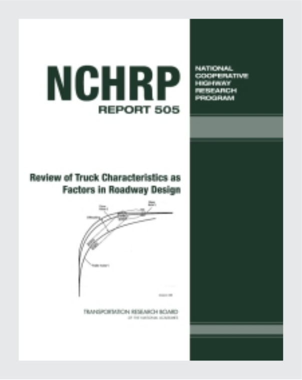

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 505

Review of Truck Characteristics as Factors in Roadway Design

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Planning and Administration • Highway and Facility Design • Highway Operations, Capacity, and Traffic Control

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TRANSPORTATION RESEARCH BOARD

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2003
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Christopher J. Hedges
Staff Officer
Transportation Research Board

This report presents guidance for roadway geometric designers on how best to accommodate large trucks on the U.S. highway system.

Under NCHRP Project 15-21, a research team reviewed the range of dimensions and performance characteristics of trucks currently used on U.S. highways and predicted how these characteristics may change in response to current political, economic, and technological trends. The research team conducted an analysis of those geometric design features affected by vehicle characteristics and then evaluated the adequacy of current geometric design policy to accommodate the current and anticipated truck fleet. Based on the findings, the report makes recommendations for a number of changes to the AASHTO *Policy on Geometric Design of Highways and Streets* ("Green Book").

The report (1) provides valuable guidance for designers of roads and facilities that need to accommodate large trucks and (2) will assist AASHTO in updating geometric design policy. The information developed in this project will also be useful as input to future editions of other documents such as the TRB *Highway Capacity Manual*, the FHWA *Manual on Uniform Traffic Control Devices*, and the AASHTO *Roadside Design Guide*.

The heavy truck vehicle fleet constitutes a significant percentage of the traffic on major routes in the United States, such as the Interstate highway system. The volume of heavy truck traffic is increasing because of factors that include economic growth; advances in freight transportation logistics, such as just-in-time delivery systems; and changing trade patterns resulting from the North American Free Trade Agreement (NAFTA).

To provide a seamless and efficient national highway transportation system, it is important to ensure that the criteria for roadway geometric design are appropriate for the current and anticipated fleet of heavy trucks on U.S. highways. Research was needed on the dimensions, performance, and operational characteristics of the current and future fleet, so that these characteristics can be evaluated and, if necessary, accommodated on a consistent basis in geometric design standards.

Transportation engineers rely on AASHTO's *Policy on Geometric Design of Highways and Streets* for information on design vehicles and roadway design criteria. Heavy truck operating characteristics are treated to a limited extent in the present AASHTO Policy and are based on generalized design vehicles that may not reflect the characteristics of the current fleet. The information currently in the AASHTO Policy needs to be reviewed and updated as appropriate to account for the current and future truck fleet using the U.S. national highway transportation system.

Under NCHRP Project 15-21, "Review of Truck Characteristics as Factors in Roadway Design," the Midwest Research Institute began by reviewing the legal size and weight limits for trucks in U.S. states, as well as limits for Canadian and Mexican trucks using U.S. highways under NAFTA. The characteristics of the current fleet were determined by analysis of FHWA and U.S. Census Bureau data. The team then evaluated those geometric design features affected by truck characteristics and made recommendations on where changes are needed to the current design policy in order to accommodate the characteristics of the truck fleet. The recommendations include several changes to the standard design vehicles now in use, as well as four new design vehicles reflecting truck configurations that could be permitted in the future under certain scenarios. As part of the research, the team developed a truck speed profile model to predict truck performance on upgrades. The model was implemented as an Excel spreadsheet program that is included with this report on diskette. The spreadsheet program can be used by highway agencies to anticipate where additional climbing lanes may be warranted.

CONTENTS

REVIEW OF TRUCK CHARACTERISTICS AS FACTORS IN ROADWAY DESIGN

SUMMARY

Trucks constitute a large and growing segment of the traffic on American highways. On many rural Interstate highways, trucks now constitute more than one-third of the total traffic stream. The increase in truck traffic is related to a strong and growing economy, shifts in manufacturing patterns and inventory reduction through just-in-time delivery, and changing trade patterns resulting from the North American Free Trade Agreement (NAFTA). In addition to growth in truck volumes, the mix of truck types on U.S. highways has shifted toward larger vehicles.

Trucks are an important consideration in geometric design of highways. Many highway geometric design policies are based on vehicle characteristics. Truck characteristics are often a key consideration in determining the recommended values of such criteria. The research presented in this report reviews the characteristics of trucks in the current U.S truck fleet, as well as possible changes to the truck fleet, and recommends appropriate changes to highway geometric design policy to ensure that highways can reasonably accommodate trucks.

The research found that NAFTA may lead to increased truck volumes using U.S. highways, but is unlikely to result in truck types not currently considered in highway geometric design policies entering the United States. Thus, geometric design must consider current trends in the United States truck fleet, but there is unlikely to be a need to accommodate truck configurations currently used in Canada and Mexico, but not currently used in the United States.

Several changes in the design vehicles presented in the AASHTO *Policy on Geometric Design of Highways and Streets*, commonly known as the Green Book, are recommended. Specifically, it is recommended that the current WB-15 [WB-50] design vehicle be dropped because it is no longer common on U.S. roads. The kingpin-to-center-of-rear-tandem (KCRT) distance for the WB-19 [WB-62] design vehicle should be increased from 12.3 to 12.5 m [40.5 to 41 ft]. The WB-20 [WB-65] design vehicle should be dropped from the Green Book and the WB-20 [WB-67] design vehicle used in its place. In addition, a three-axle truck, the SU-8 [SU-25] design vehicle, and a Rocky Mountain Double, the WB-28D [WB-92D] design vehicle should be added to the Green Book.

Four design vehicles, each larger than similar trucks currently on the road, were identified that have no current application, but might be needed if such trucks should

be permitted to operate, or to operate more extensively, on U.S. highways. These four design vehicles include a combination truck with a single 17.4-m [53-ft] semitrailer, designated the WB-22 [WB-71] design vehicle; a combination truck with two 10.1-m [33-ft] trailers, designated the WB-23D [WB-77D] design vehicle; a Turnpike Double combination truck, with two 16.1-m [53-ft] trailers, designated the WB-37D [WB-120D] design vehicle; and a B-Train double combination with one 8.5-m [28-ft] trailer and one 9.6-m [31.5-ft] trailer.

There does not appear to be any need to update the current Green Book design criteria for sight distance, lane width, horizontal curves, cross slope breaks, or vertical clearance to better accommodate trucks. In each of these cases, an evaluation found that the current geometric design criteria can reasonably accommodate trucks.

To assess the critical length of grade for trucks on long, steep upgrades, designers need a more flexible design tool than that available in the current Green Book. The currently available design charts address only one particular truck weight/power ratio, one particular initial truck speed, and a constant percent grade. The research developed a spreadsheet program, known as the truck speed profile model (TSPM), that can estimate the truck speed profile on any specified upgrade, considering any truck weight/power ratio, any initial truck speed, and any vertical profile. Field studies were also conducted to better quantify the weight/power ratios of the current truck fleet; the results of these field studies indicate that trucks in the western states have better performance than in the eastern states and the truck population on freeways generally has better performance than the truck population on two-lane highways.

It is recommended that the Green Book provide additional guidance on the maximum entry speeds and the diameter of the inscribed circle for roundabouts, as a function of design vehicle characteristics. It is also recommended that designers be provided with additional information on the swept path widths of specific design vehicles for use in the design of double and triple left-turn lanes.

The research results indicate that acceleration lane lengths designed to current Green Book criteria may accommodate average trucks, but may not fully accommodate heavily loaded trucks, such as the 85th percentile of truck performance. However, there is no indication that heavily loaded trucks are encountering any particular problems related to acceleration lane lengths. Therefore, no change in the design criteria for acceleration lane length is currently recommended, but further research on this issue, to document any problems actually encountered by trucks on acceleration lanes, is recommended.

CHAPTER **1**

INTRODUCTION

BACKGROUND

Trucks constitute a large and growing segment of the traffic on American highways. On many rural Interstate highways, trucks now constitute more than one-third of the total traffic stream. The increase in truck traffic is related to a strong and growing economy, shifts in manufacturing patterns and inventory reduction through just-in-time delivery, and changing trade patterns resulting from the North American Free Trade Agreement (NAFTA).

In addition to the growth in truck volumes, there have also been shifts in the mix of truck types on U.S. highways toward larger vehicles. The Surface Transportation Assistance Act (STAA) of 1982 established the tractor-semitrailer combination with a 14.6-m [48-ft] trailer as a standard vehicle on the U.S. highways. The 1982 STAA required all states to permit trucks with single 14.6-m [48-ft] trailers and twin 8.7-m [28.5-ft] trailers to operate on the National Truck Network. Since 1982, combination trucks with single 16.2-m [53-ft] trailers have become common on the National Network (NN) in many states and a few states permit combinations with trailers as long as 18.1 m [59.5 ft].

Trucks are an important consideration in geometric design of highways. Many geometric design criteria, as presented in the AASHTO *Policy on Geometric Design of Highways and Streets* (*1*), commonly known as the Green Book, and in the policies of individual state highway agencies, are based on vehicle characteristics. Truck characteristics are often a key consideration in determining the recommended values of such criteria. Every roadway and intersection is designed to accommodate a specific design vehicle, selected from among those presented in the Green Book and other design policies, and for many projects the appropriate design vehicle is a truck. The design vehicles in the 1994 edition of the Green Book did not adequately represent the truck fleet currently on the road. Extensive changes in the design vehicles and their dimensions have been made in the new 2001 edition of the Green Book, but further review has been conducted to determine whether these design vehicles are consistent with the current truck fleet. Furthermore, truck considerations are not addressed consistently throughout the Green Book. For some geometric design criteria, the Green Book shows how a designer can accommodate a truck as the design vehicle, while other design criteria are based solely on passenger car characteristics, with little or no mention of trucks.

Research is clearly needed to recommend a more consistent treatment of trucks in the Green Book and in other related design policies. Midwest Research Institute (MRI) and Pennsylvania Transportation Institute (PTI) undertook similar research for the FHWA in a project completed in 1990 (*2*,*3*). The objectives and scope of that project were to do as follows:

- Determine the dimensions and performance characteristics of trucks.
- Identify all geometric design criteria in the Green Book and all traffic control device criteria in the FHWA Manual on Uniform Traffic Control Devices (MUTCD) (*4*) that are based on a vehicle characteristic.
- Determine what models are used in setting the design and traffic control criteria and what vehicle characteristics are used as parameter values in those models.
- If a specific design or traffic control criterion is based on passenger car characteristics, conduct a sensitivity analysis to determine how that criterion would need to be changed to accommodate trucks.
- Recommend whether changes in either the models used to establish design and traffic control criteria or in the parameter values used in those models would be desirable and cost-effective to better accommodate trucks.

The results of this previous study have been published in *Reports No. FHWA-RD-89-226* and *-227*, entitled *Truck Characteristics for Use in Highway Design and Operation* (*2*,*3*). While this previous study was comprehensive in scope, it is in need of updating because both the truck fleet and geometric design policies have changed considerably in the intervening years. This previous work provides a firm starting point to meet the current need for updating the treatment of trucks in the Green Book.

RESEARCH OBJECTIVES AND SCOPE

The objective of the research is to ensure that geometric design criteria for highways and streets can reasonably accommodate the dimensions and performance characteristics of the current and future truck fleet using the U.S. highway system. The main product of the research is a set of recommendations on modifications and/or additions that should be made to the AASHTO Green Book (*1*). The scope of the research addresses geometric design issues, but not structural or pavement issues.

The scope of the research has included all truck-related geometric design issues currently addressed in the Green Book. The approach used by the Green Book to address each of these issues has been evaluated and any appropriate modifications have been proposed. Modifications considered included both use of (1) different parameter values in a model used in the Green Book to determine design criteria for passenger cars and (2) revised models that might be more suitable for trucks. In addition to looking at design criteria that currently consider trucks, the research also included a review to determine whether design criteria that do not currently address trucks should do so or whether new design criteria that address trucks should be added to the Green Book.

It is vital that the review of Green Book design criteria be based on the most up-to-date information available about the composition and characteristics of the truck fleet. Therefore, the research team sought to characterize the current truck fleet on U.S. highways and to make reasonable projections of changes that may occur in the years ahead. The project scope addresses what are often referred to as heavy trucks (i.e., not including light trucks like pickups and vans).

A key aspect of the research objectives is to ensure that highway design criteria can reasonably accommodate current and future trucks. Reasonable accommodation does not mean that all roads should be designed for the largest vehicles that use them or that every design criterion should be based on a large truck. Rather, it means that roads should be designed to accommodate the vehicles likely to use them with reasonable frequency and that both the potential safety benefits and the expected costs to highway agencies should be considered before any proposed change in design policy is adopted.

ORGANIZATION OF THIS REPORT

This report presents an overview of the size and characteristics of the current truck fleet, a review of geometric design issues related to trucks, and recommendations for potential future changes to geometric design policy to better accommodate trucks. The remainder of this report is organized as follows. Chapter 2 summarizes current size and weight limits for U.S. trucks, as well as comparable data for trucks in Canada and Mexico. The size, composition, and characteristics of the U.S. truck fleet are presented in Chapter 3. The current truck design vehicles used in the AASHTO Green Book are reviewed in Chapter 4, and recommendations for changes in these design vehicles are presented. Chapter 5 summarizes the characteristics of trucks that are related to highway geometric design. Chapter 6 reviews highway geometric design criteria and their relationship to truck characteristics. Chapter 7 presents recommendations for potential future changes in geometric design policy to better accommodate trucks.

Appendix A summarizes truck characteristics based on data from 1992 and 1997. Appendix B presents the results of field studies conducted at truck weigh stations to estimate selected truck characteristics. Appendix C assesses the turning performance of selected design vehicles, including their offtracking and swept path width. Appendix D presents the results of field studies to estimate weight/power ratios for the current truck population. Appendix E describes a spreadsheet program developed to estimate truck speed profiles on upgrades. Appendix F presents recommendations for future revisions to the Green Book to better accommodate trucks.

The text of this report uses both metric and U.S. customary units of measure. For consistency with the Green Book, which is the key reference addressed by this report, the quantity in metric units appears first, followed by the quantity in U.S. customary units in brackets. Some tables and figures show quantities in both units of measure, but others present only one system of units, when the data being presented were collected or published or the legal requirement being presented was adopted in that system of units. In addition, the abbreviation for miles per hour used in this report is mph, rather than mi/h, for consistency with the Green Book.

CHAPTER 2

TRUCK SIZE AND WEIGHT LIMITS

This chapter addresses the current size and weight limits for trucks as imposed by federal and state governments. These limits set the framework under which trucks currently on the road operate. Changes in these limits are a primary mechanism by which future changes in truck characteristics that affect highway geometric design might occur.

FEDERAL TRUCK SIZE AND WEIGHT LIMITS

Current federal law includes the following limits on truck size and weight:

- States may not set maximum weight limits on the Interstate System less than
  - 36,400 kg [80,000 lb] gross vehicle weight:
  - 9,100 kg [20,000 lb] for a single axle: or
  - 15,500 kg [34,000 lb] for a tandem axle.
- States must permit weights for other axle groups so long as the weight on the axle group does not violate the federal bridge formula and the gross vehicle weight does not exceed 36,400 kg [80,000 lb].
- States must permit tractor-trailer combination trucks with trailer lengths up to 14.6 m [48 ft] in length to operate on the National Network (NN).
- States must permit combination trucks consisting of two trailers with lengths up to 8.7 m [28.5 ft] per trailer to operate on the NN.
- States must permit trucks within the length limits given above with widths up to 2.6 m [8.5 ft] to operate on the NN.

The NN is a network of routes designated by the Secretary of Transportation in consultation with the states. The NN consists of the Interstate System and other selected routes. The extent of the NN on non-Interstate routes varies by region of the country. Typically, the non-Interstate routes in the NN are fairly limited in the eastern states and more extensive in the western states.

In this report, the phrase *tandem axle*, without modifiers, refers to a pair of axles separated from one another by 1.2 m [4 ft], nominally. A common practice is to spread these axles further apart (called spread tandems) to allow a greater legal weight limit. For example, if they are separated by 3 m [10 ft], their maximum weight limit is 18,200 kg [40,000 lb], twice the limit for a single axle.

The federal bridge formula referred to above is $W = 500[LN/(N\text{-}1) + 12N + 36]$, where W is the maximum weight in pounds carried on any group of two or more axles, L is the distance in feet between the extremes of any group of two or more axles, and N is the number of axles under consideration.

STATE TRUCK SIZE AND WEIGHT LIMITS

States set the truck size and weight limits on their facilities within the framework set by the federal limits discussed above. Many states have established truck size and weight limits that exceed those mandated by the federal government. For example, many states permit tractor-semitrailers with 16.2-m [53-ft] trailers to operate on the NN, even though federal law requires only that 14.6-m [48-ft] trailers be permitted. Many states also permit trucks with gross weights over 36,400 kg [80,000 lb] and trucks with trailers longer than those mandated by federal law to operate under permit on specified highways and/or under specified conditions.

The federal truck size and weight limits discussed above were established by the Surface Transportation Assistance Act (STAA) of 1982. The 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) instituted a freeze on increases in state size and weight limits for Longer Combination Vehicles (LCV). State limits in effect were allowed to remain in place ("grandfathered"), but no further increases in those limits have been permitted. ISTEA defined an LCV as

> . . . any combination of a truck tractor with two or more trailers or semitrailers which operates on the Interstate System at a gross vehicle weight greater than 80,000 lb.

Current state limits on truck sizes and weights for Interstate and non-Interstate highways are discussed below.

Table 1 summarizes general truck weight limits for each of the 50 states and the District of Columbia based on information from the FHWA Comprehensive Truck Size and Weight (CTSW) study (*5*). The table includes limits for gross vehicle weight, single-axle weight, and tandem-axle weight for Interstate highways and other highways. The table also indicates whether the state uses the federal bridge formula and the weight limits for which the state issues "routine" permits.

