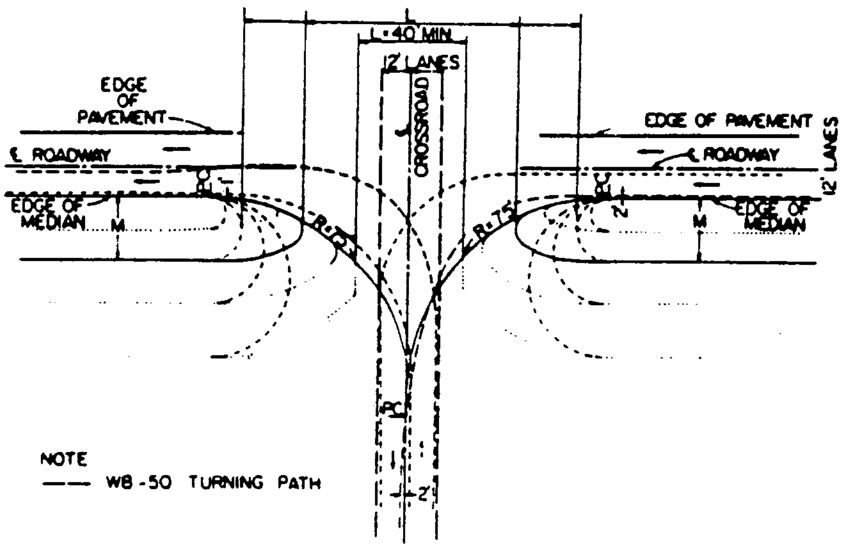


Figure 5. Details of Triangular Design
(Curbed Islands, No Shoulder)



WIDTH MEDIAN M	L= MINIMUM LENGTH OF MEDIAN OPENING, FEET	
	SEMICIRCULAR	BULLET NOSE
4	146	122
6	144	115
8	142	110
10	140	105
12	138	100
14	136	96
16	134	92
20	130	85
24	126	78
28	122	73
32	118	67
36	114	62
40	100	57
60	90	40 MIN
80	70	40 MIN
100	50	40 MIN
110	40 MIN	40 MIN
120	40 MIN	40 MIN

Figure 6. Minimum Design of Median Opening (WB-40 Design Vehicle, Control Radius of 75 Ft.) (6).

vehicle operator into the proper channel according to the intended route. (16) Channelizing islands may be installed in areas that otherwise would be broad expanses of pavement, to bring about an orderly flow of traffic.

Part V of the Traffic Control Devices Handbook (20) discusses the functions of channelizing islands in approximately the same terminology as the list given in "HRB Special Report 74." It advises that the basic island design structure should:

1. Make the island and its approach clearly visible to avoid any surprise to the driver;

2. Allow sufficient driver time for decision making reaction; and

3. Assure that the island path and approach conditions follow the natural path of movement.

Access Management for Streets and Highways (21), describes an island as a defined area between traffic lanes for control of vehicle movements or for pedestrian refuge. They are generally either elongated or triangular in shape, and are situated in areas normally not used as vehicle paths. The report advises that channelizing islands should be placed so that the proper course of travel is immediately obvious, easy to follow, and continuous. Islands should be large enough to command attention. This is usually considered to be at least 75 square feet but preferably 100 square feet. More specifically, triangular islands should be no less than 12 ft. on the side after rounding of corners, and preferably 15 feet on the side. Elongated islands should not be less than 4 feet wide and 20 to 25 feet long. When designing islands, visibility is an important consideration, and mountable curbs are preferable to barrier curbs in most conditions.

III. STUDY DESIGN

A methodology was defined to determine turning characteristics for various combinations of large design vehicles and intersection geometry. The procedure consisted of five general steps which were as follows:

1. Select design vehicle, and dimensions;
2. Establish turning radii and degree of turn;
3. Simulate path of turning vehicle;
4. Measure offtracking/encroachment; and
5. Develop channelization needs.

The details of the overall study procedure are described in the following discussion.

DESIGN VEHICLES

The design vehicles which were selected for this study were two singles, two doubles, and one triple. They are typical of the larger vehicles currently being operated on the nations highways. One vehicle, the WB-50, was the same vehicle configuration as in the "Green Book" (6) and was used to verify the correctness of this procedure. The tractor used in each combination had a 16-foot wheelbase with the cab placed behind the engine. This particular tractor was selected because its longer wheelbase, typical of cab-behind-engines, results in a wider turning path when compared to shorter wheelbase cab-over-engine tractors. The five design vehicles are illustrated in Figure 7 and described below. Their dimensions are shown in Table 1.

Singles. The WB-50 is the critical design vehicle defined by the "Green Book," i.e., it has the worst turning characteristics of the design vehicles contained therein. As of 1984, it was nearly all inclusive of the tractor-semitrailer combinations in use. The tractor and trailer in the WB-50 have wheelbases of 16 and 32 feet respectively, with an overall combination length of 50 feet from the front- most axle to the rear-most axle. The WB-55, a larger single, is the second design vehicle selected for this study. Its tractor has a 16-foot wheelbase and its 48-foot trailer has a 38.5-foot effective wheelbase for an overall wheelbase of 56 feet from the front-most to rear-most axles. The WB-55 represents the longest single trailer vehicle allowed by the STAA of 1982. It is also very close in size to the largest single allowed on the Texas highway system.

Doubles. The third design vehicle is the WB-70 with the 16-foot tractor, two 28-foot trailers and an overall wheelbase spacing of 70 feet. It is sometimes referred to as the "Western Double" and is just slightly larger than the WB-60 design vehicle used in the "Green Book." It is also slightly larger than the largest combination vehicle allowed on the Texas highway system. The fourth design vehicle, the WB-105, is frequently referred to as the "Turnpike Double" and represents, in some western states, the maximum allowable trailer lengths for combination vehicles. It consists of a 16 foot tractor towing two 48-foot trailers, for an overall length of 105 ft. The WB-105 is the most critical of the five design vehicles because as is discussed later, it has the worst turning characteristics of the vehicles studied.

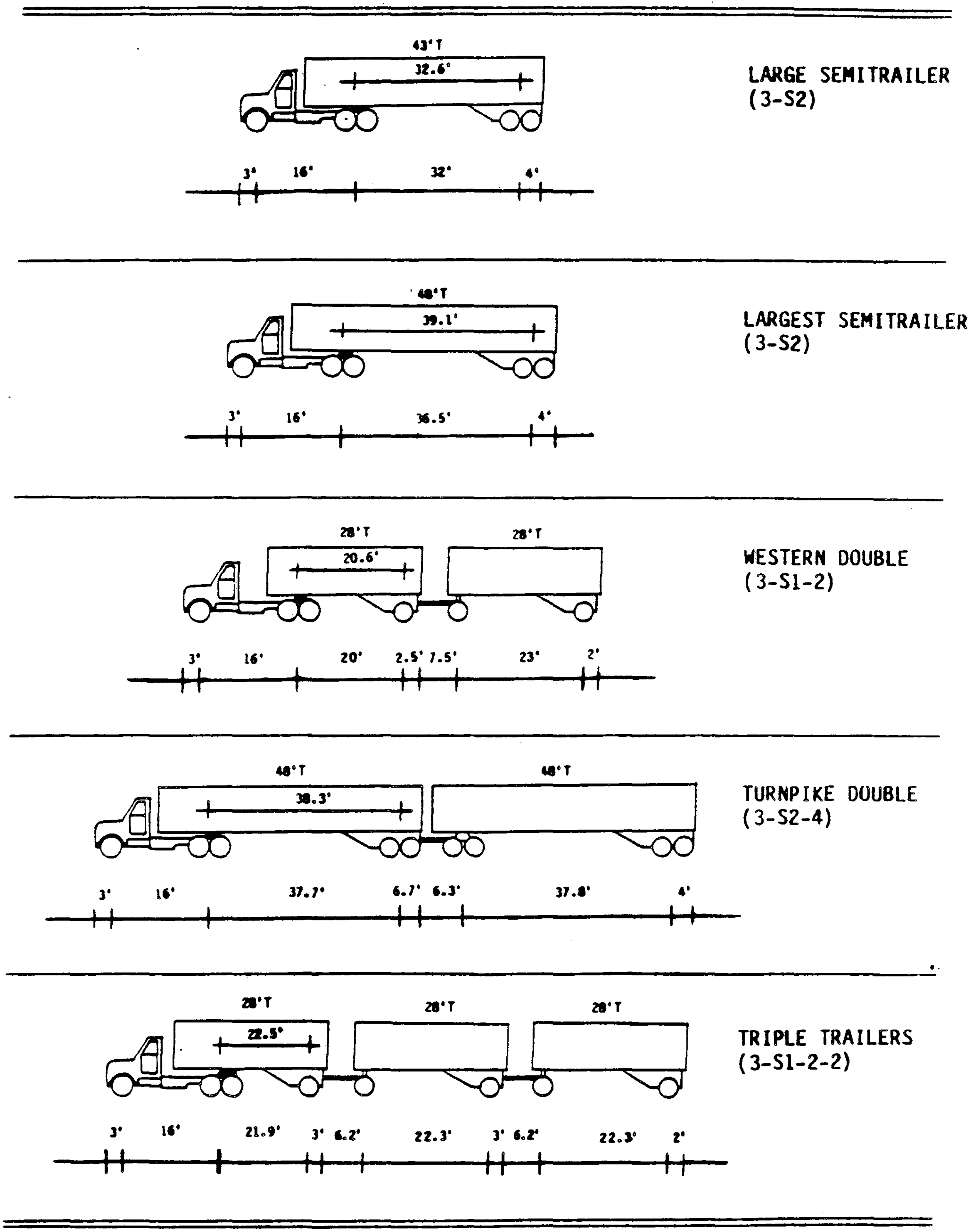


Figure 7. Design Vehicles.

Table 1. Design Vehicle Dimensions.

		Dimensions (ft)												
		Overall			Overhang									
Design Vehicle Type	Symbol	Ht.	Width	Length	Front	Rear	WB_1	WB_2	S	T	WB_3	S	T	WB_4
Combination Trucks:														
Semitrailer	WB-50	13.5	8.5	55	3	2	16	34.0	---	---	---	---	---	---
Large Semitrailer	WB-55	13.5	8.5	60	3	2	16	39.1	---	---	---	---	---	---
Semitrailer-trailer	WB-70	13.5	8.5	75	3	2	16	20	2.5	7.5	23.0	---	---	---
Large Semitrailer-trailer	WB-105	13.5	8.5	110	3	2	16	37.3	6.7	6.3	37.8	---	---	---
Semitrailer-trailer-trailer	WB-100	13.5	8.5	105	3	2	16	21.9	3.0	6.2	22.3	3.0	6.2	22.3

WB_1, WB_2, WB_3, WB_4 are effective vehicle wheelbases.
S is the distance from the rear effective axle to the hitch point.
T is the distance from the hitch point to the lead effective axle of the following unit.

Triple. The fifth design vehicle, the WB-100, is a tractor-trailer combination with three 28-foot trailers behind a 16 foot tractor, resulting in an overall length from front-most axle to rear-most axle of 100 feet. Because of these relatively short wheelbases, the WB-100 can turn a much sharper radii without encroaching than can the WB-105; however, its swept path will be much greater.

INTERSECTION GEOMETRICS

The three-dimensional experimental design matrix used in this analysis is shown in Figure 8. In addition to the design vehicle, the other parameters of interest were curb return radius and degree of turn. The values for curb return are as specified in Table III-19 in the "Green Book" (6). An additional radius of 25 feet was included in addition to the values in the table of 50, 75, 100, 150, and 200 feet. These radii were drawn to a scale of 1" = 20' on sheets of clear mylar so that the design vehicle's turning paths could be superimposed on an intersection layout.

Because a 2-foot clearance is desirable between the curb radius and the vehicle's travel path, the actual radii were respectively drawn at 27, 52, 77, 102, 152, and 202 feet. Another result of the 2-foot clearance was that the lane lines which normally would be 12 feet were drawn at 10 feet so as to show the effective lane width. Sets of the various radii were drawn for turning angles of 60, 75, 90, 105, and 120 degrees as they were considered to be representative of typical intersection geometry. The various curb radii for a 90 degree turn are illustrated in Figure 9. In addition to the typical angles of turn, a 180 degree turn was simulated for completeness and to define each design vehicle's minimum possible turning radius.

SIMULATION MODEL

The California Truck Offtracking Model (TOM) previously discussed was obtained from Caltrans along with a User's Manual (22) for the offtracking simulation portion of this study. The program, originally written for an IBM mainframe computer, was modified so as to run on a VAX 11/750 computer housed on the Texas A&M University campus. The information necessary to use the program and interpret its output are discussed in the following paragraphs.

Inputs. There are five input cards or lines of data which supply the necessary information to the offtracking program. The critical path geometry, described below, is input on card 1. The data on card 2 is the vehicle configuration, i.e. number of units and axle spacing. The simulation parameters, initial x- and y-coordinates and distance increments for simulation calculations, are input on the card 3. Card 4 includes all the plotting data as it is necessary to specify the number of paths and additional reference points to be plotted, and also to define the area in which the paths are to be plotted. The title information is given on card 5.

The critical path geometry in the computer input data stream is the radius of curvature for the turning vehicle and the angle of turn. Computer runs were made for each design vehicle making turns of 60, 75, 90, 105, and 120 degrees.

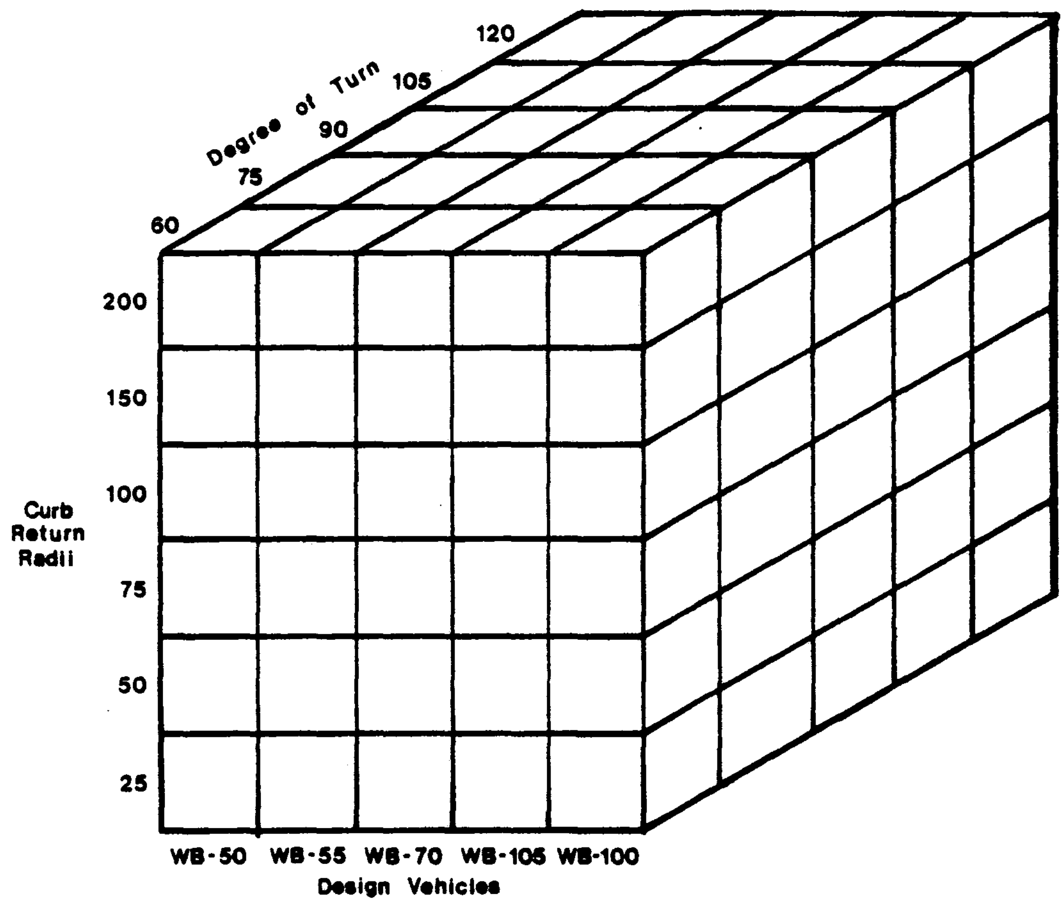


Figure 8. Three-Dimensional Study Design.