TABLE 1 General state weight limits (in units of 1,000 lb) (*5*)

	Gross vehicle		Single axle		Tandem axle		Federal bridge formula		"Routine" permit		
State	Interstate	Other hwys	Interstate	Other hwys	Interstate	Other hwys	Interstate	Other hwys	Gross vehicle weight(a)	Single axle	Tandem axle
Alabama	80	84	20	20	34	40	Yes	No-WT	110/150	22	44
Alaska	–	90(b)	–	20	–	38	–	Yes	88.6(b)/150	30	50
Arizona	80	80	20	20	34	34	Yes	No-WT	106.5(c)/250	28	46
Arkansas	80	80	20	20	34	34	Yes	Yes	102/134	20	40
California	80	80	20	20	34	34	Yes-mod	Yes-mod	119.8(d) (e)	30	60
Colorado	80	85	20	20	36	40	Yes	No	127/164	27	50
Connecticut	80	80	22.4	22.4	36	36	Yes	Yes	120/160	22.4	NS
Delaware	80	80	20	20	34	40	Yes	No-WT	120/120	20	40
D. C.	80	80	22	22	38	38	Yes-mod	Yes-mod	155-248	31	62
Florida	80	80	22	22	44	44	Yes(f)	No-WT	112/172	27.5	55
Georgia	80	80	20.34	20.34	34(g)	37.34	Yes	Yes(f)	100/175	23	46
Hawaii	80.8	88	22.5	22.5	34	34	Yes	No	Case-by-case above normal limits		
Idaho	80	105.5	20	20	34	34	Yes	Yes	Case-by-case above normal limits		
Illinois	80	80(h)	20	20(i)	34	34(i)	Yes	Yes(i)	100/120	20	48
Indiana(j)	80	80	20	20	34	34	Yes	Yes	108/120	28	48
Iowa	80	80	20	20	34	34	Yes	Yes	100/160	20	40
Kansas	80	85.5	20	20	34	34	Yes	Yes	95/120	22	45
Kentucky	80	80(k)	20	20	34	34	Yes	Yes	96/140	24	48
Louisiana	80(l)	80(l)	20	22	34	37	Yes	No	108/120	24	48
Maine	80	80(m)	20(n)	22.4	34	38	Yes-mod	No	130/167	25	50
Maryland	80	80	20(o)	20(o)	34(o)	34(o)	Yes	Yes	110/110	30	60
Massachusetts	80	80	22.4	22.4	36	36	Yes	Yes	99/130	NS	NS
Michigan(p)	80	80	20	20	34	34	Yes	Yes	80/164	13	26
Minnesota	80	80(q)	20	18	34	34	Yes	Yes-mod	92/144	20	40
Mississippi	80	80	20	20	34	34	Yes	Yes	113/190	24	48
Missouri	80	80(r)	20	20(r)	34	34(r)	Yes	Yes(r)	92/120	20	40
Montana	80	80	20	20	34	34	Yes	Yes	105.5/126	20	48
Nebraska	80	95	20	20	34	34	Yes	Yes	99/110	20	40
Nevada	80	129(s)	20	20	34	34	Yes	Yes	110(t)(u)	28	50.4
New Hampshire	80	80	20(o)	22.4	34(o)	36	Yes	No	130/150	25	50
New Jersey	80	80	22.4	22.4	34	34	Yes	No	100(v)/150(v)	25(v)	40(v)
New Mexico	86.4	86.4	21.6	21.6	34.32	34.32	Yes-mod	Yes-mod	104(w)/120	26	46
New York	80	80	20(x)	22.4	34(x)	36	Yes(x)	Yes(x)	100/150	25	42.5
North Carolina	80	80	20	20	38	38	Yes-mod	Yes-mod	94.5/122	25	50
North Dakota	80	105.5	20	20	34	34	Yes	Yes	103/136	20	45
Ohio	80	80	20	20	34	34	Yes	No	120/120	29	46
Oklahoma	80	90	20	20	34	34	Yes	Yes	95/140	20	40
Oregon	80	80	20	20	34	34	Yes-mod	Yes-mod	90/105.5	21.5	43
Pennsylvania	80	80	20(y)	20(y)	34(y)	34(y)	Yes(y)	Yes(y)	116/136	27	52
Rhode Island	80	80	22.4	22.4	36	36	Yes-mod	Yes-mod	104.8(u)	22.4	44.8
South Carolina	80	80	20	22	34(z)	39.6	Yes(z)	No	90/120	20	40
South Dakota	80	129(s)	20	20	34	34	Yes	Yes	116(u)(aa)	31	52
Tennessee	80	80	20	20	34	34	Yes	Yes	100/160	20	40
Texas	80	80	20	20	34	34	Yes-mod	Yes-mod	106.1(bb)/120	25	48.125
Utah	80	80	20	20	34	34	Yes	Yes	100/123.5	20	40
Vermont	80	80	20	22.4	34	36	Yes	Yes	108(cc)/120	24	48
Virginia	80	80	20	20	34	34	Yes	Yes	110/150	25	50
Washington	80	105.5	20	20	34	34	Yes	Yes	103/156	22	43
West Virginia	80	80(dd)	20	20	34	34	Yes	Yes	104/110	20	45
Wisconsin	80	80	20	20	34	34	Yes-mod	Yes-mod	100/191	20	60
Wyoming	117	117	20	20	36	36	Yes	No	85/135	25	55

NS	Not specified.
WT	Weight table.

Footnotes to this table are presented on the next page.

Information sources:

J. J. Keller & Associates, Vehicle Sizes and Weights Manual. July 1, 1994.

Specialized Carriers & Rigging Association (SC&RA), Permit Manual. July 19, 1994.

Western Association of State Highway and Transportation Officials (WASHTO), Guide for Uniform Laws and Regulations Governing Truck Size and Weight. June 26, 1993.

There are no overall maximum vehicle length limits on the NN, including the Interstate System. Instead, there are maximum limits on trailer lengths. This approach is intended to discourage trucking companies from decreasing tractor length to increase box length. On highways other than the NN, states are free to impose maximum overall vehicle length limits.

As noted above, states must permit 14.6-m [48-ft] trailers on single-semitrailer combination trucks and 8.7-m [28.5-ft] trailers on double-trailer combination trucks on the NN. States can permit single semitrailers that are longer than the federal minimums on the NN and on other highways. Some states allow longer semitrailers but impose a maximum kingpin-to-center-of-rear-axle (KCRA) or kingpin-to-center-of-rear-tandem (KCRT) distance to limit truck offtracking. A 14.6-m [48-ft] semitrailer and a 16.2-m [53-ft] semitrailer with the same KCRA or KCRT distance will offtrack by the same

TABLE 1 (Continued)

NOTES TO TABLE 1:

(a) "Routine" Permit Gross Vehicle Weight: the first number (left) is the highest weight a five-axle unit can gross before special (other than routine) review and analysis of an individual movement is required. The second number (right) is the highest gross weight any unit with sufficient axles can gross before special review is required.

(b) State rules allow the more restrictive of the federal bridge formula or the sum of axle weight limits. The five-axle "routine" permit value is estimated using a truck tractor-semitrailer with a 65-ft spacing between the front and rear axles (based on a 48-ft semitrailer).

(c) The five-axle "routine" permit value is estimated using a truck tractor-semitrailer with two tandem axles at 47,250 lb each and a 12,000 lb steering axle.

(d) Estimate based on State weight table values for a tandem drive axle at 46,200 lb, a rear tandem at the 60,000 lb maximum, and a 12,500 lb steering axle.

(e) Maximum based on the number of axles in the combination.

(f) Federal bridge formula applies if gross vehicle weight exceeds 73,280 lb.

(g) If gross vehicle weight is less than 73,280 lb, the tandem axle maximum is 40,680 lb.

(h) On Class III and nondesignated highways, the maximum is 73,280 lb.

(i) On nondesignated highways, the single axle maximum is 18,000 lb, the tandem axle maximum is 32,000 lb, and the bridge formula does not apply.

(j) On the Indiana Toll Road, the single axle maximum is 22,400 lb, the tandem axle maximum is 36,000 lb, and the maximum practical gross is 90,000 lb.

(k) The maximum gross weight on Class AA highways is 62,000 lb, and on Class A highways, 44,000 lb.

(l) Six- or seven-axle combinations are allowed 83,400 lb on the Interstate system, and 88,000 lb on other state highways.

(m) A three-axle tractor hauling a tri-axle semitrailer has a maximum gross vehicle weight of 90,000 lb.

(n) If the gross vehicle weight is less than 73,280 lb, the single axle maximum is 22,000 lb.

(o) If the gross vehicle weight is 73,000 lb or less, the single axle maximum is 22,400 lb, and the tandem axle maximum is 36,000 lb.

(p) Federal axle, gross and bridge formula limits apply to five-axle combinations if the gross vehicle weight is 80,000 lb or less. For other vehicles and gross vehicle weights over 80,000 lb other limits apply. State law sets axle weight controls which allow vehicles of legal overall length to gross a maximum of 164,000 lb.

(q) Most city, county, and township roads are considered "9-ton routes" with a maximum gross vehicle weight of 73,280 lb.

(r) On highways other than Interstate, primary, or other designated, the single axle maximum is 18,000 lb, the tandem axle maximum is 32,000 lb, the bridge formula is modified, and the gross vehicle weight maximum is 73,280 lb.

(s) The maximum is directly controlled by the bridge formula. Given the state's length laws, the maximum practical gross is 129,000 lb.

(t) The five-axle "routine" permit value is estimated using a truck tractor-semitrailer with a 12,500 lb steering axle, a 47,250 lb drive tandem (five-ft spacing from State weight table), and a 50,400 lb spread tandem (8-ft spacing from the State weight table).

(u) A determination is made on a case-by-case basis.

(v) All "routine" permit values are calculated using 10-in wide tires and a maximum 800 lb/in of tire width loading value.

(w) The five-axle "routine" permit value is estimated using a truck tractor-semitrailer with two 46,000 lb tandems plus a 12,000 lb steering axle.

(x) If the gross vehicle weight is less than 71,000 lb, the single axle maximum is 22,400 lb, the tandem axle maximum is 36,000 lb, and a modified bridge formula applies.

(y) If the gross vehicle weight is 73,280 lb or less, the single axle maximum is 22,400 lb, the tandem axle maximum is 36,000 lb, and the bridge formula does not apply.

(z) If the gross vehicle weight is 75,185 lb or less, the tandem-axle maximum is 35,200 lb, and the bridge formula does not apply.

(aa) The five-axle "routine" permit value is estimated using a truck tractor-semitrailer with two 52,000 lb tandems plus a 12,000 lb steering axle.

(bb) The five-axle "routine" permit value is estimated using a truck tractor-semitrailer with a 13,000 lb steering axle, a 45,000 lb drive tandem, and a 48,125 lb spread tandem. Both tandem weight values are from the State weight chart.

(cc) The five-axle "routine" permit value is estimated using a truck tractor-semitrailer with two 48,000 lb tandems plus a 12,000 lb steering axle.

(dd) The maximum gross vehicle weight on nondesignated state highways is 73,500 lb, and on county roads 65,000 lb.

amount in making a given turn, so the rear tires of the 16.2-m [53-ft] semitrailer are no more likely to encroach on a shoulder or curb than the rear tires of the 14.6-m [48-ft] semitrailer. However, because of the greater distance from the rear axle to the rear of the trailer, the rear of the trailer will follow a path outside the rear axles of the truck.

Table 2 summarizes the maximum semitrailer lengths permitted by states in 1994 on the NN and on other state highways. Both the maximum trailer length and any kingpin distance restrictions are noted. In addition, any overall length restrictions for highways not in the NN are noted.

State size and weight limits for LCVs are frozen at early 1990s levels under the provisions of ISTEA. Table 3 shows the current weight limits for trucks over 36,400 kg [80,000 lb] with two or three trailers in states where LCVs are permitted to operate. The highest gross vehicle weight limits are 74,500 kg [164,000 lb] in Michigan; such heavy trucks must typically have 10 or more axles to meet Michigan requirements. In eastern states, LCVs are typically restricted to operate on specific turnpikes or toll roads. In some western states, LCVs operate more generally on both Interstate and non-Interstate highways.

TABLE 2 Maximum semitrailer lengths by state in 1994 (*5*)

	National network (NN)		Other state highways		
State	Trailer length (ft-in)	Kingpin restrictions (ft-in)	Trailer length (ft-in)	Kingpin restrictions (ft-in)	Overall length (ft-in)
Alabama	57-0	41-0 KCRA(a)	53-0		
Alaska	48-0		45-0		70-0
Arizona	57-6(g)		53-0		65-0
Arkansas	53-6	40-0 KCRTA(h)	53-6		
California	53-0	38-0 KCSRA(i)	53-0	Same as NN	
Colorado	57-4		57-4		
Connecticut	53-0		48-0		
Delaware	53-0		53-0		60-0
Dist. of Col.	48-0	41-0 KCRT(b)	48-0		55-0
Florida	53-0		53-0	41-0 KCRT	
Georgia	53-0	41-0 KCRT	53-0	41-0 KCRT	67-6
Hawaii	No Limit		45-0		60-0
Idaho	53-0		48-0	39-0 KCRA	
Illinois	53-0	42-6 KCRA	53-0	42-0 KCRA	
Indiana	53-0	40-6 KCRA	53-0	40-6 KCRA	
Iowa	53-0		53-0	40-0 KCRA	60-0
Kansas	59-6		59-6		
Kentucky	53-0		No Limit		57-9
Louisiana	59-6		No Limit		65-0
Maine	53-0(c)	43-0	53-0		65-0
Maryland	53-0(d)	41-0 KCRT	53-0	41-0 KCRT	
Massachusetts	53-0(e)		53-0		
Michigan	53-0	41-0 KCRT	50-0		
Minnesota	53-0	41-0 KCRT	53-0	41-0 KCRT	
Mississippi	53-0		53-0		
Missouri	53-0(d)		No Limit		60-0
Montana	53-0		53-0		
Nebraska	53-0		53-0		
Nevada	53-0		53-0		70-0
New Hampshire	53-0(f)	41-0 KCRT	53-0	41-0 KCRT	
New Jersey	53-0	41-0 KCRT	53-0	41-0 KCRT	
New Mexico	57-6		No Limit		65-0
New York	53-0(d)	41-0 KCRT	48-0		65-0
North Carolina	53-0	41-0 KCRT	No Limit		60-0
North Dakota	53-0		53-0		
Ohio	53-0		53-0		
Oklahoma	59-6		59-6		
Oregon	53-0		Varies		
Pennsylvania	53-0		No Limit		60-0
Puerto Rico	48-0				
Rhode Island	48-6		48-6		
South Carolina	53-0	41-0 KCRT	48-0		
South Dakota	53-0		53-0		
Tennessee	53-0	41-0 KCRT	53-0	41-0 KCRT	
Texas	59-0		59-0		
Utah	53-0	40-6 KCRT	53-0	40-6 KCRT	
Vermont	53-0(d)	41-0 KCRT	48-0		60-0
Virginia	53-0	37-0 Last tractor axle to first trailer axle	No Limit		60-0
Washington	53-0		53-0		
West Virginia	53-0	Same as VA	No Limit		60-0
Wisconsin	53-0	41-0 KCRT	No Limit		60-0
Wyoming	60-0		60-0		

Footnotes:
(a) KCRA = Kingpin to center of rear axle
(b) KCRT = Kingpin to center of rear tandem
(c) permit may be required
(d) Interstate and designated State routes
(e) Requires annual letter of authorization; does not apply on the Massachusetts Turnpike
(f) Designated routes
(g) Only on Interstate system
(h) KCRTA = Kingpin to center of rearmost tandem axle
(i) KCSRA = Kingpin to center of single rear axle

TABLE 3 Long combination vehicle weight limits by state (*5*)

Gross vehicle weight limit (lb)	Truck tractor and two trailing units	Truck tractor and three trailing units
86,400	NM	
90,000	OK	OK
95,000	NE	
105,500	ID, ND, OR, WA	ID, ND, OR
110,000	CO	CO
111,000	AZ	
115,000		OH
117,000	WY	
120,000	KS, MO(a)	
123,500		AZ
127,400	IN, MA, OH	IN
129,000	NV, SD, UT	NV, SD, UT
131,060		MT
137,800	MT	
143,000	NY	
164,000	MI	

(a) From Kansas, within 20 miles of border.
SOURCE: Final Rule on LCVs published in the *Federal Register* at *59 FR 30392* on June 13, 1994.

NAFTA SIZE AND WEIGHT LIMITS AND PERFORMANCE CRITERIA

The North American Free Trade Agreement (NAFTA), which went into effect in 1994, is an international treaty that calls for gradual removal of tariffs and other trade barriers on most goods produced and sold in North America. NAFTA forms the world's second largest free-trade zone, bringing together 365 million consumers in Canada, Mexico, and the United States.

An important part of NAFTA is the movement of goods by truck between Canada, Mexico, and the United States. The agreement contemplates free movement of Canadian and Mexican trucks to and from freight destinations in the United States and free transit of trucks from Canada to Mexico, and vice versa, through the United States. Implementation of NAFTA has the potential to change the mix of truck types on U.S. highways and may, therefore, have implications for geometric design of highways.

Currently, Mexican trucks are generally limited to commercial areas along the U.S.-Mexican border. In fact, the vast majority of current trucking across the U.S.-Mexican border consists of drayage operations in which a trailer is moved from an industrial facility or terminal on one side of the border to another industrial facility or terminal not far away on the other side of the border. Mexican trailers that move farther into the United States would then be pulled by a tractor operated by a U.S. trucker.

NAFTA contemplated that the Mexican trucks would gradually be permitted to operate beyond the commercial areas along the border, first throughout the four border states (California, Arizona, New Mexico, and Texas), and then throughout the United States. This has not happened yet; concerns have been raised about the safety of Mexican trucks, the financial responsibility of Mexican trucking firms, and domestic security. The Mexican government has lodged a formal complaint under NAFTA that the U.S. border should be opened to Mexican trucks, and a NAFTA Arbitral Panel has so ordered. Discussions continue concerning the date on which and the conditions under which Mexican trucks should have freer access to the United States.

To consider the implications for geometric design of Canadian and Mexican trucks entering the United States, the research team has investigated current truck size and weight restrictions in Canada and Mexico and the size, weight, and performance restrictions that would apply to international trucks entering the United States.

Table 4 compares current U.S., Canadian, and Mexican size and weight limits. This table applies to normal operations within each country, not to international operations. Tables 5, 6, and 7 present more detailed current data on maximum legal lengths and maximum legal weights of trucks operating within Mexico. The tables concerning Mexican truck characteristics refer to two road types. Type B roads in Mexico are those that compose the primary road network and that, given their geometric and structural characteristics, serve interstate commerce as well as providing continuity in vehicular flows. Type A roads are a higher class of road than Type B and include roads that will accommodate the highest limits of size, capacity, and weight. Table 8 presents comparable data for trucks operating in Canada based on the interprovincial Memorandum of Understanding (*6*).

Two key NAFTA-related documents that deal with truck configuration issues are as follows:

- *Performance Criteria in Support of Vehicle Weight and Dimension Regulations: Background Paper*, Draft 1, October 1998 (*7*).

TABLE 4 Comparison of truck size and weight limits in the U.S., Canada, and Mexico (*5*)

Characteristic	U.S.	Canada	Mexico
Steering axle weight limit (lb)	N/A	12,125	14,320
Single axle weight limit (lb)	20,000	N/A	22,026
Tandem axle weight limit (lb)	34,000	37,479	39,647
Tridem axle weight limit (lb)	–	46,297 to 55,000[a]	49,559
Gross vehicle weight limit (lb)	80,000 (Federal) (more for LCVs where allowed)	140,000[b]	146,476
Width limit (ft)	8.5	8.5	8.5
Semitrailer length limit (ft)	48 (53 common)	53	N/A
Vehicle length limit (ft)	N/A	82.0	68.2 (semi) 101.7 (double)
King-pin to rear axle distance (ft)	N/A	Control limits	N/A
Minimum interaxle spacings	N/A	Yes	Yes

(a) In eastern Canada.
(b) In Ontario and far western Canada.

TABLE 5 Maximum legal length of trucks in Mexico by class of vehicle and type of road

Class of vehicle	Maximum legal length (ft) / *(meters)* Type A	Type B
Bus	45.90 *(14.00)*	45.90 *(14.00)*
SU Truck with six or more tires	45.90 *(14.00)*	45.90 *(14.00)*
SU Truck and trailer	93.44 *(28.50)*	93.44 *(28.50)*
Tractor semitrailer	68.20 *(20.80)*	68.20 *(20.80)*
Tractor semitrailer-trailer	101.60 *(31.00)*	93.44 *(28.50)*
Tractor semitrailer-semitrailer	81.97 *(25.00)*	81.97 *(25.00)*

SOURCE: Dr. Alberto Mendoza, Mexican Transportation Institute

TABLE 6 Maximum legal weight of trucks in Mexico by type and number of axles for highways of Types A and B

Axle configuration	Weight, lb *(metric tonnes)*
Single axle with two tires	14,320 *(6.50)*
Single axle with four tires	22,026 *(10.00)*
Power single axle with four tires	24,229 *(11.00)*
Power double axle or tandem with six tires	34,140 *(15.50)*
Double or tandem with eight tires	39,647 *(18.00)*
Power double axle or tandem with eight tires	42,951 *(19.50)*
Triple or tridem with twelve tires	49,559 *(22.50)*

SOURCE: Dr. Alberto Mendoza, Mexican Transportation Institute

TABLE 7 Maximum legal weight of trucks in Mexico by type of vehicle for highways of Types A and B

Vehicle class	Designation	No. of tires	GVW, lb *(metric tonnes)*
Bus	B2	6	38,546 *(17.50)*
	B3	8	48,458 *(22.00)*
	B3	10	57,268 *(26.00)*
	B4	10	67,180 *(30.50)*
Single Unit Truck	C2	6	38,546 *(17.50)*
	C3	8	48,458 *(22.00)*
	C3	10	57,268 *(26.00)*
Truck-Trailer Combination	C2 – R2	14	82,599 *(37.50)*
	C2 – R3	18	100,220 *(45.50)*
	C3 – R2	18	101,321 *(46.00)*
	C3 – R3	22	118,942 *(54.00)*
Tractor-Semitrailer	T2 – S1	10	60,572 *(27.50)*
	T2 – S2	14	78,193 *(35.50)*
	T3 – S2	18	96,916 *(44.00)*
	T3 – S3	22	160,828 *(48.50)*
Tractor-Semitrailer-Trailer	T2 – S1 – R2	18	104,625 *(47.50)*
	T3 – S1 – R2	22	123,348 *(56.00)*
	T3 – S2 – R2	26	133,260 *(60.50)*
	T3 – S2 – R3	30	138,766 *(63.00)*
	T3 – S2 – R4	34	146,475 *(66.50)*
Tractor-Semitrailer-Semitrailer	T3 – S3 – S2	30	132,158 *(60.00)*

SOURCE: Dr. Alberto Mendoza, Mexican Transportation Institute

- *Highway Safety Performance Criteria in Support of Vehicle Weight and Dimension Regulations: Candidate Criteria and Recommended Thresholds*, October 1999 (*8*).