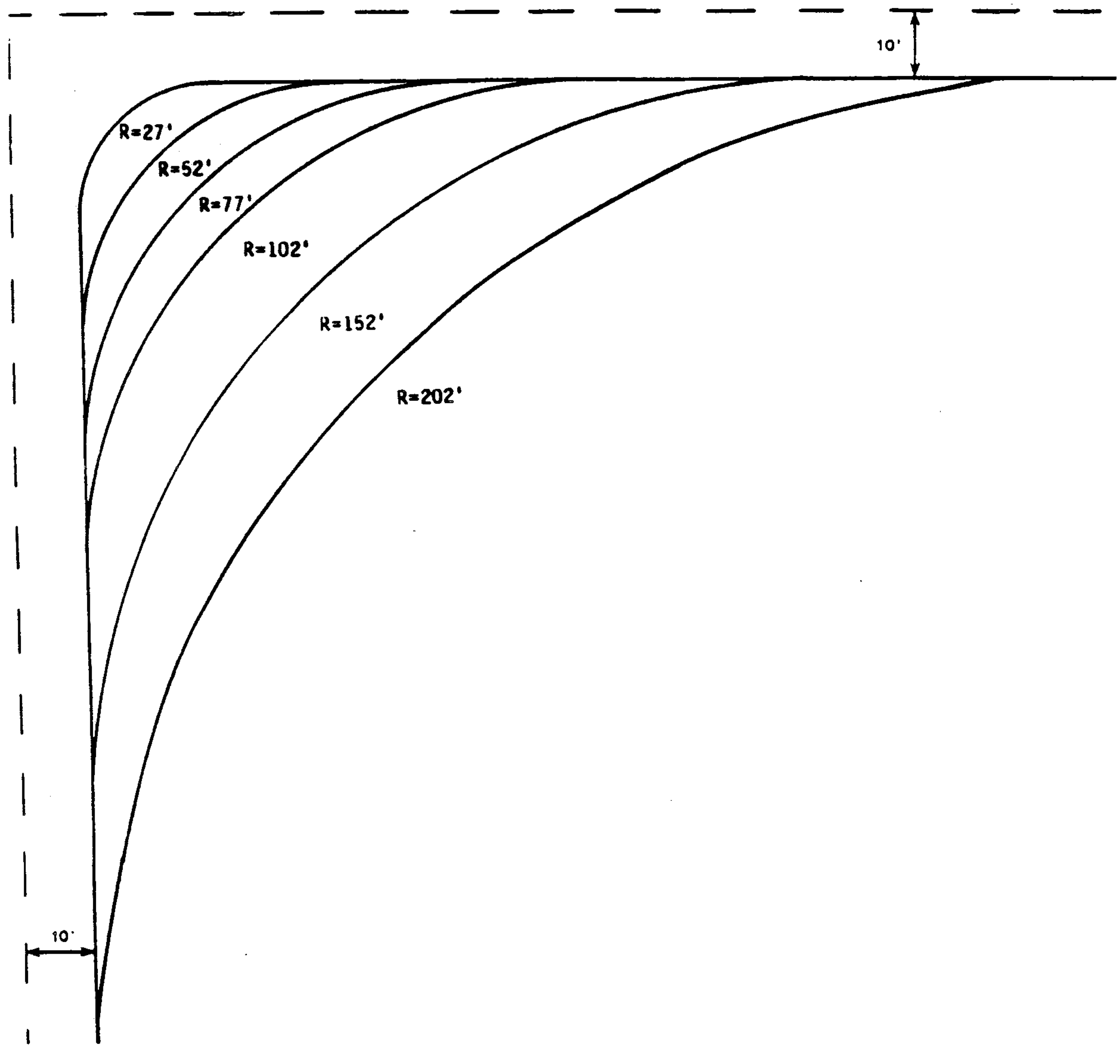


Figure 9. Curb Radii for a 90 Degree Intersection Turn.

These turns were made at the minimum radius possible (to within five ft.) and increased at intervals of 10 to 15 ft. depending on the design vehicle's minimum turning radius. The minimum radius was determined by the method described by AASHTO in 1965 (23). They state that "the minimum turning radii for the design vehicles (WB-40 and WB-50) was largely determined by the paths of the inner rear wheels." The turning path chosen was one which would result in a minimum radius of the inner rear wheel track of approximately 19 feet when negotiating turns of 90 to 180 degrees. Although semitrailer combinations are capable of turning sharper than the selected minimum turning radii, the widths of the swept paths of these vehicles at the sharper radii were considered to be impractical for minimum design control (23). The same definition of minimum turning radius was used in this study--the 19-foot minimum radius criteria.

Outputs. The three outputs of TOM are printouts detailing the input values, a table listing offtracking at the beginning of curve (BC), end of curve (EC), and the point of maximum offtracking (MOT), and the plot of the vehicle's turning path. Examples of each of these can be found in Figure 10, 11, and 12 respectively. It was necessary to rewrite the plot routine to work with the HP plotter connected to the VAX 11/750 computer used in this study. For convenience, plots were made at a scale of 1" = 20'. Other scales could have easily been specified.

The output of the Truck Offtracking Model was verified by using a vehicle configuration which closely matches that of the WB-50 design vehicle shown in the Leisch turning templates (15). A second template was made and compared to a vehicle modeled using the Tractix Integrator (6). Both templates drawn by the model closely matched the Leisch and Tractix Integrator templates. This verification was done in order to identify if mistakes were being made in the use of the program and that all the inputs were correct.

DATA ANALYSIS

Each cell or block in the experimental design will be filled with values representing the cross street width occupied and swept path width of the design vehicle when turning at the "optimum" turning radius. The optimum turning radius for each curb return is defined as the smallest turning radius which the design vehicle can negotiate without running over the inside curb, while at the same time minimizing cross street encroachment, i.e., it is the design vehicle's minimum turning radius until the curb return becomes large enough to allow the vehicle to turn on a longer radius. For each vehicle-geometric combination, the following design parameters will be determined.

Cross Street Width Occupied. The cross street width occupied is the amount of encroachment plus a 12-foot lane width. Encroachment is defined as the amount of space that the vehicle trespasses over the 12-foot lane stripe in order to complete its turn. It is assumed that the vehicle positions itself to the far left of the right most lane on the approach street and only swings wide when on the cross street, i.e. the vehicle remains within the 12-foot lane lines when approaching the turn.

```
TRUCK OFFTRACKING PROGRAM              ( 11/84 KTF )

                                  SINGLE  (16' TRACTOR, 48' TRAILER)

PATH INPUT DATA:

   DEGREE OF CURVE =     75.00
   RADIUS OF CURVE =     50.00
   DISTANCE TRAVELLED AFTER REACHING END OF CURVE =  150.00

VEHICLE INPUT DATA:

   NUMBER OF UNITS IN VEHICLE CONFIGURATION =  2      (OVERALL WIDTH =    0.00 FEET)

   VEHICLE   WHEELBASE   DISTANCE THAT 5TH WHEEL (OR HITCH)     L A B E L
    UNIT #    LENGTH       LIES IN FRONT OF THE REAR AXLE
      1       16.00                   0.60                       TRACTOR
      2       39.10                   0.00                       TRAILER

SIMULATION INPUT DATA:  OPTIONAL

   XY-COORDINATE OF THE FIRST POINT AT THE BEGINNING OF THE CURVE = (     0.00,     0.00)

   OFFSET DISTANCE BETWEEN INPUT PATH AND CENTER OF VEHICLE AT FRONT AXLE =   4.25

   DISTANCE INCREMENT FOR SIMULATION CALCULATIONS =  1.00

PLOTTER INPUT DATA:  OPTIONAL

   NUMBER OF PATHS TO BE PLOTTED =   4

     3 (SOLID  LINES):  C'L OF FRONT AXLE, AND C'L FOR EACH REAR AXLE IN THE VEHICLE CONFIGURATION

     2 (DASHED LINES):  ADDITIONAL VEHICLE REFERENCE POINTS AS SPECIFIED BELOW (IF ANY)

       VEHICLE      DISTANCE IN           DISTANCE RIGHT         L A B E L
        UNIT #    FRONT OF REAR AXLE    (OR LEFT) OF CENTER LINE
          1            16.00                  -4.25
          2             0.00                   4.25

   ACTUAL PLOT LIMITS:   MINIMUM XY = (  -10.00,  -50.00);   MAXIMUM XY = (  180.00,  150.00)

   SCALING FACTOR =  0.05000

     SCALE:  1 IN = 20.00 FEET

   PLOTTER PAPER SIZE    WIDTH (Y) =  12-INCH;  LENGTH (X) =  25-INCH
```

Figure 10. Example Printout of Programs Input Values
(WB-55, 75-Degree Turn, 50-Foot Radius).

TRUCK OFFTRACKING PROGRAM (11/84 KTF)

SINGLE (16' TRACTOR, 48' TRAILER)

OFFTRACKING SUMMARY

LOCATION (DEGREE)	AMOUNT OF OFFTRACKING	
0. 00	6. 57	(B C)
49. 45	14 06	(MOT)
75. 00	11 90	(E C)

***** END OF JOB *****

Figure 11. Example Printout of Program Output Values (WB-55, 75-Degree Turn, 50-Foot Radius).