No formal agreement on size and weight limits for international trucks has yet been reached, but the following limits have been recommended by the NAFTA Land Transportation Standards Subcommittee for trucks on highways that will constitute the International Access Network (IAN):

- Height—4.15 m [13.6 ft]
- Width—2.6 m [102.4 in]
- Overall Length—23.0 m [75.5-ft] for tractor-semitrailer combinations
  25.0 m [82.0-ft] for double-trailer combinations
- Box Length—16.2 m [53.2-ft] for trailer-semitrailer combinations
  20.0 m [65.6-ft] for double-trailer combinations
- Transient Low-Speed Offtracking—No more than 5.6-m [18.3-ft] offtracking in a 90-degree turn of 14.0-m [45.9-ft] radius
- Front Swingout—No more than 0.45-m [18-in] front swingout in a 90-degree turn of 14.0-m [45.9-ft] radius
- Rear Swingout—No more than 0.20-m [8-in] rear swingout in a 90-degree turn of 14.0-m [45.9-ft] radius
- Load Transfer Ratio—Acceptable maximum of 0.60
- Transient High-Speed Offtracking—Acceptable maximum of 0.8-m [32-in]

The overall length and box length are defined in Figure 1. The issues of transient low-speed offtracking, front swingout, rear swingout, load transfer ratio, and transient high-speed offtracking are defined and discussed in Chapter 5 of this report.

These IAN criteria are similar to current U.S. size and weight restrictions with the following exceptions:

TABLE 8 Maximum truck dimensions specified in Canadian Interprovincial Memorandum of Understanding (*6*)

Vehicle category	Maximum dimension, m [ft]			
	Overall length	Overall width	Overall height	Box length
1—Tractor-semitrailer	23.0 [75.4]	2.6 [8.5]	4.15 [13.6]	16.2 [53.8]
2—A-train double(a)	25.0 [82.0]	2.6 [8.5]	4.15 [13.6]	18.5 [60.7](d)
3—B-train double(b)	25.0 [82.0]	2.6 [8.5]	4.15 [13.6]	20.0 [65.6](d)
4—C-train double(c)	25.0 [82.0]	2.6 [8.5]	4.15 [13.6]	20.0 [65.6](d)
5—Straight truck	12.5 [41.0]	2.6 [8.5]	4.15 [13.6]	not controlled
6—Straight truck with pony trailer	23.0 [75.4]	2.6 [8.5]	4.15 [13.6]	20.0 [65.6](e)
7—Straight truck with full trailer	23.0 [75.4]	2.6 [8.5]	4.15 [13.6]	20.0 [65.6](e)

(a) Tractor/semitrailer/full trailer with conventional single-hitch connection.
(b) Tractor/semitrailer/semitrailer with converter dolly such that both trailers are semitrailers.
(c) Tractor/semitrailer/full trailer with double drawbar dolly.
(d) Combined length of both trailer cargo areas and the space between them.
(e) Combined length of the truck cargo area, the trailer cargo area, and the space between them.

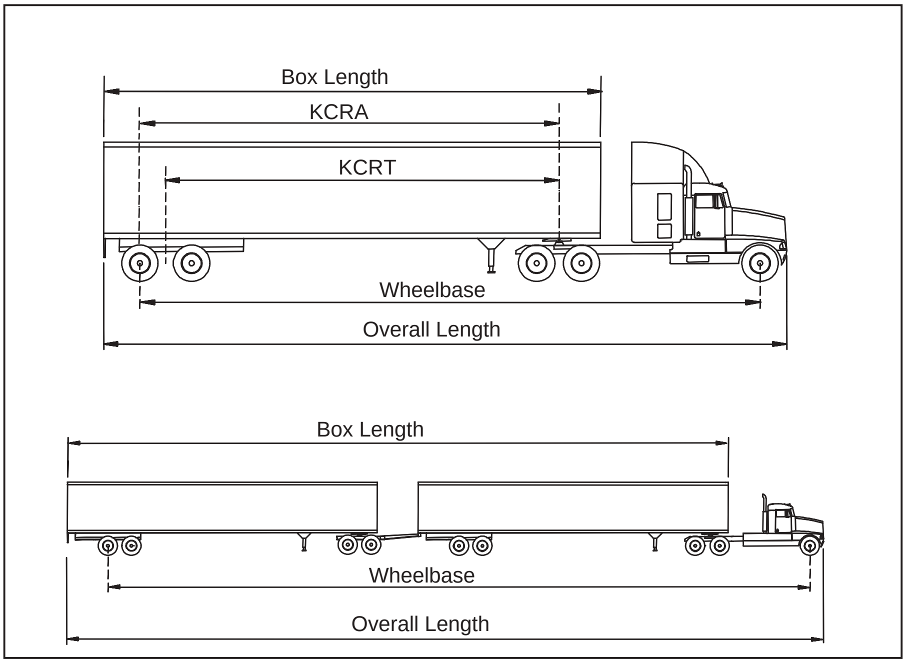


Figure 1. Definition of truck dimensions.

- Overall length limitations are included. Currently, trucks on the NN in the United States are not subject to overall length limits, only limits on trailer lengths. However, overall length limits are included because most truck travel in Canada and Mexico is on two-lane highways where overall length may restrict the ability to pass a truck.
- The box length limit for tractor-semitrailer combinations is consistent with the 16.2-m [53-ft] trailers that are used extensively in the United States. The 20.0-m [65.6-ft] limit for double-trailers is consistent with combinations with two 8.7-m [28.5-ft] trailers, which are currently the most widely used in the United States.
- Explicit regulation of transient low-speed offtracking and rear swingout is rare in the United States. Many states address this indirectly by regulating the kingpin to rearaxle distance and/or the rear overhang distance.
- Regulation of front swingout, load transfer ratio, and transient high-speed offtracking is currently rare or nonexistent in the United States.

CHAPTER 3

SIZE, COMPOSITION, AND CHARACTERISTICS OF THE U.S. TRUCK FLEET

This chapter addresses the size, composition, and characteristics of the truck fleet in the United States. The discussion includes data on the number of trucks, truck-miles of travel, truck length, and truck weight.

One of the challenges in describing the truck fleet is that the various data sources use different definitions of what constitutes a truck. The most common definition of a truck is a vehicle with more than two axles or more than four tires that is not classified as a bus or a recreational vehicle (RV). Under this definition, vehicles with three or more axles and two-axle vehicles with dual rear tires are considered trucks. However, the most extensive source of data on the truck fleet, the Vehicle Inventory and Use Survey (VIUS) (*9*), conducted every 5 years by the U.S. Bureau of the Census, includes not only trucks that meet the definition given above, but also pickup trucks, minivans, panel trucks, sport utility vehicles (SUVs), and station wagons. By contrast, the recent FHWA Comprehensive Truck Size and Weight (CTSW) study appears to have focused exclusively on trucks with three or more axles (*5*). The following discussion attempts to sort out these differences in definition using published data sources. All tables in this chapter of the report exclude pickup trucks, minivans, panel trucks, SUVs, and station wagons.

NUMBER OF TRUCKS IN THE U.S. FLEET

The VIUS estimates that in 1997 there were 5.7 million trucks in the U.S. fleet, excluding minivans, pickup trucks, panel trucks, SUVs, and station wagons (*9*). This represents an increase of nearly 11 percent from the 5.1 million trucks counted in 1992.

Table 9 shows the distribution of the truck population in 1997 and 1992 by truck use, body type, vehicle size, annual miles of travel, age, vehicle acquisition, truck type, range of operation, and fuel type. Some of the major changes indicated by Table 9, which suggest future trends, are that the 1997 population, compared with the 1992 population, included more heavy trucks, greater mileage per truck, newer trucks, a larger fraction of combination trucks (especially five or more axles), less local travel and more short- and long-range travel, and significantly more use of diesel fuel compared with gasoline.

Appendix A presents a table of the number of trucks, truck-miles of travel, and average annual mileage per truck overall and broken down by a broad variety of variables including

- Major use,
- Body type,
- Annual miles,
- Primary range of operation,
- Weeks operated per year,
- Base of operation,
- Vehicle size,
- Average weight,
- Total length,
- Year model,
- Vehicle acquisition,
- Lease characteristics,
- Primary operator classification,
- Primary products carried,
- Hazardous materials carried,
- Truck fleet size,
- Miles per gallon,
- Equipment type,
- Full conservation equipment,
- Maintenance responsibility,
- Engine type and size,
- Refueling location,
- Truck type and axle arrangement, and
- Cab type.

The VIUS database can be used to look at selected combinations of the variables that are not available in tables published by the Bureau of the Census.

TRUCK-MILES OF TRAVEL

The VIUS data indicate that there were an estimated 157 billion annual truck-miles of travel in 1997; this represents a 35 percent increase from the estimated 117 billion truck-miles of travel in 1992. This increase is very dramatic, indicating a growth rate in truck travel of 6.2 percent per year.

Average annual miles of travel per truck increased 22 percent from 22,800 miles per truck in 1992 to 27,800 miles per truck in 1997.

TABLE 9 Distribution of key variables for trucks (excluding minivans, pickup trucks, panel trucks, SUVs, and station wagons)—1997 and 1992 (*9*)

[Percent. Detail may not add to total because of rounding. For meaning of abbreviations and symbols, see introductory text]

Vehicular and operational characteristics	1997	1992
Total	**100.0**	**100.0**
MAJOR USE		
Agriculture	15.1	17.6
Forestry and lumbering	2.0	2.0
Mining and quarrying	1.4	1.5
Construction	20.5	19.9
Manufacturing	4.6	5.0
Wholesale and retail trade	16.1	17.1
For-hire transportation	16.6	15.1
Utilities and service	14.1	11.8
Personal transportation	3.2	4.5
Other and not reported	6.5	5.5
BODY TYPE		
Platform and cattlerack	28.9	28.9
Van[1]	23.9	16.9
Public utility	2.7	3.1
Multistop or stepvan	9.9	8.0
Dump	11.8	12.0
Tank for liquids or dry bulk	5.1	5.2
Other and not reported	17.7	25.9
VEHICLE SIZE		
Light	21.3	25.9
Medium	21.0	20.3
Light-heavy	12.9	14.3
Heavy-heavy	44.8	39.4
ANNUAL MILES		
Less than 5,000	27.4	32.5
5,000 to 9,999	13.3	14.7
10,000 to 19,999	19.9	19.1
20,000 to 29,999	10.3	10.0
30,000 or more	29.0	23.6
YEAR MODEL		
1 to 2 years old	11.3	8.1
3 to 4 years old	12.9	11.3
Over 4 years old and not reported	75.8	80.6
VEHICLE ACQUISITION		
Purchased new	41.0	40.9
Purchased used	48.8	50.9
Leased from someone and not reported	10.2	8.2
TRUCK TYPE		
Single-unit trucks	68.0	72.1
2 axles	57.7	62.1
3 axles or more	10.3	9.9
Combination	32.0	27.9
3 axles	2.2	2.4
4 axles	6.3	6.1
5 axles or more	23.5	19.4
Trailer not specified	V	V
RANGE OF OPERATION		
Local	52.5	58.1
Short-range	23.9	20.3
Long-range	15.1	11.0
Off-the-road and not reported	8.5	10.7
FUEL TYPE		
Gasoline	38.0	48.4
Diesel, liquefied gas, and other	59.6	49.5
Not reported	2.3	2.1

[1] Includes insulated, refrigerated and nonfrigerated vans; drop frame vans; open top vans; and basic enclosed vans.

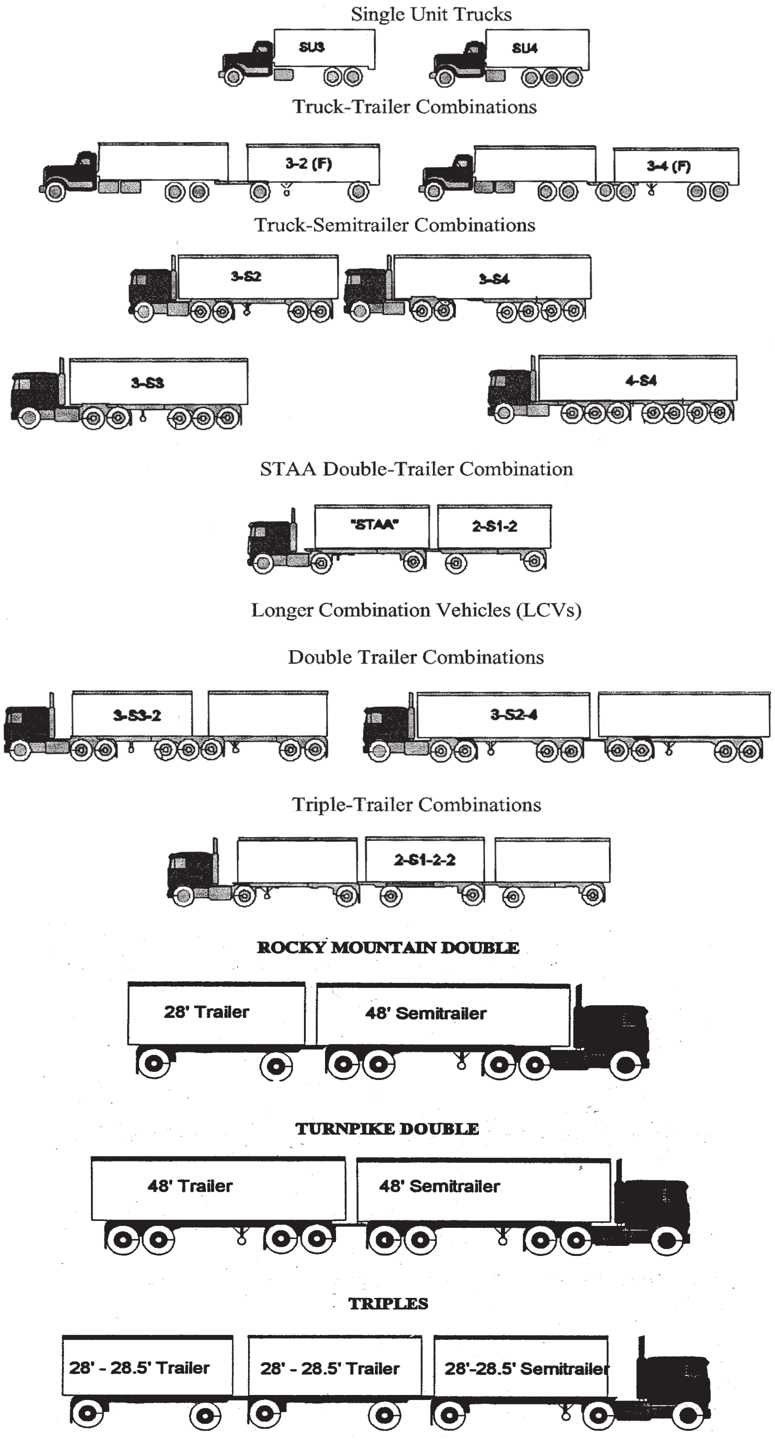


Figure 2. *Illustrative truck configurations.*

TRUCK TYPES

Figure 2 illustrates several basic truck types. The illustrations in Figure 2 are meant to convey the axle and hitch configuration, not the body types. Whereas the depicted body types are all vans, the truck configurations illustrated could also include flat-bed or platform, tanker, dump, and other body types. The truck-tractor with single trailer consists of a tractor pulling a single semitrailer. The tractor-trailer with two or three trailers consists of a tractor pulling a semitrailer followed by one or two full trailers, for the double-trailer and triple-trailer combinations, respectively. A full trailer is a trailer that is pulled by a drawbar attached to the preceding unit, but the drawbar transfers no weight to the preceding unit. A semitrailer has one end that rests on the preceding unit and can, therefore, transfer part of its load to the preceding unit. Not shown in Figure 2 is a single-unit truck pulling a full trailer.

Table 10, adapted from the CTSW study (*5*), illustrates the characteristics of representative trucks, including trucks in general operation and LCVs.

The data in Table 11 show that, while single-unit trucks constitute the majority of the truck fleet, combination trucks (i.e., tractor-trailer combinations) travel the majority of truck miles. Truck-tractors with single trailers, also referred to as tractor-semitrailer combinations or single-semitrailer combinations, are the predominant type of combination truck, both in terms of number of trucks and truck-miles traveled.

Table 12 presents data on the truck types in the current U.S. truck fleet from the FHWA CTSW study. The table includes both 1994 data and a projection to the year 2000. The source

TABLE 10 Characteristics of typical vehicles and their current uses

Configuration type	Number of axles	Common maximum weight (lb)	Current use
Single-Unit Truck	2	under 40,000	Two-axle single-unit (SU) trucks. General hauling primarily in urban areas.
	3	50,000 to 65,000	SUs are the most commonly used trucks. They are used extensively in all urban areas for short hauls. Three-axle SUs are used to carry heavy loads of materials and goods in lieu of the far more common two-axle SU.
	4 or more	62,000 to 70,000	SUs with four or more axles are used to carry the heaviest of the construction and building materials in urban areas. They are also used for waste removal.
Semitrailer	5	80,000 to 99,000	Most used combination vehicle. It is used extensively for long and short hauls in all urban and rural areas to carry and distribute all types of materials, commodities, and goods.
	6 or more	80,000 to 100,000	Used to haul heavier materials, commodities, and goods for hauls longer than those of the four-axle SU.
STAA Double	5, 6	80,000	Most common multitrailer combination. Used for less-than-truckload (LTL) freight mostly on rural freeways between LTL freight terminals.
B-Train Double	8, 9	105,500 to 137,800	Some use in the northern plains states and the Northwest. Mostly used in flatbed trailer operations and for bulk hauls.
Rocky Mountain Double	7	105,500 to 129,000	Used on turnpike in Florida, the Northeast, and Midwest and in the Northern Plains and Northwest in all types of motor carrier operations, but most often it is used for bulk hauls.
Turnpike Double	9	105,500 to 147,000	Used on turnpikes in Florida, the Northeast, and Midwest and on freeways in the Northern Plains and Northwest for mostly truckload operations.
Triple	7	105,500 to 131,000	Used to haul LTL freight on the Indiana and Ohio Turnpikes and in many of the most Western states, used on rural freeways between LTL freight terminals.

SOURCE: adapted from CTSW (*5*)

TABLE 11 Number of trucks and truck-miles of travel by truck type and number of axles (VIUS, 1997) (*9*)

	Number of trucks (thousands)	Percent of trucks	Annual truck-miles (millions)	Percent of truck-miles	Annual truck-miles per truck (thousands)
Single-unit trucks	3,853	68.0	51,467	32.7	13.4
2 axles	3,267	57.7	41,321	26.3	12.6
3 axles	475	8.4	7,189	4.6	15.1
4 or more axles	111	2.0	2,960	1.9	26.6
Combination trucks	1,811	32.0	105,896	67.3	58.5
Single-unit truck with trailer	106	1.9	2,674	1.7	25.3
4 axles	49	0.9	783	0.5	16.1
5 axles or more	57	1.0	1,891	1.2	33.1
Single-unit truck with utility trailer	162	2.9	2,098	1.3	13.0
3 axles	44	0.8	489	0.3	11.1
4 axles	97	1.7	1,285	0.8	13.3
5 axles or more	21	0.4	324	0.2	15.3
Truck tractor with single trailer	1,438	25.4	99,221	63.1	64.1
3 axles	78	1.4	2,183	1.4	28.0
4 axles	212	3.7	8,809	5.6	41.6
5 axles or more	1,149	20.3	81,229	51.6	70.7
Truck tractor with double trailers	101	1.8	8,467	5.4	83.8
5 axles	56	1.0	4,730	3.0	84.1
6 axles	24	0.4	2,239	1.4	93.3
7 axles or more	21	0.4	1,497	1.0	72.1
Truck tractor with triple trailers	5	0.1	437	0.3	97.1
7 axles	0.2	0.0	22	0.0	97.1
8 axles or more	4	0.1	415	0.3	97.3
Total trucks	5,665	100.0	157,364	100.0	27.8

TABLE 12 Existing U.S. truck fleet and vehicle miles of travel, 1994 and 2000 projections (*5*)

	Number of vehicles			Vehicle miles traveled (in millions)		
Vehicle class	1994	2000	Percent share of truck fleet	1994	2000	Percent share of truck fleet
3-axle single-unit truck	594,197	693,130	24.9	8,322	9,707	7.6
4-axle or more single-unit truck	106,162	123,838	4.4	2,480	2,893	2.2
3-axle tractor-semitrailer	101,217	118,069	4.2	2,733	3,188	2.5
4-axle tractor-semitrailer	227,306	265,152	9.5	9,311	10,861	8.5
5-axle tractor-semitrailer	1,027,760	1,198,880	43.0	71,920	83,895	65.4
6-axle tractor-semitrailer	95,740	111,681	4.0	5,186	6,049	4.7
7-axle tractor-semitrailer	8,972	10,466	0.3	468	546	0.4
3- or 4-axle truck-trailer	87,384	101,934	3.6	1,098	1,280	1.0
5-axle truck-trailer	51,933	60,579	2.2	1,590	1,855	1.4
6-axle or more truck-trailer	11,635	13,572	0.5	432	503	0.4
5-axle double	51,710	60,319	2.2	4,512	5,263	4.1
6-axle double	7,609	8,876	0.3	627	731	0.6
7-axle double	7,887	9,201	0.3	542	632	0.5
8-axle or more double	9,319	10,871	0.4	650	759	0.6
Triples	1,203	1,404	0.0	108	126	0.1
Total	2,390,034	2,787,972		109,979	128,288	

of these data are not stated in the CTSW report, but they are thought to be based, at least in part, on VIUS data.

To make Tables 11 and 12 more comparable, Table 13 presents a revised version of Table 12 with data for two-axle single-unit trucks added (based on 1992 and 1997 VIUS data). Table 13 suggests that two-axle single-unit trucks constitute a much larger percentage of the truck population and of truck-miles than does Table 11.

TRUCK LENGTH

The lengths of trucks are constrained by truck size and weight regulations that are discussed in Chapter 2 of this report.

Table 14 presents data on the distribution of truck lengths for specific truck types from the 1997 VIUS data. The table shows that most single-unit trucks are less than 11.0 m [36 ft] in length, while nearly all combination trucks are 13.7 m [45 ft] or more in length. The table is not very informative about longer trucks because the greatest length category used in the VIUS is 13.7 m [45 ft] or more, which includes nearly all the tractor-trailer combinations.

TRUCK GROSS WEIGHT

The gross weight of trucks and the weights that can be carried on specific axle types are limited by truck size and weight regulations that are discussed in Chapter 2 of the report.

Table 15 presents data on the distribution of gross vehicle weights for specific truck weights from the 1997 VIUS data. The table shows that most single-unit trucks have gross vehicle weights below 9,100 kg [20,000 lb], while most combination trucks have weights of 27,300 kg [60,000 lb] or more. Approximately 3% of single-trailer combination trucks and 11% of double-trailer combination trucks operate at gross vehicle weights above 36,400 kg [80,000 lb]. Such operation is

TABLE 13 Existing U.S. truck fleet and vehicle miles of travel, 1994 and 2000 projections including two-axle single-unit trucks (adapted from Reference 5)

Vehicle class	Number of vehicles 1994	Number of vehicles 2000	Number of vehicles Percent share of truck fleet	Vehicle miles traveled (in millions) 1994	Vehicle miles traveled (in millions) 2000	Vehicle miles traveled (in millions) Percent share of truck fleet
2-axle single-unit truck	3,213,020	3,747,984	57.3	46,035	53,700	29.5
3-axle single-unit truck	594,197	693,130	10.6	8,322	9,707	5.3
4-axle or more single-unit truck	106,162	123,838	1.9	2,480	2,893	1.6
3-axle tractor-semitrailer	101,217	118,069	1.8	2,733	3,188	1.8
4-axle tractor-semitrailer	227,306	265,152	4.1	9,311	10,861	6.0
5-axle tractor-semitrailer	1,027,760	1,198,880	18.3	71,920	83,895	46.1
6-axle tractor-semitrailer	95,740	111,681	1.7	5,186	6,049	3.3
7-axle tractor-semitrailer	8,972	10,466	0.2	468	546	0.3
3- or 4-axle truck-trailer	87,384	101,934	1.6	1,098	1,280	0.7
5-axle truck-trailer	51,933	60,579	0.9	1,590	1,855	1.0
6-axle or more truck-trailer	11,635	13,572	0.2	432	503	0.3
5-axle double	51,710	60,319	0.9	4,512	5,263	2.9
6-axle double	7,609	8,876	0.1	627	731	0.4
7-axle double	7,887	9,201	0.1	542	632	0.4
8-axle or more double	9,319	10,871	0.2	650	759	0.4
Triples	1,203	1,404	0.0	108	126	0.1
Total	5,603,054	6,535,956		156,014	181,988	

TABLE 14 Truck gross weight for specific truck types by truck-miles traveled (adapted from VIUS, 1997) (*9*)

Truck weight category (lb)	Single-unit trucks		Single-unit truck with trailer		Single-unit truck with utility trailer		Truck-tractor with single trailer		Truck-tractor with double trailer		Truck-tractor with triple trailer	
	(10^6 mi)	%	(10^6 mi)	%	(10^6 mi)	%	(10^6 mi)	%	(10^6 mi)	%	(10^6 mi)	%
less than 19,501	27,717	53.9	306	11.2	998	47.6	343	0.4	0	0.0	0	0.0
19,501 - 26,000	8,476	16.5	200	7.3	395	18.8	880	1.0	177	2.1	0	0.0
26,001 - 33,000	5,039	9.8	115	4.2	261	12.5	1,652	1.8	26	0.3	0	0.0
33,001 - 40,000	1,720	3.3	186	6.8	113	5.4	3,381	3.7	825	9.8	369	89.8
40,001 - 50,000	3,119	6.1	229	8.4	85	4.1	9,262	10.0	364	4.3	0	0.0
50,001 - 60,000	2,588	5.0	133	4.9	102	4.9	8,641	9.4	1,189	14.0	0	0.0
60,001 - 80,000	2,757	5.4	1,205	44.0	116	5.5	65,688	71.2	4,916	58.1	42	10.2
80,001 - 100,000	45	0.1	225	8.2	15	0.7	1,828	2.0	311	3.7	0	0.0
100,001 - 130,000	7	0.0	119	4.4	13	0.6	426	0.5	485	5.7	0	0.0
130,001 and more	0	0.0	18	0.6	0	0.0	122	0.1	172	2.0	0	0.0
Total	51,467	100.0	2,736	100.0	2,098	100.0	92,221	100.0	8,463	100.0	410	100.0

TABLE 15 Truck gross weight for specific truck types by truck miles traveled (adapted from VIUS, 1997) (*9*)

Truck weight category (lb)	Single-unit trucks		Single-unit truck with trailer		Single-unit truck with utility trailer		Truck-tractor with single trailer		Truck-tractor with double trailer		Truck-tractor with triple trailer	
	(10^6 mi)	%	(10^6 mi)	%	(10^6 mi)	%	(10^6 mi)	%	(10^6 mi)	%	(10^6 mi)	%
less than 19,501	27,717	53.9	306	11.2	998	47.6	343	0.4	0	0.0	0	0.0
19,501 - 26,000	8,476	16.5	200	7.3	395	18.8	880	1.0	177	2.1	0	0.0
26,001 - 33,000	5,039	9.8	115	4.2	261	12.5	1,652	1.8	26	0.3	0	0.0
33,001 - 40,000	1,720	3.3	186	6.8	113	5.4	3,381	3.7	825	9.8	369	89.8
40,001 - 50,000	3,119	6.1	229	8.4	85	4.1	9,262	10.0	364	4.3	0	0.0
50,001 - 60,000	2,588	5.0	133	4.9	102	4.9	8,641	9.4	1,189	14.0	0	0.0
60,001 - 80,000	2,757	5.4	1,205	44.0	116	5.5	65,688	71.2	4,916	58.1	42	10.2
80,001 - 100,000	45	0.1	225	8.2	15	0.7	1,828	2.0	311	3.7	0	0.0
100,001 - 130,000	7	0.0	119	4.4	13	0.6	426	0.5	485	5.7	0	0.0
130,001 and more	0	0.0	18	0.6	0	0.0	122	0.1	172	2.0	0	0.0
Total	51,468	100.0	2,736	100.0	2,098	100.0	92,223	100.0	8,465	100.0	411	100.0

legal in commercial zones around many metropolitan areas and in other areas under permit. [Note: The data in the table for triple-trailer trucks are not credible; these data are probably based on a small sample.]

TRUCKS ENTERING THE UNITED STATES FROM CANADA AND MEXICO

A substantial volume of trucks enter the United States from Canada and Mexico. In 1997, more than 9 million trucks entered the United States at the Canadian and Mexican borders. This large volume of cross-border trucking is expected to increase as NAFTA implementation proceeds.

Table 16 shows the annual number of trucks entering the United States from Canada for each major border crossing point, based on 1997 data. The table shows that two areas (Buffalo/Niagara Falls and Detroit/Port Huron), each with multiple crossings, account for more than 50% of trucks entering the United States from Canada. Table 17 shows comparable data for trucks entering the United States from Mexico. One crossing (Laredo-Nuevo Laredo) accounts for more than 35% of trucks entering the United States from Mexico, and the three busiest crossings (i.e., Laredo, El Paso, and San Diego) together account for 68% of trucks entering the United States from Mexico.

As noted in Chapter 2, the Canadian and Mexican borders operate differently in that Mexican trucks are, at present, not generally free to proceed to destinations in the United States away from the commercial zone along the border. Most truck crossings of the U.S.-Mexican border are drayage operations in which a trailer is moved from an industrial facility or terminal on one side of the border to another industrial facility or terminal not far away on the other side of the border. A recent study by Economic Data Resources found that the 4.2 million trucks entering the United States in 1999 were actually made by only 82,000 distinct vehicles (straight trucks or tractors), with an average of 52 crossings per vehicle per year (*10*). This is consistent with the nature of drayage operations, described above. Both the number of border crossings and the number of vehicles involved in those crossings is likely to increase when the border is fully opened.

No broad-based quantitative data have been found on the types of trucks actually entering the United States from Canada and Mexico. Table 18 compares the distribution of truck types operating in the United States, Canada, and Mexico (*11*).

The comparison of truck types in the United States, Canada, and Mexico shown in Table 18 probably suffers from some of the common definition problems discussed earlier. For example, the table shows a substantial number of six-axle doubles (3-S1-2) in the United States. In fact, five-axle doubles (2-S1-2), not shown in the table, are far more common in the United States than six-axle doubles (see Tables 11 and 12).

It should be recognized that NAFTA does not permit Canadian or Mexican trucks entering the United States to violate established U.S. truck size and weight limits. Thus, NAFTA is not expected to result in new truck types operating on U.S. highways. Canada and Mexico currently permit larger and heavier trucks than are permitted in the United States. However, any Canadian or Mexican truck that crosses the border must comply with applicable Federal and state laws in the United States, so the larger and heavier Canadian and Mexican trucks cannot cross the border and operate legally on U.S. highways.

As noted in Chapter 2, the adoption of an international access network of truck routes is under consideration, and vehicle size and performance criteria for trucks operating in that network have been proposed, but not yet agreed on. However, the proposed International Access Network (IAN) criteria limit single semitrailers to 16.2 m [53.2 ft] in length, equivalent to truck trailer lengths that already operate in many states. The proposed IAN criteria could permit trailer lengths of double-trailer trucks to increase from 8.7 m [28.5 ft] to approximately 9.3 m [30.5 ft], an increase of 0.6 m [2 ft]. However, such a change would require international agreement to be implemented.

The assessment conducted in this research indicates that, overall, NAFTA should have very little effect on the sizes

TABLE 16 Number of trucks entering the U.S. from Canada, 1997

Border crossing point	Number of trucks entering U.S.	Percentage of trucks entering U.S.
Maine-New Brunswick		
Calais-St. Stephen	125,713	2.2
Houlton-Woodstock (I-95)	103,153	1.8
Others (7 crossings)	88,629	1.5
Maine-Quebec		
Jackman-Armstrong	86,826	1.5
Vermont-Quebec		
Derby Line-Rock Island (I-91)	100,720	1.7
Highgate Spring-St. Armand (I-89)	99,133	1.7
Others (3 crossings)	53,692	0.9
New York-Quebec		
Champlain/Rouses Point-Lacolle (I-87)	298,933	5.2
Others (2 crossings)	13,389	2.3
New York-Ontario		
Alexandria Bay-Lansdowne (I-81)	219,956	3.8
Buffalo-Fort Erie/Niagara Falls	1,053,588	18.3
Others (2 crossings)	76,087	1.3
Michigan-Ontario		
Detroit-Windsor	1,419,728	24.6
Port Huron-Sarnia	679,441	11.8
Sault Ste. Marie	66,035	1.1
Minnesota-Ontario		
All (3 crossings)	88,052	1.5
Minnesota-Manitoba		
All (4 crossings)	18,013	0.3
North Dakota-Manitoba		
Pembina-Emerson (I-29)	152,110	2.6
Others (11 crossings)	58,991	1.0
North Dakota-Saskatchewan		
All (6 crossings)	90,225	1.6
Montana-Saskatchewan		
All (6 crossings)	20,035	0.3
Montana-Alberta		
Sweetgrass-Coutts (I-15)	111,962	1.9
Others (3 crossings)	3,522	0.1
Montana-British Columbia		
Roosville	20,875	0.4
Idaho-British Columbia		
All (2 crossings)	52,309	0.9
Washington-British Columbia		
Blaine-Surrey (I-5)	463,074	8.0
Others (11 crossings)	191,891	3.3
Alaska-British Columbia		
All (2 crossings)	6,643	0.1
Alaska-Yukon		
Alkan-Beaver Creek	5,346	0.1
TOTAL	5,768,071	

SOURCES: U.S. Customs Service; DOT Bureau of Transportation Statistics

TABLE 17 Number of trucks entering the U.S. from Mexico, 1997

Border crossing point	Number of trucks entering U.S.	Percentage of trucks entering U.S.
Texas-Tamaulipas		
Brownsville-Matamoros	247,578	7.0
Hidalgo-Reynosa	234,800	6.6
Laredo-Nuevo Laredo (I-35)	1,251,365	35.4
Texas-Coahuila		
Eagle Pass-Piedras Negras	116,715	3.3
Del Rio-Ciudad Acuna	71,656	2.0
Texas-Chihuahua		
El Paso-Juarez	582,707	16.5
Others (2 crossings)	4,920	0.1
New Mexico-Chihuahua		
Columbus-Palomas	2,305	0.1
Arizona-Sonora		
Douglas-Agua Prieta	35,718	1.0
Nogales (I-19)	242,830	6.9
San Luis	42,351	1.2
Others (3 crossings)	11,792	0.3
California-Baja California Norte		
Calexico-Mexicali	33,611	1.0
Tecate	61,804	1.7
San Diego-Tijuana (Otay Mesa)	567,715	16.1
Others (1 crossing)	2,647	0.1
TOTAL	3,510,514	

SOURCES: U.S. Customs Service; DOT Bureau of Transportation Statistics

TABLE 18 Comparison of truck types used in the U.S., Canada, and Mexico (*11*)

Truck type	Description	Percentage of the total truck fleet			Percentage of tonne-km transported		
		U.S.	Canada	Mexico	U.S.	Canada	Mexico
Type 2	2-axle single-unit	47.9	9.7	38.9	12.5	–	7.8
Type 3	3-axle single-unit	11.2	2.3	19.8	6.8	–	14.8
2-S1	3-axle single-semitrailer	2.1	–	–	2.3	–	–
2-S2	4-axle single-semitrailer	5.7	–	–	12.6	–	–
3-S2	5-axle single-semitrailer	16.1	51.0	21.6	50.3	–	30.4
3-S3	6-axle single-semitrailer	–	18.5	16.0	–	–	39.6
3-S1-2	6-axle double	13.6	–	–	9.9	–	–
3-S2-2	7-axle double	–	5.2	–	–	–	–
3-S2-4	9-axle double	–	–	1.9	–	–	6.0
3-S2-S2	7-axle double B-train	–	5.3	–	–	–	–
3-S3-S2	8-axle double B-train	–	7.9	–	–	–	–
Others	–	3.4	0.1	1.8	5.6	–	1.4

and weights of trucks operating on U.S. highways. It is likely, however, that NAFTA will increase the volume of trucks operating on U.S. highways and could also result in a change in the mix of truck types in some areas or some highway corridors. Because the types of trucks that operate on U.S. highways will remain the same or nearly the same, NAFTA is not expected to have any major effect on geometric design policies for U.S. highways.

CHAPTER 4

DESIGN VEHICLES

This chapter reviews the design vehicles used in the 2001 Green Book and presents recommended changes to the design vehicles for consideration in future editions of the Green Book. This chapter also describes the recommended changes in design vehicles and documents the reasons for these recommended changes.

OVERVIEW OF DESIGN VEHICLES

The physical characteristics and proportions of vehicles of various sizes that use the highway represent a key control in highway geometric design. Specific design vehicles are presented in the Green Book to represent classes or categories of vehicles. A design vehicle is not intended to represent an average or typical vehicle in its class but, rather, to have larger physical dimensions and a larger minimum turning radius than most vehicles in its class. Thus, geometric design of the roadway to accommodate a specific design vehicle should accommodate most vehicles in the same class as the design vehicles, as well as nearly all vehicles in classes composed of smaller vehicles.

The 2001 Green Book presents design vehicle dimensions and turning radii for 19 design vehicles, including 8 trucks. The trucks addressed in the Green Book are as follows:

- Single-Unit Truck, SU;
- Intermediate Semitrailer, WB-12 [WB-40];
- Intermediate Semitrailer, WB-15 [WB-50];
- Interstate Semitrailer, WB-19 [WB-62];
- Interstate Semitrailer, WB-20 [WB-65 or WB-67];
- “Double-Bottom”-Semitrailer/Trailer, WB-20D [WB-67D];
- Turnpike Double-Semitrailer/Trailer, WB-33D [WB-109D]; and
- Triple-Semitrailer/Trailers, WB-30T [WB-100T].

Table 19, based on Green Book Exhibit 2-1, presents the dimensions of the design vehicles, and Table 20, based on Green Book Exhibit 2-2, presents their minimum turning radii. The appropriateness for the current and future truck fleet of each of the truck design vehicles, shown in Tables 19 and 20, are discussed below. In addition, other classes of trucks that may merit inclusion are discussed.