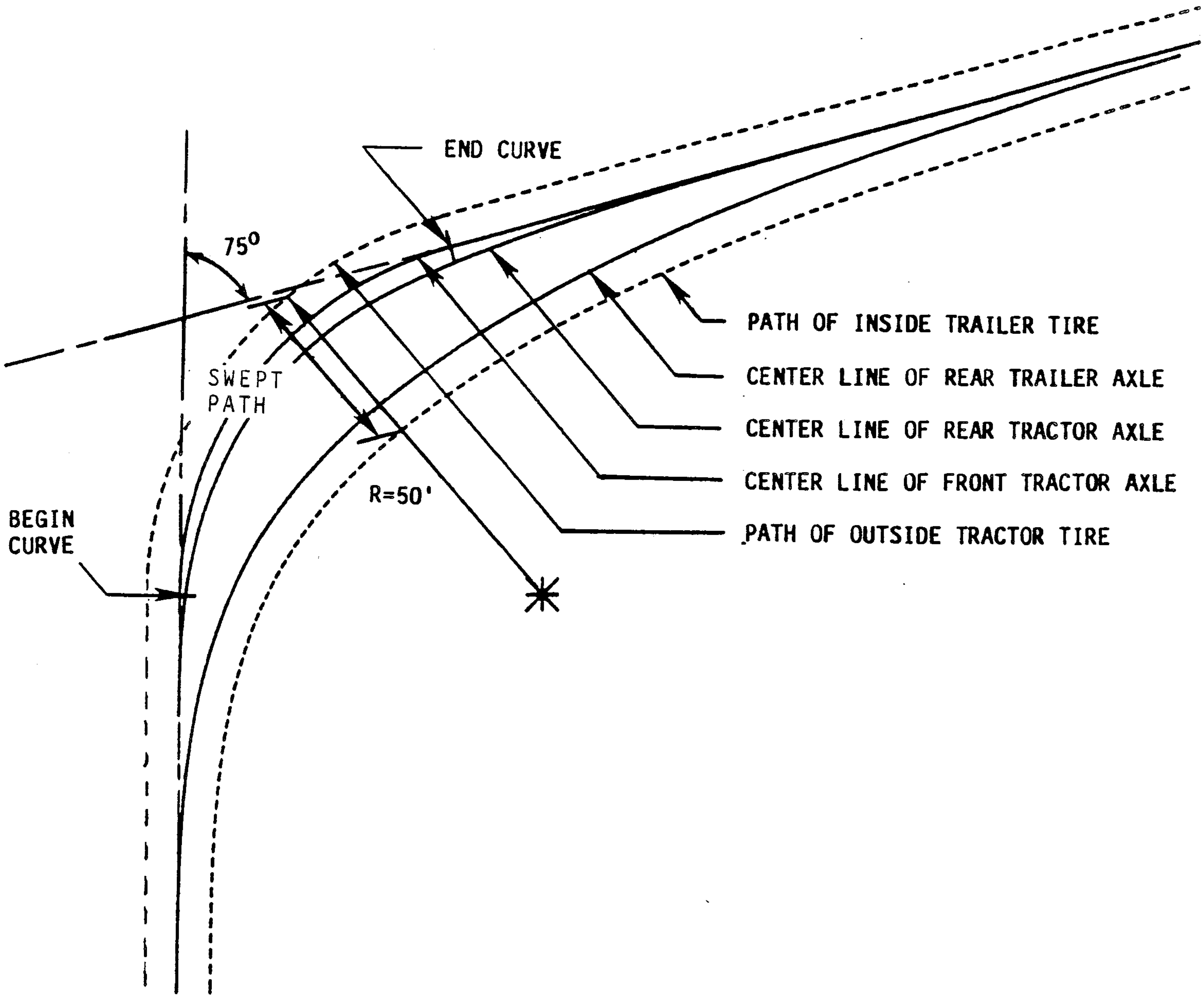


Figure 12. Example Plot From Truck Offtracking Model (WB-55, 75-Degree Turn, 50-Foot Radius).

Swept Path Width. Swept width, as defined earlier in this report, is the difference in paths of the front-most outside wheel and rear-most inside wheel of a vehicle as it negotiates a turn. It can also be defined as simply the offtracking plus the width of the vehicle. Swept widths are important in determining the width of turning roadways. The maximum swept widths measured from the plots generally agreed with the offtracking values from the computer printouts.

Channelization. The critical design consideration in deciding whether or not to use channelization is the curb return radius of the intersection. It is **not** the same as the turning radius of the vehicle. In order to determine where there was enough pavement area to justify channelization, the 12-foot lane lines on each street were extended until they intersected. An island was then drawn on a mylar sheet with the curb radii that would satisfy the preferred criteria in the "Green Book," i.e. 3-foot offset from through traffic, 3 foot corner radii, and minimum leg lengths of 15 feet. Figure 13 illustrates the island placement and its minimum size for the 90 degree curb radii.

In order to determine the values for each vehicle-geometric combination, the turning templates were grouped first according to the design vehicle and then according to the angle of turn. For each design vehicle at each angle of turn, the minimum turning path (determined from the 180 degree turns) was placed over the 27-foot curb radius at that same angle of turn. Wheel paths of the vehicles could lie on the line, offset 2 feet from the curb, because of the allowances previously made. The amount of maximum encroachment was measured at the end of the turning curve, EC, as this is the point where the truck begins moving back into its lane. The encroachment is the distance that the vehicle trespasses over the 12-foot lane line. The assumptions made are that the vehicle turns from the proper lane of the approach; therefore, all of the encroachment occurs on the cross street lane. No allowances were made in the simulation for shoulders for the truck to encroach upon.

As the curb radius was increased, the minimum turning path, i.e. 45 feet for the WB-50, became too tight and it was necessary to go to a larger turning path. Preferably, the turning path that encroaches the least or not at all is the one chosen. If, for example, both the 60-foot turning radius and the 75-foot turning radius could each turn a 150-foot curb radius without encroaching, then the 75-foot turning path would be selected because it has a smaller swept width.

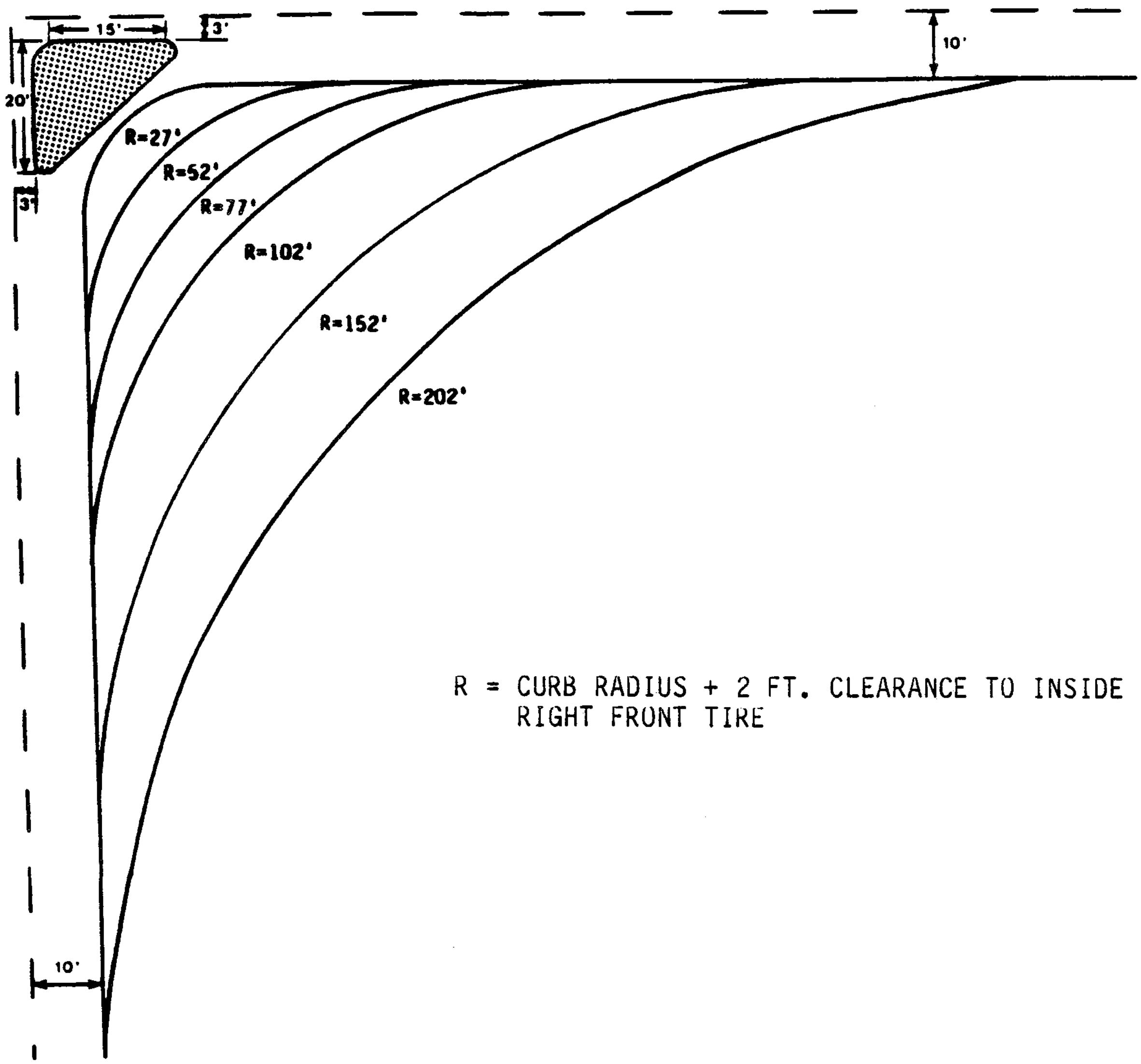


Figure 13. Minimum Island Size for a 90 Degree Intersection Turn.

IV. STUDY RESULTS

Once the study's design had been formulated and the analysis procedure defined, simulation runs were made for each of the different scenarios and the resultant output converted to a more understandable format. Thus the study's results can be broken down into five topic areas--minimum turning radii, turning templates, cross street width occupied, swept path widths, and channelization guidelines. Each of these topics is discussed in the following sections.

MINIMUM TURNING RADII

The boundaries of the turning paths for a design vehicle making its sharpest possible turn are established by the paths followed by its outer front wheel and inner rear wheel as it makes the turn. The minimum turn radii of the outside and inside wheel paths for each of the five design vehicles are given in Table 2. The values for the WB-50 vary slightly from those in the "Green Book" due to a shorter tractor and longer trailer axle spacings. The minimum turning radii and the transition lengths shown here and in the "Green Book" are for turns at less than 10 mph. This assumption minimizes the effects of driver characteristics (such as the rate at which the driver approaches centripetal acceleration) and of the slip angles of wheels.

TURNING TEMPLATES

Turning templates for each of the five design vehicles were developed using their minimum turning paths for various angles of turn, i.e., 60, 90, 120, and 180 degrees. They were patterned after the Leisch templates (15) and are shown in Figures 14 through 18. These templates were prepared by drawing each design vehicle on a sheet of mylar and then tracing its turning path onto that same sheet, for each of the four angles of turn. They were originally drawn at a scale of 1" = 20' and then reduced for inclusion in this report. Templates at different scales and other than minimum turning paths could easily have been prepared as they involved change of only a few inputs to the programs and preparation of additional drawings.

CROSS STREET WIDTH OCCUPIED

Table 3 illustrates the effect of the angle of intersection on turning paths of various design vehicles on streets without parking lanes. It is structured similarly to Table IX-3 in the "Green Book." The dimensions d_1 and d_2, shown in Figure 19 are the widths occupied by the turning vehicle on the main street and on the cross street, respectively, while negotiating turns through various angles. Both dimensions are measured from the right-hand curb to the point of maximum swept width. These widths, generally increase with increasing angle of turn and decrease with increasing curb radii. The right-turn maneuver modeled in this study assumes that the vehicle positioned itself

Table 2. Minimum Turning Radii of Design Vehicles.

Design Vehicle Type	Semitrailer Combination	Semitrailer Combination (Large)	Semitrailer-Full Trailer Combination	Semitrailer-Full Trailer Combination (Large)	Semitrailer Full Trailer-Full Trailer Combination
Symbol	WB-50	WB-55	WB-70	WB-105	WB-100
Configuration	3-S2	3-S2	3-S1-2	3-S2-4	2-S1-2-2
Minimum Turning radius (ft.)	45	50	50	65	55
Minimum Inside radius (ft.)	20.5	19	24.3	25.8	25.6

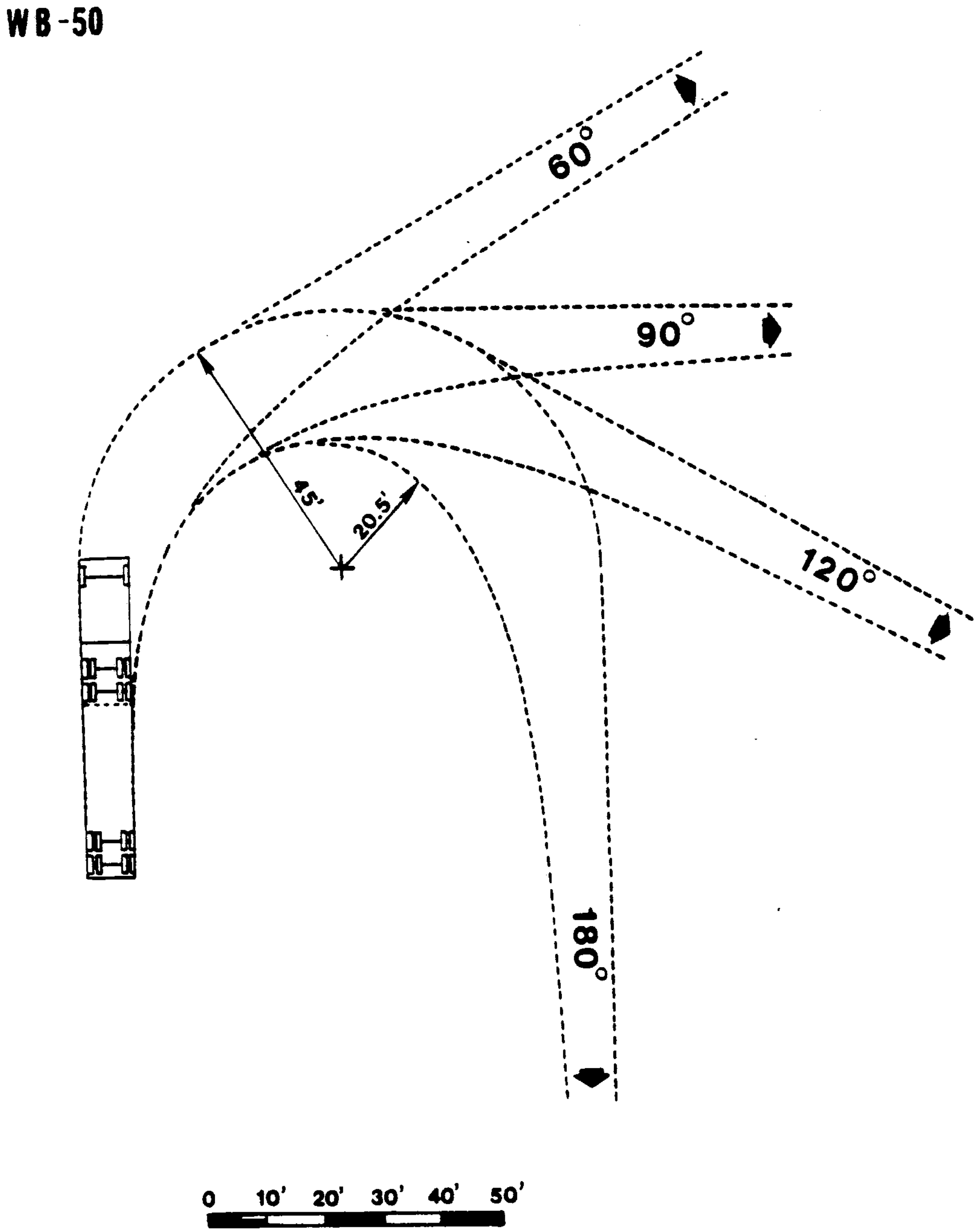


Figure 14. Minimum Turning Paths for WB-50 Design Vehicle.

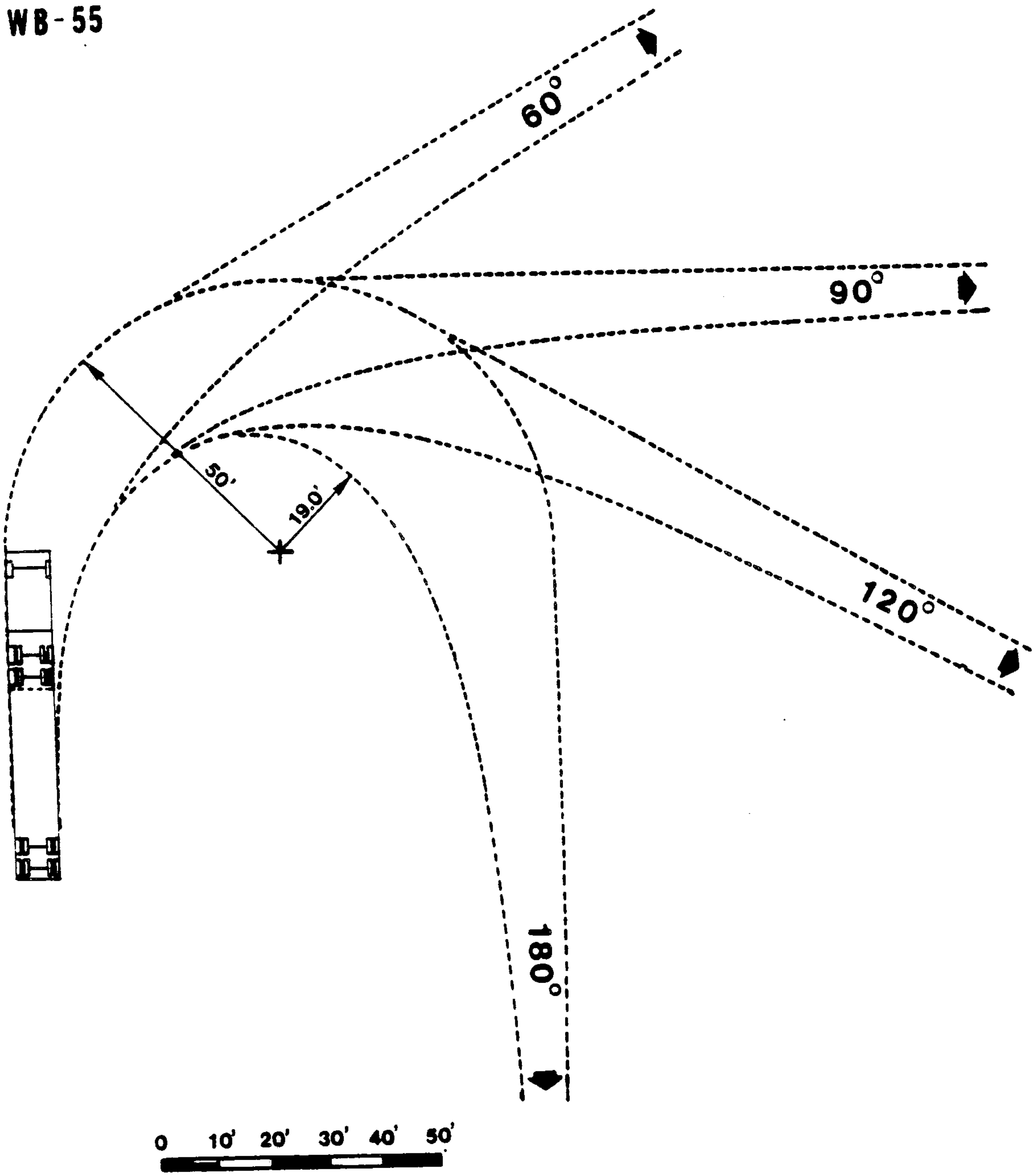


Figure 15. Minimum Turning Paths for WB-55 Design Vehicle.