The Green Book does not specify which design vehicle should be selected for the design of any specific highway project. This is, and should be, a choice left to the designer who is familiar with local highway and traffic conditions. However, the Green Book does provide some general guidelines to designers on the appropriate selection of design vehicles. Green Book Chapter 2 indicates that [how much is quote?]

- A passenger car may be selected when the main traffic generator is a parking lot or series of parking lots.
- A single-unit truck may be used for intersection design of residential streets and park roads.
- A city transit bus may be used in the design of state highway intersections with city streets that are designated bus routes and that have relatively few large trucks using them.
- Depending on expected usage, a large school bus (84 passengers) or a conventional school bus (65 passengers) may be used for the design of intersections of highways with low-volume county highways and township/local roads under 400 ADT. The school bus may also be appropriate for the design of some subdivision street intersections.
- The WB-20 [WB-65 or 67] truck should generally be the minimum size design vehicle considered for intersections of freeway ramp terminals with arterial crossroads and for other intersections on state highways and industrialized streets that carry high volumes of traffic and/or that provide local access for large trucks.

The Green Book could provide guidance to assist designers in selecting trucks as design vehicles in other instances. Such instances are discussed below. The text of potential future Green Book changes is presented in Appendix F.

FUTURE CHANGES TO THE U.S. TRUCK FLEET

This research was charged with assessing the effect on geometric design of both current and future truck populations. The current truck population has been documented from existing data sources and field data collection (see Chapter 3). Future truck populations are not known and can only be hypothesized. The factors reasonable to consider in

TABLE 19 **Design vehicle dimensions from the 2001 Green Book (*1*)**

Metric

Design Vehicle Type	Symbol	Dimensions (m)											
		Overall			Overhang								Typical Kingpin to Center of Rear Axle
		Height	Width	Length	Front	Rear	WB_1	WB_2	S	T	WB_3	WB_4	
Passenger Car	P	1.3	2.1	5.8	0.9	1.5	3.4	–	–	–	–	–	–
Single Unit Truck	SU	3.4-4.1	2.4	9.2	1.2	1.8	6.1	–	–	–	–	–	–
Buses													
Inter-city Bus (Motor Coaches)	BUS-12	3.7	2.6	12.2	1.8	1.9[e]	7.3	1.1	–	–	–	–	–
	BUS-14	3.7	2.6	13.7	1.8	2.6[e]	8.1	1.2	–	–	–	–	–
City Transit Bus	CITY-BUS	3.2	2.6	12.2	2.1	2.4	7.6	–	–	–	–	–	–
Conventional School Bus (65 pass.)	S-BUS 11	3.2	2.4	10.9	0.8	3.7	6.5	–	–	–	–	–	–
Large School Bus (84 pass.)	S-BUS 12	3.2	2.4	12.2	2.1	4.0	6.1	–	–	–	–	–	–
Articulated Bus	A-BUS	3.4	2.6	18.3	2.6	3.1	6.7	5.9	1.9[a]	4.0[a]	–	–	–
Trucks													
Intermediate Semitrailer	WB-12	4.1	2.4	13.9	0.9	0.8[e]	3.8	8.4	–	–	–	–	8.4
Intermediate Semitrailer	WB-15	4.1	2.6	16.8	0.9	0.6[e]	4.5	10.8	–	–	–	–	11.4
Interstate Semitrailer	WB-19*	4.1	2.6	20.9	1.2	0.8[e]	6.6	12.3	–	–	–	–	13.0
Interstate Semitrailer	WB-20**	4.1	2.6	22.4	1.2	1.4-0.8[e]	6.6	13.2-13.8	–	–	–	–	13.9-14.5
“Double-Bottom”-Semitrailer/Trailer	WB-20D	4.1	2.6	22.4	0.7	0.9	3.4	7.0	0.9[b]	2.1[b]	7.0	–	7.0
Triple-Semitrailer/ Trailers	WB-30T	4.1	2.6	32.0	0.7	0.9	3.4	6.9	0.9[c]	2.1[c]	7.0	7.0	7.0
Turnpike Double-Semitrailer/Trailer	WB-33D*	4.1	2.6	34.8	0.7	0.8a	4.4	12.2	0.8[d]	3.1[d]	13.6	–	13.0
Recreational Vehicles													
Motor Home	MH	3.7	2.4	9.2	1.2	1.8	6.1	–	–	–	–	–	–
Car and Camper Trailer	P/T	3.1	2.4	14.8	0.9	3.1	3.4	–	1.5	5.8	–	–	–
Car and Boat Trailer	P/B	–	2.4	12.8	0.9	2.4	3.4	–	1.5	4.6	–	–	–
Motor Home and Boat Trailer	MH/B	3.7	2.4	16.2	1.2	2.4	6.1	–	1.8	4.6	–	–	–
Farm Tractor[f]	TR	3.1	2.4-3.1	4.9[g]	–	–	3.1	2.7	0.9	2.0	–	–	–

NOTE: Since vehicles are manufactured in U.S. Customary dimensions and to provide only one physical size for each design vehicle, the values shown in the design vehicle drawings have been soft converted from numbers listed in feet, and then the numbers in this table have been rounded to the nearest tenth of a meter.

* = Design vehicle with 14.63 m trailer as adopted in 1982 Surface Transportation Assistance Act (STAA).

** = Design vehicle with 16.16 m trailer as grandfathered in with 1982 Surface Transportation Assistance Act (STAA).

[a] = Combined dimension is 5.91 m and articulating section is 1.22 m wide.

[b] = Combined dimension is typically 3.05 m.

[c] = Combined dimension is typically 3.05 m.

[d] = Combined dimension is typically 3.81 m.

[e] = This is overhang from the back axle of the tandem axle assembly.

[f] = Dimensions are for a 150-200 hp tractor excluding any wagon length.

[g] = To obtain the total length of tractor and one wagon, add 5.64 m to tractor length. Wagon length is measured from front of drawbar to rear of wagon, and drawbar is 1.98 m long.

- WB1, WB2, and WB4 are the effective vehicle wheelbases, or distances between axle groups, starting at the front and working towards the back of each unit.
- S is the distance from the rear effective axle to the hitch point or point of articulation.
- T is the distance from the hitch point or point of articulation measured back to the center of the next axle or center of tandem axle assembly.

(*continued on next page*)

TABLE 19 (Continued)

US Customary

Design Vehicle Type	Symbol	Dimensions (ft)											
		Overall			Overhang								Typical Kingpin to Center of Rear Axle
		Height	Width	Length	Front	Rear	WB_1	WB_2	S	T	WB_3	WB_4	
Passenger Car	P	4.25	7	19	3	5	11	–	–	–	–	–	–
Single Unit Truck	SU	11-13.5	8.0	30	4	6	20	–	–	–	–	–	–
Buses													
Inter-city Bus (Motor Coaches)	BUS-40	12.0	8.5	40	6	6.3[e]	24	3.7	–	–	–	–	–
	BUS-45	12.0	8.5	45	6	8.5[e]	26.5	4.0	–	–	–	–	–
City Transit Bus	CITY-BUS	10.5	8.5	40	7	8	25	–	–	–	–	–	–
Conventional School Bus (65 pass.)	S-BUS 36	10.5	8.0	35.8	2.5	12	21.3	–	–	–	–	–	–
Large School Bus (84 pass.)	S-BUS 40	10.5	8.0	40	7	13	20	–	–	–	–	–	–
Articulated Bus	A-BUS	11.0	8.5	60	8.6	10	22.0	19.4	6.2[a]	13.2[a]	–	–	–
Trucks													
Intermediate Semitrailer	WB-40	13.5	8.0	45.5	3	2.5[e]	12.5	27.5	–	–	–	–	27.5
Intermediate Semitrailer	WB-50	13.5	8.5	55	3	2[e]	14.6	35.4	–	–	–	–	37.5
Interstate Semitrailer	WB-62*	13.5	8.5	68.5	4	2.5[e]	21.6	40.4	–	–	–	–	42.5
Interstate Semitrailer	WB-65** or WB-67	13.5	8.5	73.5	4	4.5-2.5[e]	21.6	43.4-45.4	–	–	–	–	45.5-47.5
"Double-Bottom"-Semitrailer/Trailer	WB-67D	13.5	8.5	73.3	2.33	3	11.0	23.0	3.0[b]	7.0[b]	23.0	–	23.0
Triple-Semitrailer/ Trailers	WB-100T	13.5	8.5	104.8	2.33	3	11.0	22.5	3.0[c]	7.0[c]	23.0	23.0	23.0
Turnpike Double-Semitrailer/Trailer	WB-109D*	13.5	8.5	114	2.33	2.5[e]	14.3	39.9	2.5[d]	10.0[d]	44.5	–	42.5
Recreational Vehicles													
Motor Home	MH	12	8	30	4	6	20	–	–	–	–	–	–
Car and Camper Trailer	P/T	10	8	48.7	3	10	11	–	5	19	–	–	–
Car and Boat Trailer	P/B	–	8	42	3	8	11	–	5	15	–	–	–
Motor Home and Boat Trailer	MH/B	12	8	53	4	8	20	–	6	15	–	–	–
Farm Tractor[f]	TR	10	8-10	16[g]	–	–	10	9	3	6.5	–	–	–

* = Design vehicle with 48 ft trailer as adopted in 1982 Surface Transportation Assistance Act (STAA).

** = Design vehicle with 53 ft trailer as grandfathered in with 1982 Surface Transportation Assistance Act (STAA).

[a] = Combined dimension is 19.4 ft and articulating section is 4 ft wide.

[b] = Combined dimension is typically 10.0 ft.

[c] = Combined dimension is typically 10.0 ft.

[d] = Combined dimension is typically 12.5 ft.

[e] = This is overhang from the back axle of the tandem axle assembly.

[f] = Dimensions are for a 150-200 hp tractor excluding any wagon length.

[g] = To obtain the total length of tractor and one wagon, add 18.5 ft to tractor length. Wagon length is measured from front of drawbar to rear of wagon, and drawbar is 6.5 ft long.

- WB1, WB2, and WB4 are the effective vehicle wheelbases, or distances between axle groups, starting at the front and working towards the back of each unit.
- S is the distance from the rear effective axle to the hitch point or point of articulation.
- T is the distance from the hitch point or point of articulation measured back to the center of the next axle or center of tandem axle assembly.

TABLE 20 Minimum turning radii of design vehicles from the 2001 Green Book (*1*)

Metric

Design Vehicle Type	**Passenger Car**	**Single Unit Truck**	**Inter-city Bus (Motor Coach)**		**City Transit Bus**	**Conventional School Bus (65 pass.)**	**Large[2] School Bus (84 pass.)**	**Articulated Bus**	**Intermediate Semi-trailer**	**Intermediate Semi-trailer**
Symbol	P	SU	BUS-12	BUS-14	CITY-BUS	S-BUS11	S-BUS12	A-BUS	WB-12	WB-15
Minimum Design Turning Radius (m)	7.3	12.8	13.7	13.7	12.8	11.9	12.0	12.1	12.2	13.7
Centerline[1] Turning Radius (CTR)	6.4	11.6	12.4	12.4	11.5	10.6	10.8	10.8	11.0	12.5
Minimum Inside Radius (m)	4.4	8.6	8.4	7.8	7.5	7.3	7.7	6.5	5.9	5.2
Design Vehicle Type	**Interstate Semi-trailer**		**“Double Bottom” Combination**	**Triple Semi-trailer/ trailers**	**Turnpike Double Semi-trailer/ trailer**	**Motor Home**	**Car and Camper Trailer**	**Car and Boat Trailer**	**Motor Home and Boat Trailer**	**Farm[3] Tractor w/One Wagon**
Symbol	WB-19*	WB-20** or WB-20	WB-20D	WB-30T	WB-33D*	MH	P/T	P/B	MH/B	TR/W
Minimum Design Turning Radius (m)	13.7	13.7	13.7	13.7	18.3	12.2	10.1	7.3	15.2	5.5
Centerline[1] Turning Radius (CTR)	12.5	12.5	12.5	12.5	17.1	11.0	9.1	6.4	14.0	4.3
Minimum Inside Radius (m)	2.4	1.3	5.9	3.0	4.5	7.9	5.3	2.8	10.7	3.2

NOTE: Numbers in table have been rounded to the nearest tenth of a meter.

* = Design vehicle with 14.63 m trailer as adopted in 1982 Surface Transportation Assistance Act (STAA).

** = Design vehicle with 16.16 m trailer as grandfathered in with 1982 Surface Transportation Assistance Act (STAA).

[1] = The turning radius assumed by a designer when investigating possible turning paths and is set at the centerline of the front axle of a vehicle. If the minimum turning path is assumed, the CTR approximately equals the minimum design turning radius minus one-half the front width of the vehicle.

[2] = School buses are manufactured from 42 passenger to 84 passenger sizes. This corresponds to wheelbase lengths of 3,350 mm to 6,020 mm, respectively. For these different sizes, the minimum design turning radii vary from 8.78 m to 12.01 m and the minimum inside radii vary from 4.27 m to 7.74 m.

[3] = Turning radius is for 150–200 hp tractor with one 5.64 m long wagon attached to hitch point. Front wheel drive is disengaged and without brakes being applied.

hypothesizing future truck populations are (1) the current truck population, (2) current trends in the truck population, and (3) the likelihood of specific future changes in truck size and weight laws or regulations. As noted in Chapter 2, the 1982 STAA required all states to permit trucks with single 14.6-m [48-ft] trailers and twin 8.7-m [28.5-ft] trailers to operate on the National Truck Network. Since 1982, combination trucks with single 16.2-m [53-ft] trailers have become common on the National Network (NN) in many states, and a few states permit combinations with trailers as long as 18.1 m [59.5 ft]. There has been some recent interest in Congress in eliminating trailers longer than 16.2 m [53 ft].

Many states, particularly in the West, allow so-called Longer Combination Vehicles (LCVs) to operate, often under permit. LCVs include doubles combinations with trailers longer than 8.7 m [28.5 ft], B-train doubles (doubles combinations connected with a B-dolly), Rocky Mountain doubles (combinations with two trailers of unequal length), Turnpike doubles (combinations of two long trailers), and triple-trailer combinations. LCVs are used primarily by segments of the

TABLE 20 (Continued)

US Customary

Design Vehicle Type	Passenger Car	Single Unit Truck	Inter-city Bus (Motor Coach)		City Transit Bus	Conventional School Bus (65 pass.)	Large[2] School Bus (84 pass.)	Articulated Bus	Intermediate Semitrailer	Intermediate Semitrailer
Symbol	P	SU	BUS-40	BUS-45	CITY-BUS	S-BUS36	S-BUS40	A-BUS	WB-40	WB-50
Minimum Design Turning Radius (ft)	24	42	45	45	42.0	38.9	39.4	39.8	40	45
Centerline[1] Turning Radius (CTR)	21	38	40.8	40.8	37.8	34.9	35.4	35.5	36	41
Minimum Inside Radius (ft)	14.4	28.3	27.6	25.5	24.5	23.8	25.4	21.3	19.3	17.0
Design Vehicle Type	**Interstate Semitrailer**		**"Double Bottom" Combination**	**Triple Semitrailer/trailers**	**Turnpike Double Semitrailer/trailer**	**Motor Home**	**Car and Camper Trailer**	**Car and Boat Trailer**	**Motor Home and Boat Trailer**	**Farm[3] Tractor w/One Wagon**
Symbol	WB-62*	WB-65** or WB-67	WB-67D	WB-100T	WB-109D*	MH	P/T	P/B	MH/B	TR/W
Minimum Design Turning Radius (m)	45	45	45	45	60	40	33	24	50	18
Centerline[1] Turning Radius (CTR)	41	41	41	41	56	36	30	21	46	14
Minimum Inside Radius (m)	7.9	4.4	19.3	9.9	14.9	25.9	17.4	8.0	35.1	10.5

* = Design vehicle with 48 ft trailer as adopted in 1982 Surface Transportation Assistance Act (STAA).

** = Design vehicle with 53 ft trailer as grandfathered in with 1982 Surface Transportation Assistance Act (STAA).

[1] = The turning radius assumed by a designer when investigating possible turning paths and is set at the centerline of the front axle of a vehicle. If the minimum turning path is assumed, the CTR approximately equals the minimum design turning radius minus one-half the front width of the vehicle.

[2] = School buses are manufactured from 42 passenger to 84 passenger sizes. This corresponds to wheelbase lengths of 132 in to 237 in, respectively. For these different sizes, the minimum design turning radii vary from 28.8 ft to 39.4 ft and the minimum inside radii vary from 14.0 ft to 25.4 ft.

[3] = Turning radius is for 150-200 hp tractor with one 18.5 ft long wagon attached to hitch point. Front wheel drive is disengaged and without brakes being applied.

trucking industry that haul bulky, low-density freight. The ability of states to permit new LCV operations has been frozen by Congress (limited to operations that were legal prior to the early 1990s), but LCV volumes are growing where they are permitted and could grow more if the Congressional freeze were ended.

The economics of the trucking industry strongly influence the demand for highway agencies to permit larger and heavier trucks to operate. Serious consideration has been given in recent years to allowing an increase in truck loads, without increase in axle loads, by adding more axles and spacing the axles differently to minimize potential impacts on structures and pavements; an example of this is the so-called Turner Truck proposal, named after former Federal Highway Administrator Frank Turner (*12*). The state of Michigan already allows trucks with up to 11 axles to operate with much higher gross weights than are normally allowed by other states.

TRB Special Report 267, *Regulation of Weights, Lengths, and Widths of Commercial Motor Vehicles* (*13*), recently recommended that Federal law be changed to allow two specific truck types to operate under state permits:

- Six-axle tractor-semitrailers with a maximum weight of 35,400 kg [90,000 lb]; and
- Double-trailer configurations with each trailer up to 10.1 m [33 ft] long; with seven, eight, or nine axles; and with a weight governed by the present Federal bridge formula

As noted in Chapter 3, NAFTA is likely to result in increased volumes of trucks entering the United States from Canada and Mexico, but NAFTA does not change the limits imposed by existing U.S. truck size and weight regulations.

SINGLE-UNIT TRUCKS

Figure 3, based on Green Book Exhibit 2-4, illustrates the dimensions of the current single-unit (SU) truck design vehicle. The SU design vehicle is a two-axle truck with an overall length of 9.2 m [30 ft] and a turning radius of 12.8 m [42 ft].

It is potentially confusing that the single-unit truck appears in the upper portion of Table 19, rather than in section of the table labeled "Trucks." It is recommended that the "Trucks" section of the table should be renamed "Combination Trucks."

There is concern that the AASHTO SU design vehicle is not representative of larger single-unit trucks. The vast majority of single-unit trucks on the road are two-axle trucks. However, the truck population includes a substantial number of three- or four-axle SU trucks. The population of these trucks is small compared with the population of two-axle SU trucks, but large when compared with the population of truck types larger than an SU truck.

The current SU design vehicle is representative of the largest two-axle trucks currently in use. Table 21 compares the current SU design vehicle with several representative three-axle SU trucks that were evaluated in the FHWA Comprehensive Truck Size and Weight (CTSW) study (*5*). Seven of the 10 representative single-unit trucks shown in the table are larger than the SU design vehicle, including the larger van and all of the tank, garbage, grain, and concrete mixer trucks.

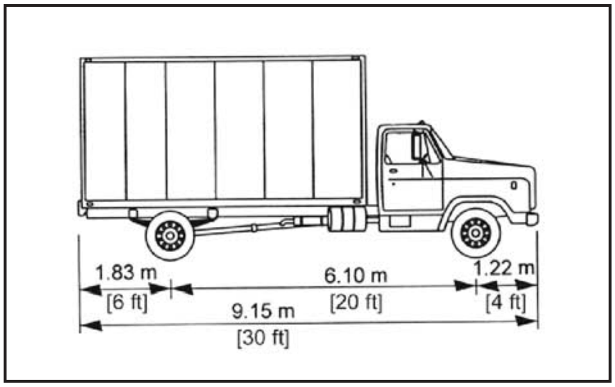


Figure 3. Dimensions of single-unit (SU) truck design vehicle in current Green Book (1).

Based on the data in Tables 11, 13, and 21, the research team recommends that a three-axle SU design vehicle with a wheelbase of 7.6 m [25.0 ft] be added to the Green Book, in addition to the current two-axle SU design vehicle. Figure 4 illustrates the dimensions of the recommended design vehicle.

TRUCK TRACTORS

There is no AASHTO design vehicle representing a truck tractor (without a trailer), but Figure 5 depicts dimensional data for truck tractors shown in Green Book Exhibit 212. No changes in this exhibit are recommended. Figure 5 depicts the fifth wheel as located directly over the rear axles of each

TABLE 21 Dimensions of single-unit trucks—SU design vehicle vs. other representative vehicles

Body type	Overall lengths m [ft]	Box length m [ft]	Number of axles	Spacing between axles or axle groups m [ft]
SU Design Vehicle				
Van	9.2 [30.0]	–	2	6.1 [20.0]
Other Representative Vehicles[a]				
Van	9.0 [29.5]	6.1 [20.0]	3	7.6 [25.0]
Van	12.0 [39.5]	9.2 [30.0]	3	7.6 [25.0]
Tank	9.8 [32.0]	6.9 [22.5]	3	6.3 [20.5]
Tank	11.6 [38.0]	8.7 [28.5]	3	7.3 [24.0]
Dump	7.5 [24.5]	4.6 [15.0]	3	7.3 [24.0]
Dump	9.0 [29.5]	6.1 [20.0]	3	5.8 [19.0]
Garbage	9.9 [32.5]	7.0 [23.0]	3	6.3 [20.8]
Grain	12.0 [39.5]	9.2 [30.0]	3	7.6 [25.0]
Concrete mixer	9.8 [32.0]	6.9 [22.5]	3	6.3 [20.5]
Concrete mixer	11.6 [38.0]	8.7 [28.5]	3[b]	7.3 [24.0]

[a] Representative vehicles taken from Reference 15.
[b] Larger concrete mixers may have four or more axles.

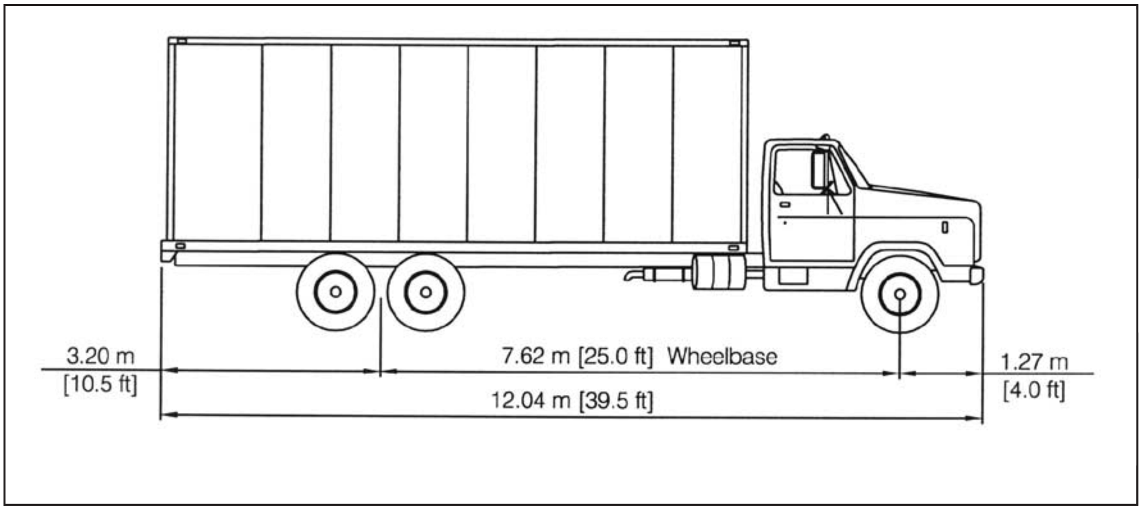


Figure 4. Dimensions of recommended three-axle single-unit (SU-8 [SU-25]) design vehicle.

tractor; in actual practice, the kingpin is often set forward about 0.3 m [1 ft] from the axle centerline. This forward displacement of the kingpin generally has only a small effect on offtracking and swept path width and, therefore, this effect has not been addressed in this report.

Figure 5 refers to tractors for Rocky Mountain and Turnpike doubles configurations. It should be noted that Rocky Mountain doubles combinations are mentioned nowhere else in the Green Book, but should be because they may be more common than Turnpike doubles combinations.

SINGLE-TRAILER COMBINATIONS (FIVE-AXLE TRACTOR-SEMITRAILERS)

The Green Book includes four design vehicles that are single-trailer combination trucks. These are as follows:

- WB-12 [WB-40] design vehicle, with a 10.1-m [33-ft] trailer;
- WB-15 [WB-50] design vehicle, with a 13.0-m [42.5-ft] trailer;
- WB-19 [WB-62] design vehicle, with a 14.6-m [48-ft] trailer; and
- WB-20 [WB-65 or WB-67] design vehicle, with a 16.2-m [53-ft] trailer.

The dimensions and turning paths of these vehicles are shown in Figures 6 through 9, based on Green Book Exhibits 2-13 through 2-16.

The AASHTO design vehicles are drawn showing these trucks with van-type trailers. In fact, there are many other types of tractor-semitrailer combinations, such as flat-bed, dump, tanker, and container-carrying trailers. Because of vehicle-weight limitations, these other trailer types tend to be shorter than those used for van trailers. Thus, it is reasonable to envision the design vehicles as van trailers.

The WB-12 [WB-40] and WB-15 [WB-50] are rarely seen today on highways, with some exceptions discussed below. The AASHTO Green Book states that these design vehicles may be appropriate for design of local roads and streets. Note that this is only true if the locations under consideration *do not* serve the larger and more common combinations with 14.6-m [48-ft] and 16.2-m [53-ft] trailers.

Another use for the WB-12 [WB-40] design vehicle, although with a trailer other than a van, is as a container-carrying vehicle. These trailers are similar to flat-bed trailers, but are designed for carrying containers such as are commonly loaded on ships and trains. It is recommended that the WB-12 [WB-40] design vehicle be retained. The Green Book should state that this design vehicle is appropriate for local streets not used by larger tractor-semitrailers and for access roads to ports and train yards where container traffic may predominate.

The WB-15 [WB-50] design vehicle has a 13.0-m [42.5-ft] trailer. This trailer size, or similar trailers with lengths of 12.2 m [40 ft] or 13.7 m [45 ft] was quite common prior to the 1982 STAA. However, since the 1982 STAA mandated that states allow 14.6-m [48-ft] trailers on the NN, trailers in the 12.2 m [40 ft] to 13.7 m [45 ft] length range have largely disappeared. Table 22, based on VIUS data for single-semitrailer trucks by trailer length, shows that trucks in the length range of the WB-15 [WB-50] truck constitute only 8% of the population of single-semitrailer combination trucks. By contrast, single-semitrailer combination trucks with trailer lengths of 13.7 m [45 ft] or more, typically represented in design by either the WB-19 [WB-62] or a larger design vehicle, constitute more than 65% of the single-semitrailer truck population. Given that the situations in which the WB-15 [WB-50] is an appropriate design vehicle are very limited, it is recommended that this design vehicle be eliminated from the Green Book.

The WB-19 [WB-62] design vehicle is a tractor-semitrailer with a 14.6-m [48-ft] trailer. This was, at one time, nearly

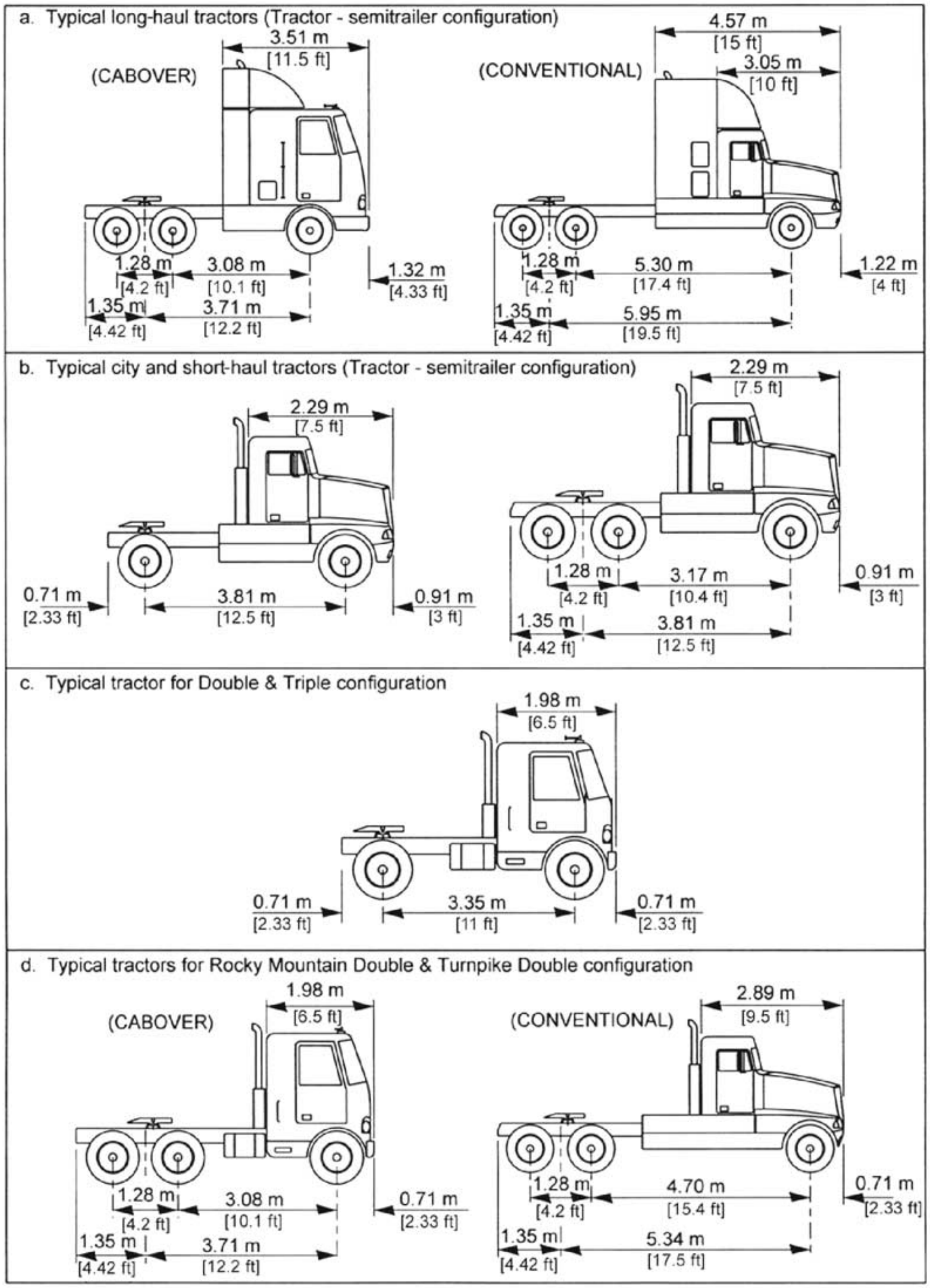
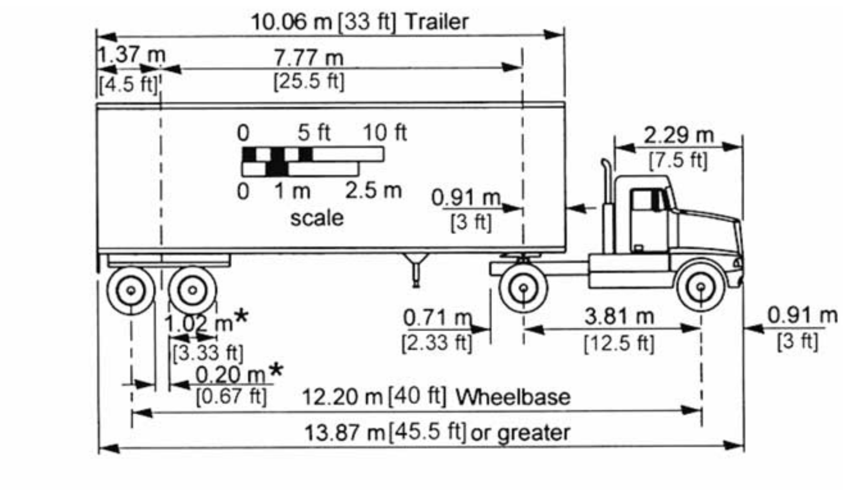


Figure 5. Lengths of commonly used truck tractors (1).

the largest tractor-semitrailer on the highway. The WB-20 [WB-65 or WB-67] with a 16.2-m [53-ft] trailer is now perhaps more common than the 14.6-m [48-ft] trailer. Consideration might be given to dropping the WB-19 [WB-62] design vehicle because it has become less common, but it is recommended that it be retained because it represents a vehicle size limit specified in Federal law to be allowed to operate anywhere on the NN and it represents very closely the offtracking performance of longer trucks with their rear axles pulled forward to meet state KCRT distance requirements. The current WB-19 [WB-62] design vehicle has a KCRT distance of 12.3 m [40.5 ft]. The most common KCRT distance is 12.5 m [41 ft] because 19 states limit the KCRT distance to about 12.5 m [41 ft] (see Table 2). Therefore, it is recommended that the WB-19 [WB-62] design vehicle be modified slightly in the next edition of the Green Book to incorporate this



* Typical tire size and space between
tires applies to all trailers.

Figure 6. Dimensions of intermediate semitrailer (WB-12 [WB-40]) design vehicle in current Green Book (1).

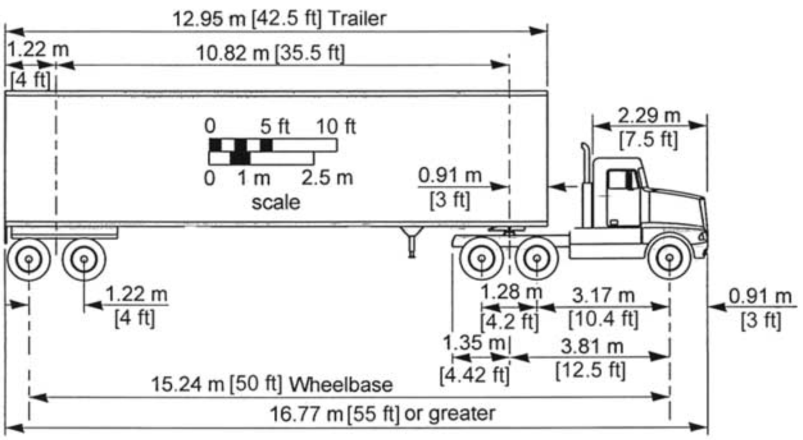


Figure 7. Dimensions of intermediate semitrailer (WB-15 [WB-50]) design vehicle in current Green Book (1).

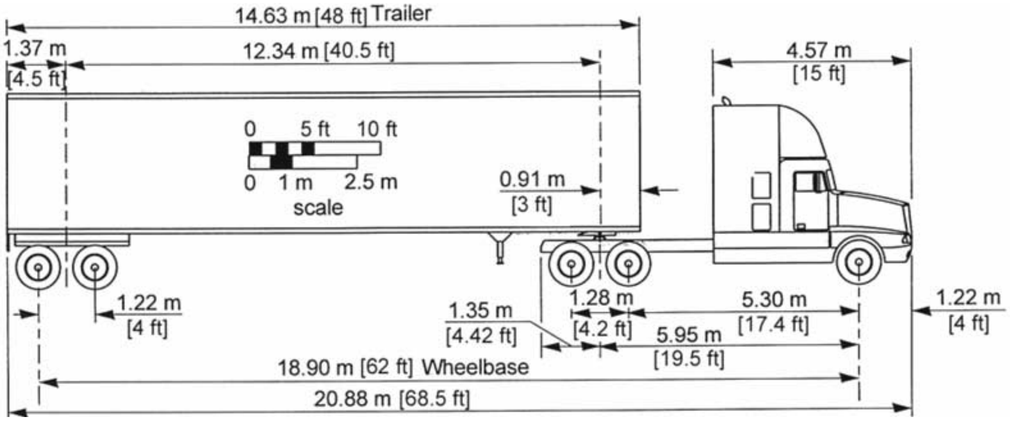


Figure 8. Dimensions of intermediate semitrailer (WB-19 [WB-62]) design vehicle in current Green Book (1).

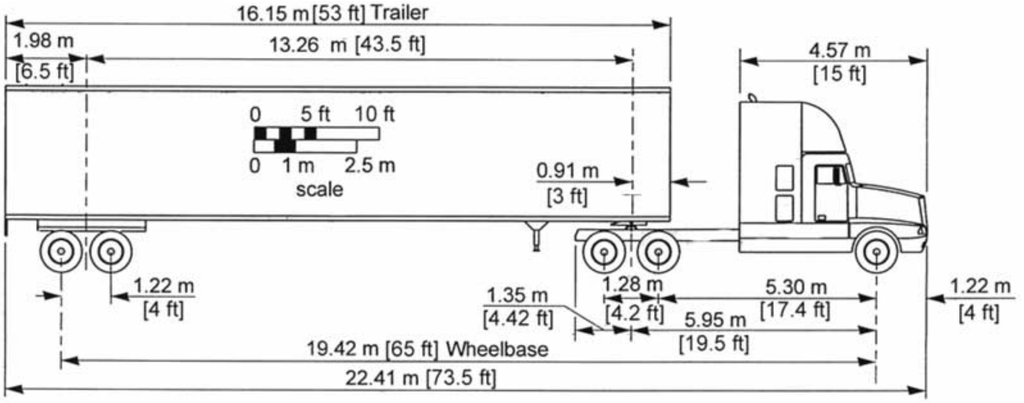


Figure 9. Dimensions of interstate semitrailer (WB-20 [WB-65]) design vehicle in current Green Book (1).

TABLE 22 Distribution of trailer lengths for tractor-semitrailers from 1997 VIUS data

Length of trailer	Number of tractor-semitrailers					Estimated vehicle miles traveled (VMT)				
	1 axle on 1 semi-trailer	2 axles on 1 semi-trailer	3 axles on 1 semi-trailer	Total	Percentage	1 axle on 1 semi-trailer	2 axles on 1 semi-trailer	3 axles on 1 semi-trailer	Sum of row	Percentage
1-20 ft	4,913	12,305	1,297	18,515	1.3	49,980,417	295,974,708	28,481,053	374,436,178	0.4
21-28 ft	46,507	48,175	5,244	99,926	6.9	1,290,291,305	1,540,429,521	186,823,947	3,017,544,773	3.3
29-35 ft	20,606	70,709	12,600	103,915	7.2	444,861,237	2,231,595,411	543,069,119	3,219,525,767	3.5
36-40 ft	6,638	184,967	15,753	207,358	14.4	141,988,342	8,114,772,425	597,410,431	8,854,171,198	9.6
41-44 ft	1,460	112,331	6,980	120,771	8.4	41,260,168	6,600,238,638	376,937,640	7,018,436,446	7.6
45-47 ft	6,910	195,385	40,473	242,768	16.9	344,488,954	11,404,888,159	3,107,112,371	14,856,489,484	16.1
48-52 ft	2,733	405,086	24,108	431,927	30.0	159,852,808	32,530,535,430	1,487,776,128	34,178,164,366	37.1
53 ft or more	1,303	188,841	22,905	213,049	14.8	140,054,006	19,312,020,893	1,250,456,865	20,702,531,764	22.4
Totals	91,070	1,217,799	129,360	1,438,229	100.0	2,612,777,237	82,030,455,185	7,578,067,554	92,221,299,976	

12.5-m [41-ft] dimension. The revised WB-19 [WB-62] design vehicle is illustrated in Figure 10.