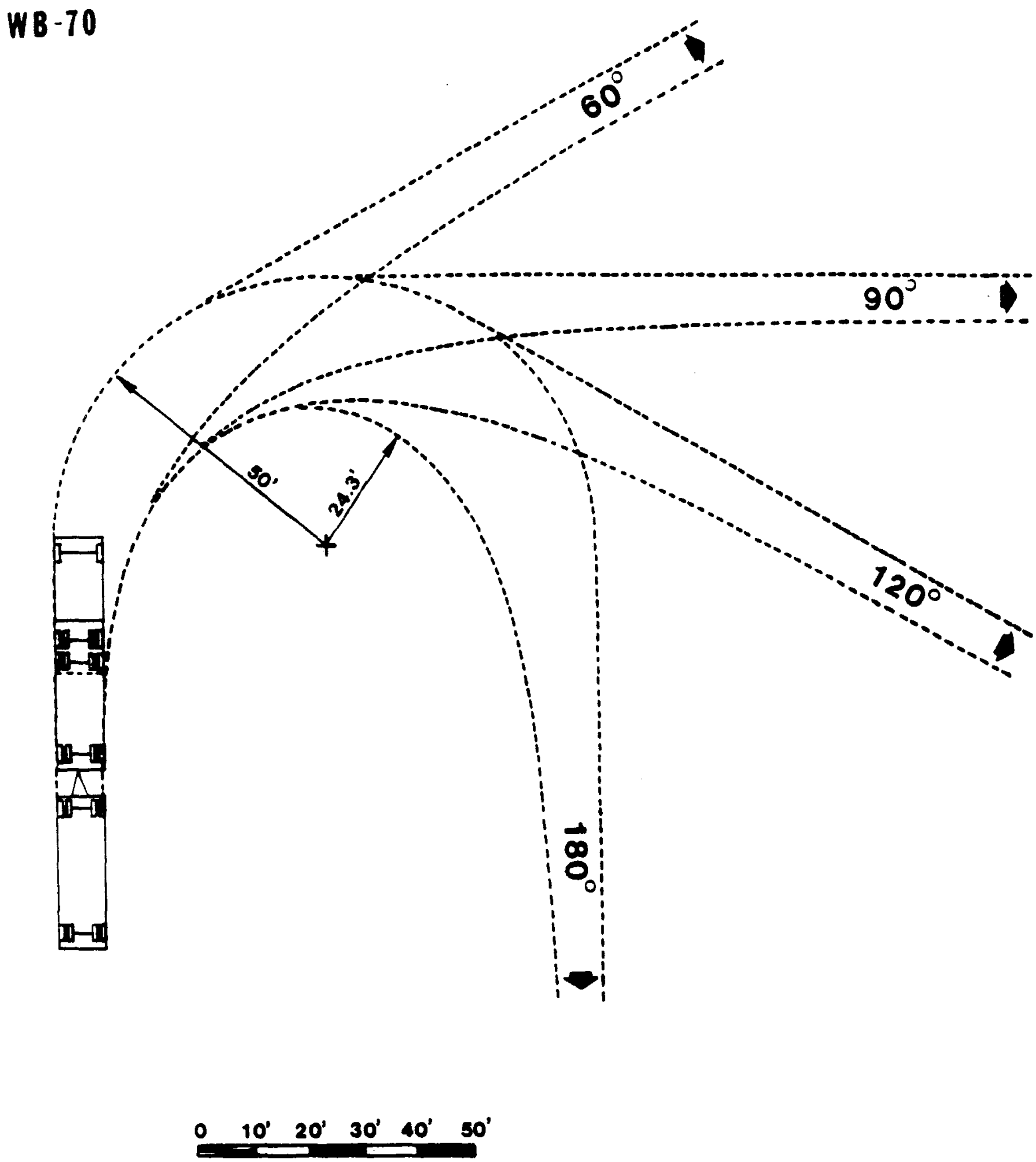


Figure 16. Minimum Turning Paths for WB-70 Design Vehicle.

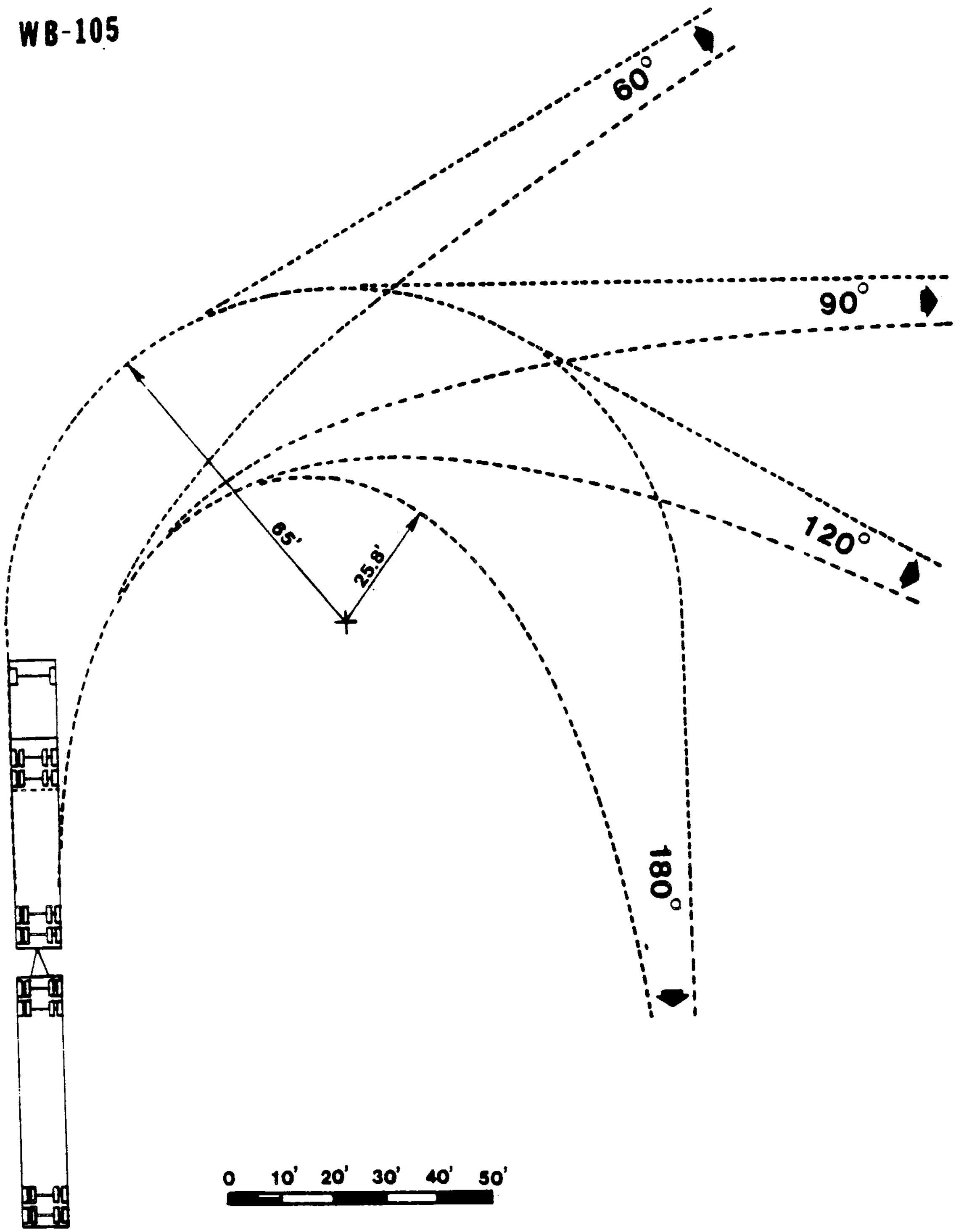


Figure 17. Minimum Turning Paths for WB-105 Design Vehicle.