A variant of the WB-19 [WB-62] configuration is becoming more common, especially on flat-bed trailers, and to some extent on van trailers. This variant involves the use of a split or spread tandem axle set at the rear of the trailer. The normal tandem axle set has a nominal spacing of 1.2 m [4 ft] between axles. The spread option moves these axles apart to distances up to 3.1 m [10 ft]. This increases the load-carrying capacity of the tandem from 15,500 to 18,200 kg [34,000 to 40,000 lb], in accordance with the Federal bridge formula. Increases of spread-axle spacing beyond 3.1 m [10 ft] do not provide any increase in load-carrying capacity because the single-axle load limit of 9,100 kg [20,000 lb] becomes a constraint.

This increase in loading of the rear tandem axle by spreading the rear axles farther apart does not permit the gross vehicle weight (GVW) of the truck to legally exceed 36,400 kg [80,000 lb], but it is popular with truckers in that it provides

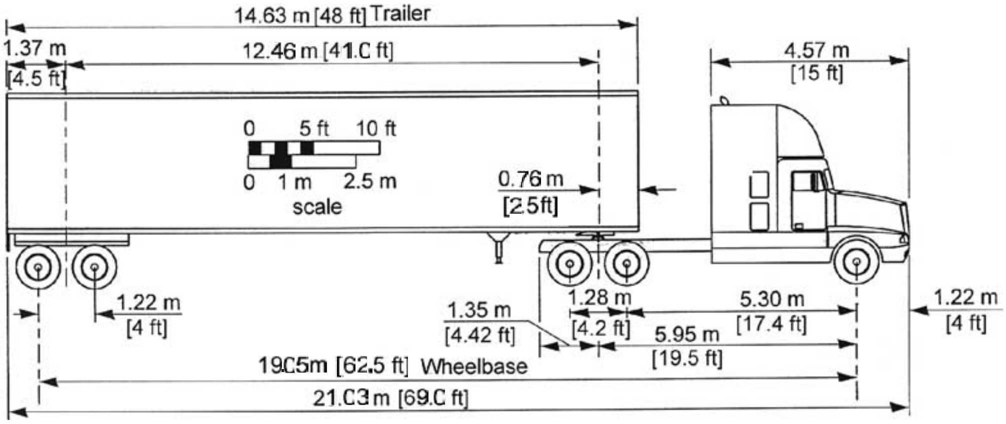


Figure 10. Recommended revision in the dimensions of interstate semitrailer (WB-19 [WB-62]) design vehicle.

more flexibility in loading the truck, and in keeping the load on the steering axle of the tractor to a more driver-friendly level. With a normal tandem spacing, the maximum GVW of 36,400 kg [80,000 lb] is met by loading both the trailer and tractor tandem axles to their maximum of 15,500 kg [34,000 lb], and the steering axle to 5,500 kg [12,000 lb] (which is about the maximum that truckers want, for comfort and ease of driving.) With a spread tandem at the rear of the trailer, the 36,400-kg [80,000-lb] load can be moved somewhat rearward, keeping all axle loads at or below their individual maxima. As an additional (albeit minor) benefit, spreading the axles by an additional 1.8 m [6 ft] also reduces the KCRT distance by 0.9 m [3 ft], reducing the total offtracking.

Because spreading the rear axles results in a slight reduction in offtracking and swept path width, the current design vehicles with a 1.2-m [4-ft] axle spacing are more appropriate for use as design vehicles than the comparable trucks with 3.1-m [10-ft] spread tandem axles. Therefore, there is no need to consider a tractor-semitrailer design vehicle with a rear spread tandem axle.

The WB-20 [WB-65] design vehicle, shown in Figure 9, has a 16.2-m [53-ft] trailer. Tractor-semitrailers with 16.2-m [53-ft] trailers can operate in most states; all but three jurisdictions (i.e., Alaska, the District of Columbia, and Rhode Island) allow trailers of 16.2 m [53 ft] or larger to operate on the NN. All but an additional six states allow them on all state roads. Table 22 shows 22.4% of veh-mi by trucks with single semitrailers with length of 16.2 m [53 ft] or more. However, field studies conducted for this research at rural sites in three states found that trucks with 16.2-m [53-ft] trailers constitute approximately 47% of all combination trucks (see Appendix B). A principal reason why 16.2-m [53-ft] trailers are used so commonly is that a significant number of loaded trucks do not weigh 80,000 lb. Trucks carrying low- or medium-density cargo often “cube out” (their volume becomes filled) before they “gross out” (reach the gross vehicle weight limit).

The current Green Book incorporates a design vehicle very similar to the WB-20 [WB-65], known as the WB-20 [WB-67] design vehicle, which also has a 16.2-m [53-ft] trailer. The WB-20 [WB-67] design vehicle, illustrated in Figure 11, is identical to the WB-20 [WB-65] design vehicles, except that the rear tandem axle of the WB-20 [WB-67] is positioned closer to the rear of the truck. There is no need for both of these design vehicles to be included in the Green Book, given that they are variations of one another. It makes more sense to include the WB-20 [WB-67] design vehicle, rather than the WB-20 [WB-65], because the WB-20 [WB-67] design vehicle has a greater turning radius, greater offtracking, and greater swept path width.

Although the inclusion of the WB-20 [WB-67] design vehicle in the Green Book is recommended, this design vehicle will not be applied as widely as might be expected because 19 states limit the KCRT distance to a maximum of about 12.5 m [41 ft]. One state (California) is more stringent, two states (Illinois and Maine) are more liberal, and the remaining states do not limit kingpin-to-rear-axle distance.

Beyond simply complying with state regulations, many truckers move the rear axles of the trailer forward to improve maneuverability. (Indeed, it is even common to see 14.6-m [48-ft] trailers with their rear axles moved forward, resulting in kingpin-to-rear-axle distances of 11.6 m [38.0 ft] or less.)

Although many truckers prefer to move the rear axles of the trailer forward, where practical, the use of 16.2-m [53-ft] trailers introduces a potential axle load limitation. If a 36,400-kg [80,000-lb] truck carries a 22,700-kg [50,000-lb] payload, and if that load is spread evenly along a 14.6-m [48-ft] trailer, the individual axle loads are close to the maximums described earlier. However, if such a load is spread evenly along the length of a 16.2-m [53-ft] trailer with the rear trailer axles moved forward, the trailer axle load would reach about 19,500 kg [43,000 lb], an overload of 4,100 kg [9,000 lb]. Stated differently, to keep the trailer axle load within legal limits, a 16.2-m [53-ft] trailer with the axles moved forward could carry no more than about 18,200 kg [40,000 lb] if loaded evenly along the length of the trailer with the axles forward.

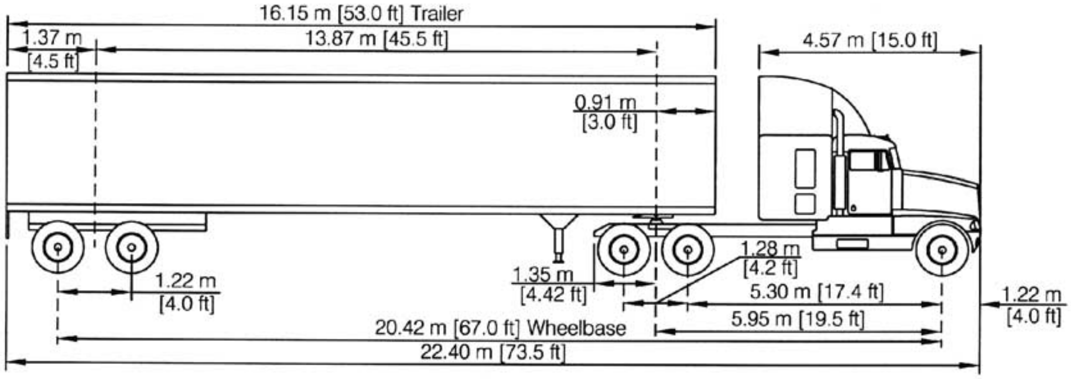


Figure 11. Recommended dimensions of interstate semitrailer (WB-20 [WB-67]) design vehicle.

For other configurations, the use of trailer types other than vans have been discussed. However, it is doubtful that there are many 16.2-m [53-ft] trailers other than vans, because trailer types other than vans are used primarily for higher density cargo for which 16.2-m [53-ft] trailers provide no advantage.

If a designer is considering the offtracking and swept path of a tractor-semitrailer combination truck with a 16.2-m [53-ft] trailer with the axles moved forward to maintain a 12.5-m [41-ft] KCRT distance, the WB-19 [WB-62] design vehicle should be used. The offtracking and swept path width of the WB-20 [WB-67] design vehicle with its axles pulled forward is identical to the offtracking and swept path width of the revised WB-19 [WB-62] shown in Figure 10. The rear swingout of the WB-20 [WB-67] with its axles pulled forward exceeds the rear swingout of the WB-19 [WB-62] design vehicle by approximately 0.15 m [0.5 ft] for a 90-deg turn with a 15-m [50-ft] radius (see the discussion of this issue in Chapter 5 of this report).

Where the length of a tractor-semitrailer combination truck with a 16.2-m [53-ft] trailer is critical to design, its overall length of 22.4 m [73.5 ft] should be used.

Eight states permit trucks with trailer lengths greater than 16.2 m [53 ft] to operate on the NN. However, even in these states, trucks with trailer lengths greater than 16.2 m [53 ft] were found to be very rare. Appendix C reports the results of field studies in two states that permit trailer lengths greater than 16.2 m [53 ft]—Kansas and Texas. The field studies conducted at weigh stations on major interstate highways found that only 0.7 percent of trucks in Kansas and 4.4 percent of trucks in Texas had trailers whose lengths exceeded 16.2 m [53 ft]. A recent paper by Clayton et al. (*14*) reported that a field study at a different Texas location found only 0.5 percent of single-semitrailer trucks had lengths over 16.2 m [53 ft].

Based on the data reported above, the inclusion in the Green Book of a design vehicle with a trailer length greater than 16.2 m [53 ft] currently is not recommended. However, an appropriate design vehicle has been developed for future consideration, should the number and proportion of trucks with trailers greater than 16.2 m [53 ft] in length increase. This design vehicle for possible future use is designated as the WB-22 [WB-71] design vehicle and is illustrated in Figure 12. The WB-22 [WB-71] design vehicle has a 17.4-m [57-ft] trailer and a KCRT distance of 15.1 m [49.5 ft] and will offtrack substantially more than the other tractor-semitrailer design vehicles (see Chapter 5 of this report). However, many trucks with 17.4-m [57-ft] trailers are operated with maximum 12.5-m [41-ft] KCRT distances to meet state limitations. The offtracking and swept path width of the WB-22 [WB-71] design vehicle with the axles pulled forward can be considered in design using the WB-19 [WB-62] design vehicle. The WB-22 [WB-71] with the axles pulled forward will have rear swingout that exceeds the WB-19 [WB-62] by 0.23 m [0.76 ft] for a 90-deg turn with a 15-m [50-ft] radius (see Chapter 5 of this report). Where the length of the vehicle is critical to design, the overall length of 23.6 m [77.5 ft] for the WB-22 [WB-71] design vehicle should be used.

SINGLE-TRAILER COMBINATIONS (SIX-AXLE TRACTOR-SEMITRAILERS)

A future change in Federal law may allow states to issue permits for operation of six-axle tractor-semitrailers with maximum weights up to 35,400 kg [90,000 lb]. Six-axle tractor-semitrailers can operate legally now. However, within current gross vehicle weight and axle limits, there is no particular advantage to using a six-axle combination rather than a five-axle combination. Six-axle tractor-semitrailers are likely to come into common use only if Federal law were to permit

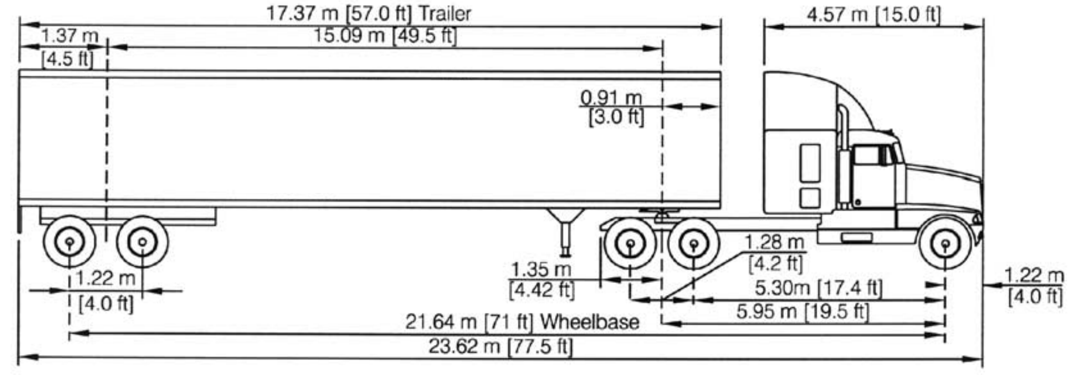


Figure 12. Dimensions of long semitrailer (WB-22 [WB-71]) design vehicle for possible future use.

six-axle trucks to carry greater loads than five-axle trucks. Such a change in Federal law has been recently recommended in *TRB Special Report 267* (*13*). A six-axle tractor-semitrailer would have a single tractor steering axle, a tandem tractor drive axle, and a tridem (triple) axle at the rear of the trailer. Although such a vehicle would be an important factor in pavement and bridge design, it would have little effect on geometric design because six-axle tractor semitrailers actually offtrack about 5 percent less than comparable five-axle tractor-semitrailers (*15*). Therefore, the possible wider use of six-axle tractor-semitrailer trucks does not constitute a reason to add a new Green Book design vehicle.

SINGLE-TRAILER COMBINATIONS (TRUCK/FULL TRAILER COMBINATIONS)

A truck/full trailer combination is created when an SU truck has a full trailer attached to it. Trucks pulling small to modest trailers (4.6 m [15 ft] to 6.1 m [20 ft]) are seen quite commonly in the United States. Conceivably, however, such a combination could include a long trailer and exhibit substantial offtracking (more than a tractor-semitrailer combination). In practice, however, such combinations are not used routinely, but rather as needed. SU trucks are not designed to routinely pull a large full trailer—their engines lack the horsepower of over-the-road tractors, and their drivers are usually not accustomed to driving them on a daily basis. The Green Book does not include a truck/full trailer combination as a design vehicle, and there does not appear to be any strong reason to add one.

DOUBLE-TRAILER TRUCKS

Tractor/Semitrailer/Full Trailer Combinations

The Green Book includes two double-trailer trucks as design vehicles. These are as follows:

- WB-20D [WB-67D] with "twin" 8.7-m [28.5-ft] trailers and
- WB-33D [WB-109D] with two 14.6-m [48-ft] trailers, known as a Turnpike Double.

Figures 13 and 14 illustrate their dimensions. Both double-trailer design vehicles represent combination trucks consisting of a tractor, coupled to a semitrailer, followed by a towed full trailer.

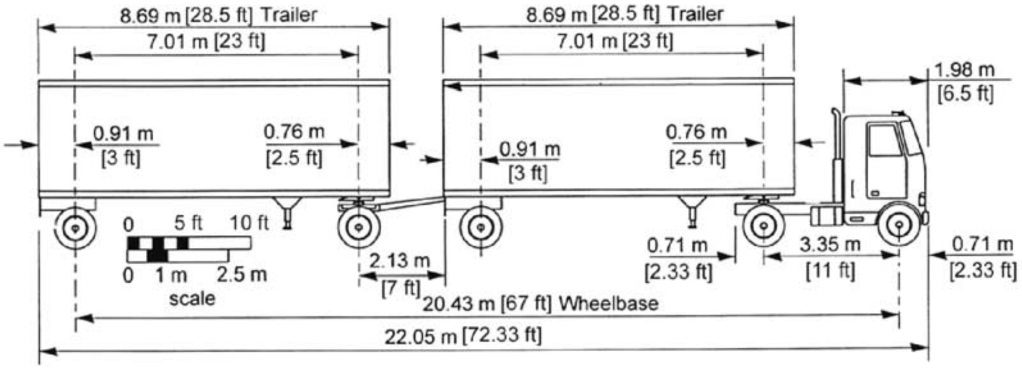


Figure 13. Dimensions of double-trailer combination (WB-20D [WB-67D]) design vehicle in current Green Book (1).

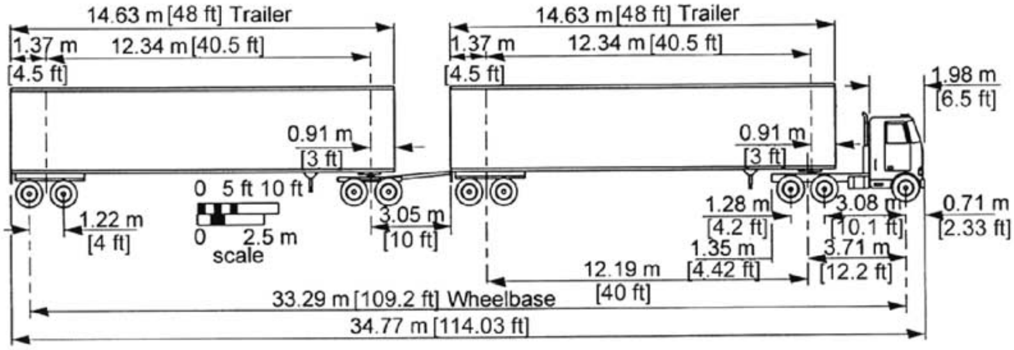


Figure 14. Dimensions of turnpike-double combination (WB-33D [WB-109D]) design vehicle in current Green Book (1).

The WB-20D [WB-67D] "twin-trailer" truck with two 8.7-m [28.5-ft] trailers has been permitted to operate freely on the NN since 1982 and has become a very common truck on intercity roads. It has smaller offtracking and swept path width than the 14.6-m [48-ft] and 16.2-m [53-ft] tractor-semitrailer combinations discussed above. An advantage of having two shorter trailers, rather than one larger trailer, for over-the-road operations, is that a tractor pulling a single 8.7-m [28.5-ft] trailer can serve as a highly maneuverable pick-up and delivery vehicle. The dimensions of the WB-20D [WB-67D] design vehicle are comparable with those used in the FHWA CTSW Study.

The circumstances in which the WB-20D [WB-67D] would be appropriate as a design vehicle are probably quite limited because it has less offtracking and swept path width than the WB-19 [WB-62] and WB-20 [WB-65 and WB-67] tractor-semitrailers that are more numerous and generally travel the same roads. However, it is recommended that the WB-20D [WB-67D] be retained as a design vehicle in the Green Book because it represents a maximum vehicle size limit specified in Federal law.

If the current LCV freeze were lifted, one vehicle that might possibly be legalized is a "twin trailer" truck with two 10.1-m [33-ft] trailers. TRB Special Report 267 (*13*) recently recommended that Federal law be changed to allow such trucks to operate under state permits. It is not recommended that a design vehicle with two 10.1-m [33-ft] trailers be included in the Green Book at this time, but an appropriate design vehicle has been developed for consideration, should such trucks be permitted and become common in the future. This design vehicle for possible future use is designated as the WB-23D [WB-77D] and is illustrated in Figure 15.

The WB-33D [WB-109D] or Turnpike Double design vehicle consists of a truck with two 14.6-m [48-ft] trailers. This design vehicle acquired its name because it was first permitted to operate on a number of Eastern toll roads and turnpikes. Turnpike Doubles generally operate only under permit on specific roadways approved for their use. The situations in which a Turnpike Double is the appropriate design vehicle are typically quite limited because Turnpike Doubles are often made up and broken down at staging areas at the entrances to or exits from specific highway facilities; they do not typically operate beyond that point onto the local road system. Situations in which a Turnpike Double might be expected to make a right or left turn at an at-grade intersection are relatively rare. However, for those roadways where Turnpike Doubles operate in substantial numbers, they may be an appropriate design vehicle because they will almost certainly be the largest and least maneuverable vehicle on the road.