WB-100

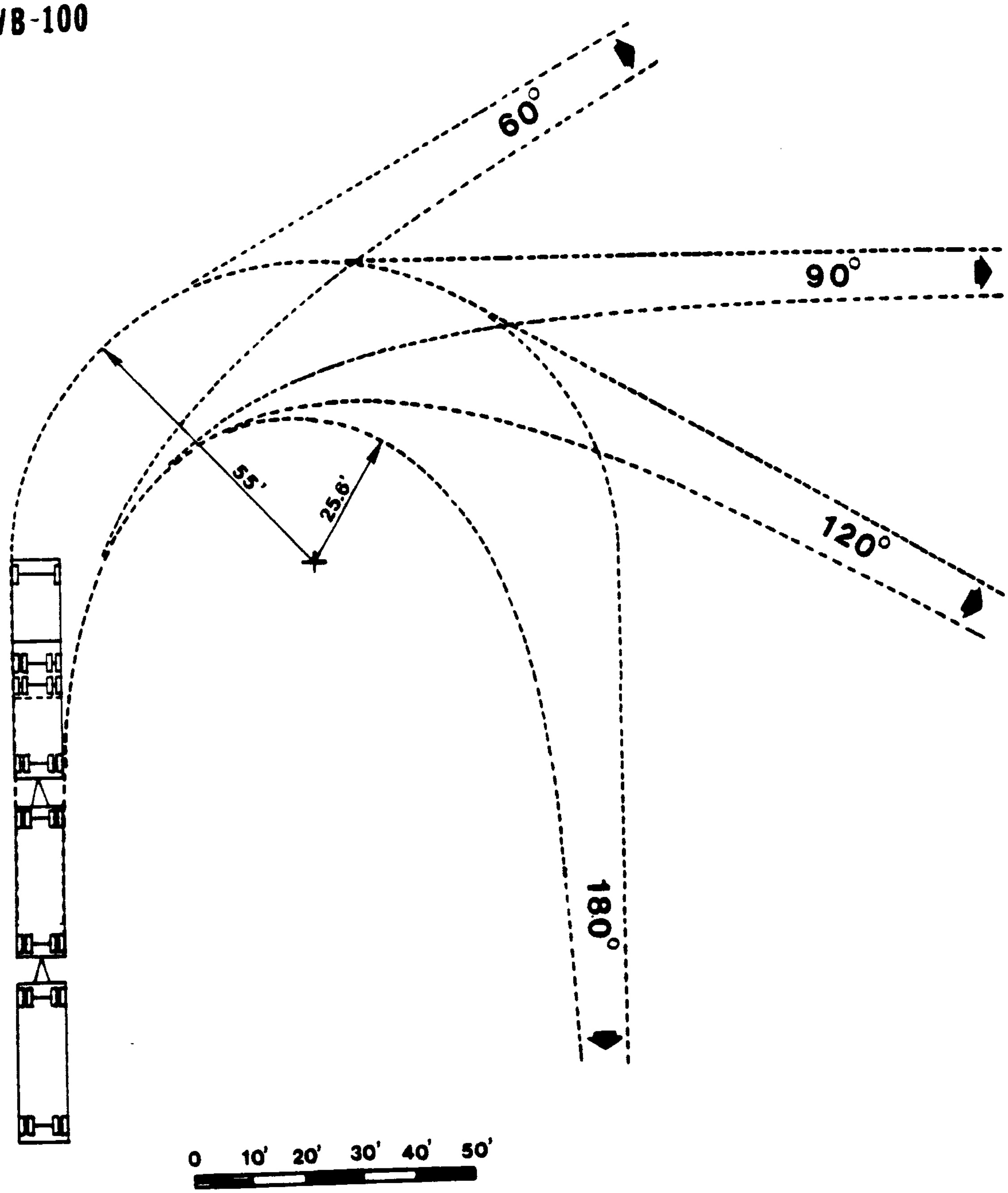


Figure 18. Minimum Turning Paths for WB-100 Design Vehicle.

Table 3. Cross Street Width Occupied by Turning Vehicle for Various Intersection Angles and Curb Radii.

Angle of Turn (Degrees)	Design Vehicle	Curb Radius					
		25 ft.	50 ft.	75 ft.	100 ft.	150 ft.	200 ft.
60	WB-50	33.5	24.0	17.0	14.0	12.0	12.0
	WB-55	40.0	29.8	21.5	17.3	13.0	12.0
	WB-70	38.8	23.7	19.5	15.0	12.0	12.0
	WB-100	46.5	36.2	27.0	18.0	12.0	12.0
	WB-105	56.0	46.5	37.0	29.0	18.0	12.0
75	WB-50	37.0	26.0	16.5	13.5	12.0	12.0
	WB-55	44.0	34.7	21.5	16.8	12.0	12.0
	WB-70	43.0	34.0	20.0	14.5	12.0	12.0
	WB-100	52.0	41.0	28.5	17.0	12.0	12.0
	WB-105	65.0	36.0	42.5	30.0	17.0	12.0
90	WB-50	43.0	26.0	17.0	13.0	12.0	12.0
	WB-55	53.0	37.0	21.8	17.0	13.0	12.0
	WB-70	53.0	36.0	21.0	14.0	12.0	12.0
	WB-100	66.0	46.5	31.0	17.5	12.0	12.0
	WB-105	81.0	63.0	48.0	33.0	17.3	12.0
105	WB-50	52.0	32.0	18.0	13.0	12.0	12.0
	WB-55	62.0	42.0	23.5	18.0	12.0	12.0
	WB-70	61.5	42.0	23.0	14.0	12.0	12.0
	WB-100	74.0	52.0	32.5	19.0	12.0	12.0
	WB-105	95.0	75.0	55.0	39.0	18.0	12.0
120	WB-50	59.0	40.0	23.0	14.5	12.0	12.0
	WB-55	80.0	51.0	35.0	21.0	13.5	12.0
	WB-70	72.0	52.0	34.0	17.0	12.0	12.0
	WB-100	84.5	63.0	47.0	29.0	13.0	12.0
	WB-105	106.0	85.0	68.5	49.0	21.0	12.0

Note: Boxed-in areas are conditions with enough room for an adequately-sized island, i.e., they may require channelization.

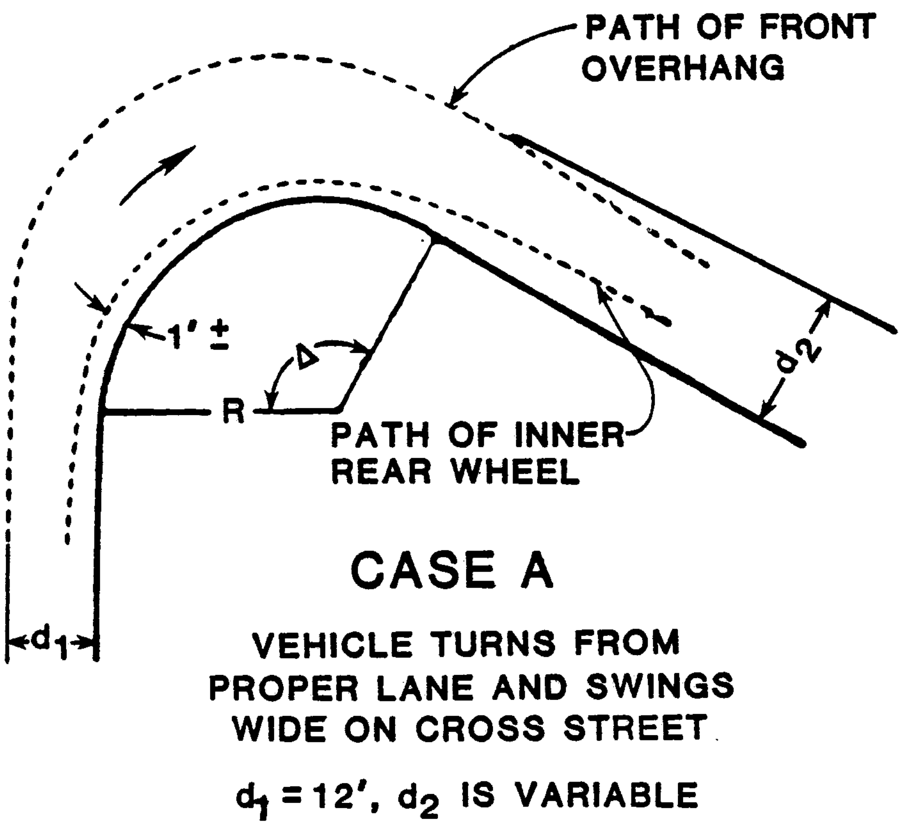


Figure 19. Cross Street Width Occupied by Turning Vehicle.

to the far left of the right-most lane on the approach street and only swing wide when on the cross street. This assumption results in the worst case scenario on the cross street. Therefore, the dimension d_1 = 12 feet and d_2 is the value shown in the Table 3.

The values for the WB-50 design vehicle in Table IX-3 of the "Green Book" should have closely resembled values for the WB-50 vehicle used in this study The values from Table IX-3 in the "Green Book" indicate that AASHTO WB-50 has less severe turning characteristics than the WB-50 with a slightly shorter tractor wheelbase used in this study; however, it should be remembered that associated with a shorter tractor wheelbase is a longer semitrailer wheelbase and as offtracking is a function of the sum of squares of the different wheelbase lengths, a decrease in a short wheelbase will be more than offset by a corresponding increase in a long wheelbase. Thus, the larger values of cross street width occupied are consistent with theory.

Some of the turns which were modeled in this study are totally unrealistic. For example, it is not advisable to use 25-foot curb radii when designing for larger vehicles. The turnpike double has several problems due to its extra long configuration which are complicated by the procedure that this research uses. The combination, when modeled at 180 degrees, requires a 65-foot turning radius for a 19-foot inside radius. The large minimum turning radius combines with the unwieldy turning characteristics to make curb radii of less than 75 feet unfeasible.

Assuming a road with two 12-foot lanes in either direction, a truck must be able to turn without occupying more than 24 feet of the cross street width. Referring to Table 3, none of the vehicles can turn a 25-foot or a 50-foot radius under these circumstances. At a 75-foot radius, all of the vehicles except the WB-105 (turnpike double) and the WB-100 (triple) will be able to turn within 24 feet of cross street width. These two larger vehicles can make the turn within the stated constraints at radii of 100 and 150 feet respectively.

If the example were modified and there was a 10-foot shoulder or parking lane provided on the cross street, the available cross street width would be 34 feet. Under these circumstances, the less critical design vehicles (WB-50, WB-55, and WB-70) could turn at 50-foot curb radii, the WB-100 could turn the smaller angle turns at 75-foot and all angles at the 100-foot curb radii; however, the most critical design vehicle (WB-105) can still only turn 150-foot and 200-foot curb radius turns. As the angle of turn increases past 90 degrees, the WB-105's turning problems become much more pronounced, especially at a 105 degree, 150-foot curb radius where the other four vehicles maneuver well.

The "Green Book" recognizes that when a simple, single-radius curve is used for the curb return, a very large radius must be used or the streets must be very wide to accommodate the longer vehicles, particularly where the central angle is greater than 90 degrees. (6) In instances where there is curb parking, vehicles are able to turn smaller radii with less encroachment. Intersections should not be built with smaller radii because of the advantages that curb parking offers. Areas with on-street parking often become congested and should the parking be removed, the same turning conditions will prevail as did when there was no parking.

TURNING ROADWAY WIDTH

Table 4 contains the values for the swept width of the various design vehicles shown for various angles of turn and curb radii. The swept width is a function of the optimum turning radius of the vehicle at a certain angle and curb return. By close inspection of Table 3, it is possible to determine the point at which the minimum turning radius of each design vehicle reached the point where it was no longer the optimum, and a larger turning radius (with a smaller swept width) could negotiate the curb radius equally well, if not better than the minimum. This point is identifiable by the decrease in the swept width for a particular design vehicle at a certain degree of turn as the radius increases. The 65-foot minimum radius of the turnpike double is not ever replaced by a greater radius as the curb radii increases up to 200 feet.

The greater the swept width of a vehicle negotiating a turn, the greater the width of turning pavement necessary. The "Green Book" classifies pavement widths for turning roadways for the following types of operations: Case 1--one-lane, one-way operation with no provision for passing a stalled vehicle; Case 2--one-lane, one-way operation with provision for passing a stalled vehicle; and Case 3--two-lane operation, either one-way or two-way. Case 1 is the type of operation which will be considered in this study.

Although the WB-105 (turnpike double) has a wheelbase just slightly longer than the WB-100 (triple), its swept width is much greater due to its greater axle spacings. The sum of the squares of axle spacings and the number of points of articulation govern the way a vehicle will offtrack around a curve. The number of articulations will affect the shape of the curve while the sum of the squares will determine the magnitude of offtracking (10). The turnpike double's two 48-foot trailers cause more severe offtracking than the triple's 28-foot trailers.

CHANNELIZATION GUIDELINES

The boxed-in area in both Tables 3 and 4 are the conditions where the curb radius combines with the optimum turning radius in such a way as to leave room for an adequately-sized island. Areas where channelization is feasible are the larger curb radii, and frequently the larger degrees of turn. Channelization is recommended at a 200 ft. curb radius for all of the vehicles except the turnpike double at 60 and 70 degree turns. As the curb radius decreases, it is the angle of turn in combination with the design vehicle that influences whether channelization is feasible. Overall, as the angle of turn increases beyond 90 degrees, the skewed intersection angle leaves an open pavement area that when combined with curb radii of 75 to 200 feet, and a fairly narrow swept width, results in a good-sized island area to channelize the right turns. At the 60 degree and 75 degree turns, the geometry is such that few of the combinations warrant channelization.

Table 5, similar to Table IX-4 in the "Green Book," contains minimum designs and channelization guidelines for turning roadways. The parameters which govern the design are angle of turn, design vehicle, curb radius, width of lane, and approximate island size. For each design vehicle, Table 5 lists a suggested island size and width of turning lane at each angle of turn that

Table 4. Swept Path Width Occupied by Turning Vehicle for Various Intersection Angles and Curb Radii.

Angle of Turn (Degrees)	Design Vehicle	Curb Radius					
		25 ft.	50 ft.	75 ft.	100 ft.	150 ft.	200 ft.
60	WB-50	18.0	18.0	18.0	18.0	16.5	15.0
	WB-55	20.5	20.5	20.5	20.5	18.8	17.0
	WB-70	19.0	19.0	19.0	19.0	16.5	15.5
	WB-100	20.7	20.7	20.7	20.7	20.0	17.8
	WB-105	24.9	24.9	24.9	24.9	24.9	24.9
75	WB-50	19.5	19.5	19.5	19.5	16.0	15.0
	WB-55	22.5	22.5	22.5	22.5	20.0	18.0
	WB-70	20.0	20.0	20.0	20.5	17.5	16.5
	WB-100	22.5	22.5	22.5	22.5	21.8	17.5
	WB-105	27.7	27.7	27.7	27.7	27.7	27.7
90	WB-50	20.5	20.5	20.5	20.5	16.5	15.0
	WB-55	24.0	24.0	24.0	24.0	22.2	18.5
	WB-70	21.5	21.5	21.5	21.5	18.0	16.5
	WB-100	24.2	24.2	24.2	24.2	23.1	19.0
	WB-105	30.0	30.0	30.0	30.0	30.0	30.0
105	WB-50	21.3	21.3	21.3	21.3	16.5	15.0
	WB-55	25.5	25.5	25.5	25.5	23.3	19.0
	WB-70	22.5	22.5	22.5	22.5	18.5	16.5
	WB-100	25.5	25.5	25.5	25.5	24.4	19.5
	WB-105	32.1	32.1	32.1	32.1	32.1	32.1
120	WB-50	22.0	22.0	22.0	22.0	19.0	15.0
	WB-55	26.8	26.8	26.8	26.8	26.8	22.0
	WB-70	23.5	23.5	23.5	23.5	21.0	18.5
	WB-100	26.5	26.5	26.5	26.5	26.5	22.0
	WB-105	33.8	33.8	33.8	33.8	33.8	22.0

Note: Boxed-in areas are conditions with enough room for an adequately sized island, i.e., they may require channelization.

Table 5. Minimum Designs and Channelization Guidelines for Turning Roadways.

Angle of Turn (degrees)	Design Vehicle	Curb Radius (ft.)	Width of Turning Lane (ft.)	Approximate Island Size (sq. ft.)
60	WB-50	200	27	250
	WB-55	200	22	160
	WB-70	200	22	160
	WB-100	200	27	160
	WB-105	-	-	-
75	WB-50	150	28	320
	WB-55	150	23	200
	WB-70	150	30	160
	WB-100	200	34	300
	WB-105	-	-	-
90	WB-50	150	30	670
	WB-55	150	22	560
	WB-70	200	38	900
	WB-100	200	40	900
	WB-105	200	54	260
105	WB-50	150	32	980
	WB-55	150	31	1320
	WB-70	200	41	1940
	WB-100	200	41	1940
	WB-105	200	57	940
120	WB-50	150	40	1640
	WB-55	150	39	1600
	WB-70	200	45	3400
	WB-100	200	48	2580
	WB-105	200	60	1740

might need channelization, i.e. those conditions that were boxed-in in Tables 3 and 4. As the curb return radius increases towards 200 feet, the area of the island becomes larger and the width of the turning lane decreases. The size of islands for the larger turning angles indicates the otherwise unused and uncontrolled areas of pavement that are eliminated by the use of islands. Turning roadways for flat-angle turns, less than 75 degrees, involve relatively large radii and require design to fit site controls and traffic conditions (6).

Because the truck configurations spiral into a curve, it might be preferable to fit the edge of the pavement closely to the minimum path of the design vehicle by using compound curves to minimize the amount of unused pavement. The sometimes unnecessarily wide turning lane widths in Table 5 are an indication that three centered compound curves or simple curves with tapers might be preferable to the simple radius curves researched.

V. SUMMARY

This study addresses truck problems at intersections due to the increased offtracking of the longer and wider vehicles. The goal was to establish a set of guidelines for intersection channelization to accommodate these larger vehicles. Results of the research include several truck turning templates; tables containing cross street width occupied and swept width for various combinations of design vehicle, curb radii, and degree of turn; and recommendations for the use of channelization when designing for the longer and wider trucks.

This research was needed because although adequate research concerning offtracking had been done on the newly approved, longer and wider truck configurations, none had been performed to relate the offtracking to intersection geometry. The "Green" Book contains pages of information on channelization, but because 48-foot trailers and 102-inch wide trucks were not considered, none of the tables in the "Green Book" evaluate the effects of the new larger vehicles on the highway system.

CONCLUSIONS

The selection of a design vehicle is a critical decision. It is generally based on the largest standard or typical vehicle type that would regularly use the intersection. Where reliable vehicle classification counts are available, they can be used to select a design vehicle. More often, selection is based on the area type and functional classification of the intersecting highways. (19)

The adoption of the Truck Offtracking Model that was developed by Caltrans for use in this study was advantageous because it was capable of simulating various truck paths in a short time period compared to other methods. It is a powerful program once the user is familiar with all of the items which may be varied. Many mistakes were made while learning how to adjust the input values and what effect the adjustments would have. Left turns of each design vehicle should have been completed but were not because of the additional time required to learn all the intricate details involved in the modeling and especially the plotting routine.

The procedure used herein could be used for intersection design where there are high volumes of trucks because of its ability to specify any design vehicle, degree of turn, and curb return radius. It might be feasible to design at-grade intersections along Interstate Highways and the Designated System for the larger truck combinations. Concentrations of larger vehicles in other areas, i.e. truck terminals and lumber yards, may also warrant special design consideration. TOM could be used to develop turning templates for special design vehicles. For example, intersections between a logging area and a lumber yard which experience high turning movements could be designed using turning templates of a typical logging truck. The same procedure used in this study could be used in these instances.

RECOMMENDATIONS

Recommendations for further research:

- o Develop additional turning templates at various angles of turn and turning radii.
- o Plot the overhang of the design vehicles as they traverse different angle of the turn at the various radii.
- o Develop tables containing width of pavement information for each of the three cases; one-lane, one-way operation with no provision for passing a stalled vehicle; one-lane, one-way operation with provision for passing a stalled vehicle; and two-lane operation, either one-way or two-way.
- o Develop additional tables for curb radii consisting of three-centered compound curves and simple curves with tapers.
- o Simulate design vehicles making left turn maneuvers. Develop guidelines for these circumstances.
- o Develop step-by-step procedures, similar to steps followed in this study, to be used to evaluate geometry at existing intersections, i.e., step 1 - identify design vehicle; step 2 - run computer simulation to obtain plots; step 3 - compare to existing curb geometry to determine effects of offtracking.
- o Prepare computer inputs for several design vehicles in order to make program more "user friendly".

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