The dimensions of the Turnpike Double combination are reasonable, except that the Green Book uses a cab-over tractor with a 3.7-m [12-ft] wheelbase. A conventional tractor with a larger wheelbase—4.9 m [16 ft] or more—would probably be more realistic. However, the effect of the larger tractor on offtracking would be minimal, and it is not recommended that any change in the WB-33D [WB-109D] design vehicle be made at this time.

If the current LCV freeze were lifted, there might be interest in the trucking industry for use of a Turnpike Double truck with two 16.2-m [53-ft] trailers. The trucking industry might find it economically advantageous to use such trucks to move low-density commodities because so many 16.2-m [53-ft] trailers are currently in use in single tractor-semitrailer combinations. However, it is far from certain whether such trucks would be permitted to operate by states, even if allowed by Federal law, because such trucks would offtrack more than even the Turnpike Double with 14.6-m [48-ft] trailers. The Turnpike Double with 16.2-m [53-ft] trailers cannot make

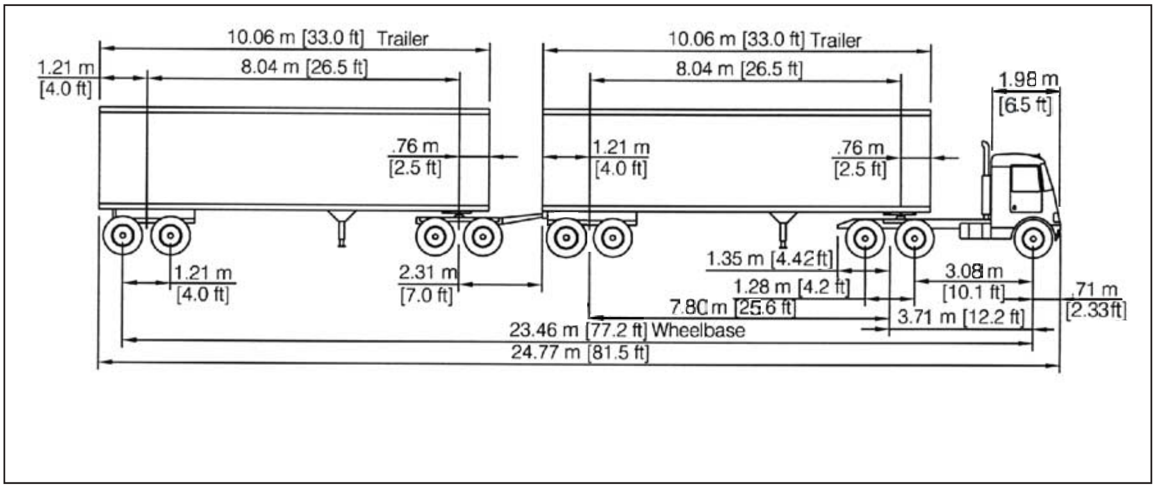


Figure 15. Dimension of double-trailer combination (WB-23D [WB-77D]) design vehicle for possible future use.

a 90-deg right turn with a 22.9-m [75-ft] radius, while a Turnpike Double with 14.6-m [48-ft] trailers can. It is not recommended that a design vehicle with two 16.2-m [53-ft] trailers be included in the Green Book at this time, but an appropriate design vehicle has been developed for future consideration, should such trucks be permitted and become common in the future. This design vehicle for possible future use is designated as the WB-37D [WB-120D] and is illustrated in Figure 16.

In addition to the twin- or double-trailer truck and the Turnpike Double truck in the Green Book, there is another combination, the Rocky Mountain Double, that is also fairly common. It appears as a cross between twin-trailer and Turnpike Double trucks, combining a longer semitrailer and a shorter full trailer. A typical Rocky Mountain Double combination has a 14.6-m [48-ft] semitrailer followed by an 8.7-m [28.5-ft] full trailer. Rocky Mountain Doubles currently operate in 20 states (mostly in the western United States), including 3 states where Turnpike Doubles are not permitted and 6 states where triples are not permitted.

In these states, Rocky Mountain Doubles may offtrack more than any other relatively common truck type. Therefore, a Rocky Mountain Double design vehicle is recommended for inclusion in the Green Book for potential application by state highway agencies that need it. The Rocky Mountain Double is designated the WB-28D [WB-92D] design vehicle. The recommended design vehicle has nine axles and an overall length of 30.0 m [98.3 ft] as shown in Figure 17.

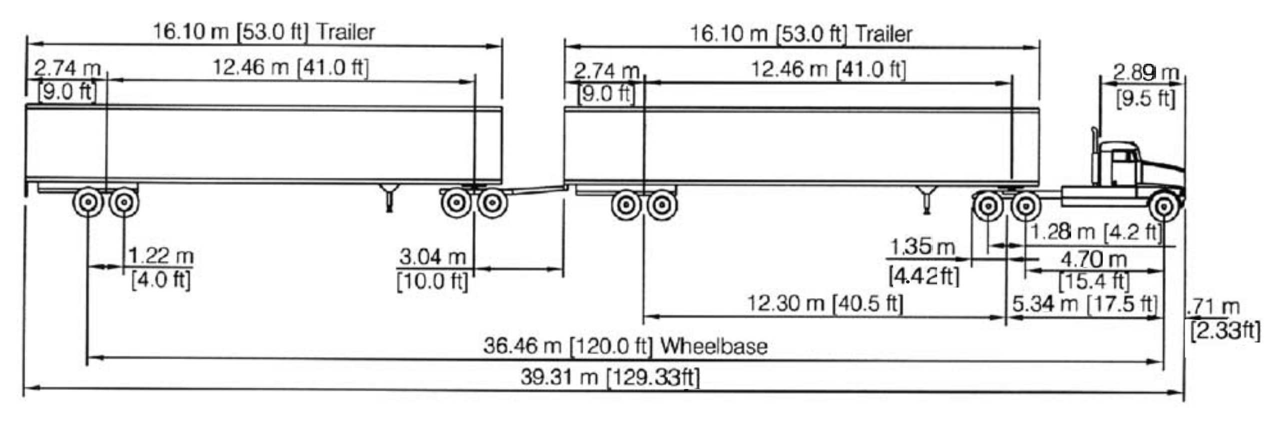


Figure 16. Dimensions of larger Turnpike Double combination (WB-37D [WB-120D]) design vehicle for possible future use.

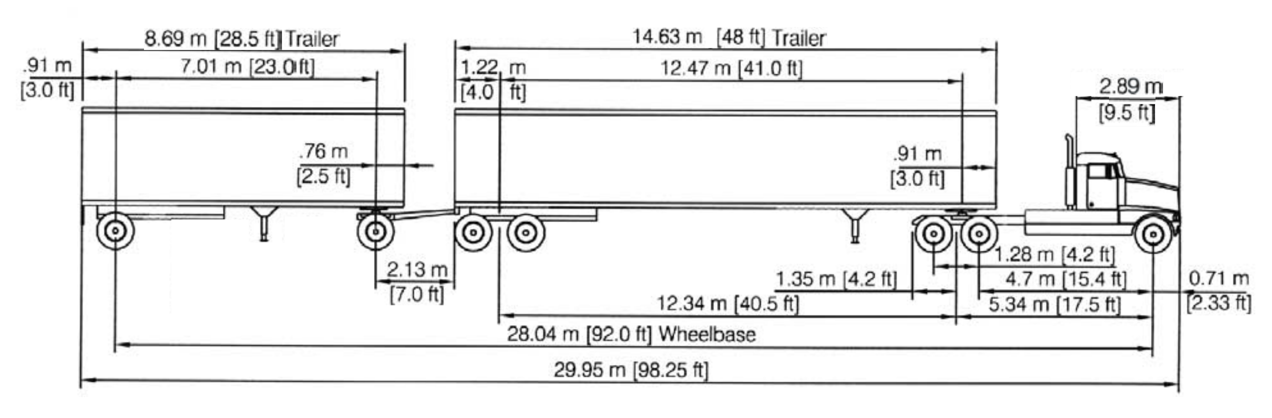


Figure 17. Recommended dimensions of Rocky Mountain Double combination (WB-28D [WB-92D]) design vehicle.

Tractor/Semitrailer/Semitrailer Combinations (B-Trains)

B-Train double-trailer trucks are fairly common in Canada and are used to some extent in some of the northern tier of the United States. B-Train doubles are also operating under permit between Monterey, Mexico, and Brownsville, Texas. A B-Train has a hitching mechanism that differs from the common double trailers seen in the United States. The hitch of the U.S. double trailer is typically referred to as an A-hitch. It is essentially a tow bar, fastened at one end to the dolly under the front of the full trailer being towed by the first trailer and at the other end by an eye which is hooked over a pintle hook attached to the first trailer. The second trailer of a B-Train is connected to the first by a fifth-wheel arrangement mounted on a dolly, which protrudes from the rear of the first trailer. Thus, the rear trailer in a B-Train double is a semitrailer rather than a full trailer.

B-Trains are heavier than their twin-trailer counterparts. Having one less articulation point, B-Trains offtrack slightly more than the U.S. twin-trailers, but are more easily backed up. Most importantly, however, they can carry heavier loads (with their extra axles), so are used for bulk and other types of loads that are particularly heavy. (In the United States, therefore, they are only used in areas where heavier loads are legal.)

There is no design vehicle in the Green Book corresponding to the B-Train, and because of its limited use in the United States, there is no compelling reason to add it at this time. However, a potential B-Train design vehicle is presented in Figure 18 should future changes in U.S. truck size and weight laws encourage its use. The B-Train is designated the WB-23BD [WB-75BD] design vehicle. Its dimensions are based on a current Canadian design vehicle (*16*), but might need to be adapted for future U.S. application, depending on which configurations become most common in the United States.

TRIPLE-TRAILER TRUCKS

The Green Book includes one triple-trailer truck as a design vehicle. This is the WB-30T [WB-100T] with three 8.7-m [28.5-ft] trailers—one semitrailer and two full trailers. Figure 19 shows the dimensions for this design vehicle.

The WB-30T [WB-100T] is representative of the most common triple-trailer combination on the road today. Larger triple-trailer combinations are not generally permitted, so the WB-30T [WB-100T] is an appropriate design vehicle, and no changes in this design vehicle are recommended.

SUMMARY OF DESIGN VEHICLE RECOMMENDATIONS

The following changes in or additions to the Green Book design vehicles are recommended.

Single-Unit Trucks

- The current two-axle SU design vehicle should be retained and designated the SU-30 design vehicle.
- A longer three-axle SU design vehicle should be added and designated the SU-8 [SU-25] design vehicle.

Single-Trailer Combinations (Five-Axle Tractor-Semitrailers)

- The WB-12 [WB-40] should be retained for application to container trucks and local pickup and delivery operations.
- The WB-15 [WB-50] is no longer common and should be dropped.

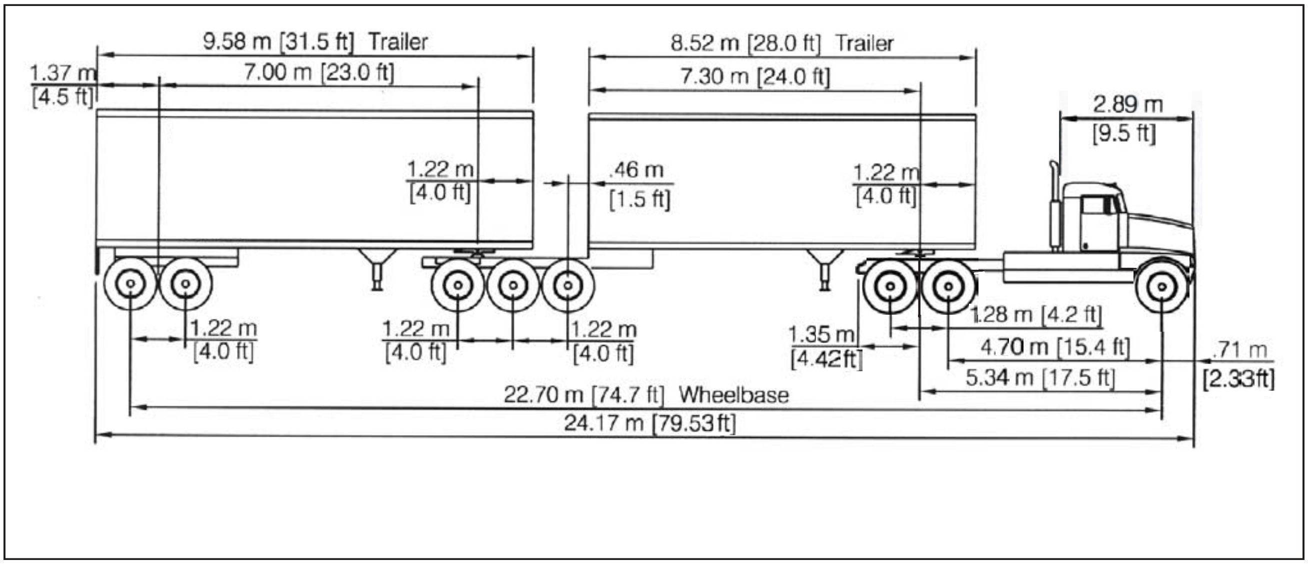


Figure 18. Dimension of B-Train double combination (WB-23BD [WB-75BD]) for possible future use.

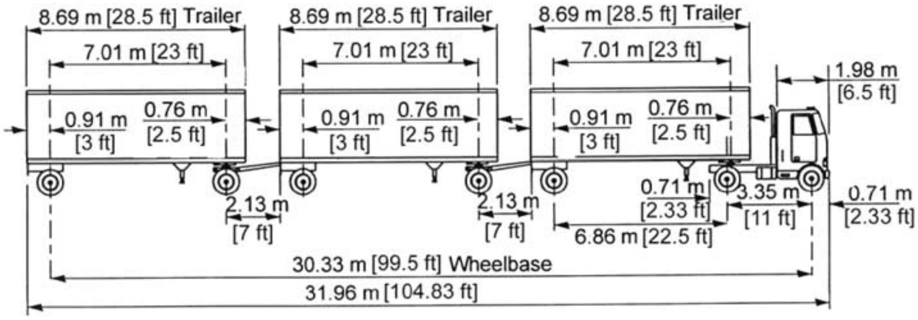


Figure 19. Dimensions of triple-trailer combination (WB-30T [WB-100T]) design vehicle in current Green Book (1).

- The WB-19 [WB-62] design vehicle represents a truck configuration specified in Federal law and should be retained. The KCRT distance for this design vehicle should be increased from 12.3 to 12.5 m [40.5 to 41 ft] to correspond to the maximum limits applicable in 19 states. The WB-19 [WB-62] design vehicle should be used for design of offtracking and swept path width for all longer tractor-semitrailer combinations that are configured with a 12.5-m [41-ft] maximum kingpin-to-center-of-rear-axle-set distance.
- The WB-20 [WB-65] design vehicle represents an “in between” axle placement that is neither a best nor a worst case for design. This design vehicle should be dropped.
- The WB-20 [WB-67] design vehicle should be retained, but the KCRT distance should be increased from 13.3 to 13.9 m [43.5 to 45.5 ft] to represent a “worst case” condition.
- A tractor-semitrailer design vehicle with a trailer length greater than 16.2 m [53 ft] is not needed at this time. However, a WB-22 [WB-71] design vehicle has been developed for future application should such a truck become more common.

Single-Trailer Combinations (Six-Axle Trailer-Semitrailer)

- No six-axle tractor-semitrailer design vehicle is needed because such trucks are not common at present and because a six-axle tractor-semitrailer is not a critical design consideration because it would offtrack less than a comparable five-axle tractor-semitrailer.

Double-Trailer Trucks

- The WB-20D [WB-67D] design vehicle with two 8.7-m [28.5-ft] trailers should be retained because it represents a truck configuration specified in Federal law.
- A twin-trailer truck with two 10.1-m [33-ft] trailers is not needed at this time but might become more common if Federal law permitted such a truck to operate at gross vehicle weights over 36,400 kg [80,000 lb]. A WB-23D [WB-77D] design vehicle has been developed for potential future application should such a truck become more common.
- The Turnpike Double design vehicle with two 14.6-m [48-ft] trailers, known as the WB-33D [WB-109D] design vehicle, should be retained.
- A Turnpike Double design vehicle with two 16.2-m [53-ft] trailers is not needed at this time. However, a WB-37D [WB-120D] design vehicle has been developed for future application should such a truck become common.
- A Rocky Mountain Double design vehicle with a 14.6-m [48-ft] semitrailer and a 8.7-m [28.5-ft] full trailer currently operates under permit in 20 states. The addition of a Rocky Mountain Double WB-30D [WB-92D] design vehicle is recommended.
- A B-Train double design vehicle is not needed at this time. However, a B-Train WB-23BD [WB-75BD] design vehicle has been developed for future application should this truck become more common.

Triple-Trailer Trucks

- The current triple-trailer WB-30T [WB-100T] design vehicle with three 8.7-m [28.5-ft] trailers should be retained.

CHAPTER 5

TRUCK CHARACTERISTICS RELATED TO GEOMETRIC DESIGN

This chapter reviews the available data on truck characteristics that should be considered in the development of highway design and operational criteria. The review of truck characteristics is based primarily on data from existing sources in published and unpublished literature.

The review focuses primarily on the characteristics of the current truck population. The effects of recent trends in trucking and recent legislative changes are accounted for whenever possible.

This review of truck characteristics provides the basic data used in Chapter 6 to consider the highway design and operational criteria that would be suitable to accommodate trucks. Thus, the review is selective, rather than exhaustive; it focuses on the data needed for the analyses in Chapter 6. For example, some frequently discussed truck safety issues, such as rearward amplification in emergency steering maneuvers by multitrailer combinations, are addressed only briefly because they have no clear implications for highway design and operational criteria. Many such truck safety issues are more in the realm of truck policy and vehicle design than geometric design.

More complete reviews of many specific truck characteristics can be found in the references cited. In particular, the National Highway Traffic Safety Administration (NHTSA) report, *Heavy Truck Safety Study* (*17*), provides an excellent overview of many truck design issues, and another NHTSA report, *A Factbook of the Mechanical Properties of the Components for Single-Unit and Articulated Heavy Trucks* (*18*), provides the most detailed available data on the ranges of specific truck characteristics. Some of the material in these sources is updated in NCHRP Synthesis 241, *Truck Operating Characteristics* (*19*). This section is similar in form to comparable material presented in the FHWA *Truck Characteristics* study (*2*,*3*), but has been updated, as appropriate, to describe the current truck fleet.

The truck characteristics reviewed in this chapter include the following:

- Turning radius,
- Offtracking and swept path width,
- Trailer swingout,
- Braking distance,
- Driver eye height,
- Acceleration characteristics,
- Speed-maintenance capabilities on grades,
- Vehicle length,
- Vehicle height,
- Rearward amplification,
- Suspension characteristics,
- Load transfer ratio, and
- Rollover threshold.

The lengths of trucks, their configurations, their weights, and recommended design vehicle configurations have been addressed in preceding chapters.

TURNING RADIUS

The minimum turning radius of a truck is defined as the path of the outer front wheel, following a circular arc at a very low speed, and is limited by the vehicle steering mechanism. Parameters such as weight, weight distribution, and suspension characteristics have a negligible role in turns at very low speeds (e.g., less than 16 km/h [10 mph]). The dimensions and turning radii of the current and recommended Green Book design vehicles are presented in Chapter 4 of this report.

OFFTRACKING AND SWEPT PATH WIDTH

There are two types of offtracking, referred to as low-speed and high-speed offtracking. Low-speed offtracking occurs as vehicles traveling at very low speed make a turn; in low-speed offtracking, the weight, weight distribution, suspension characteristics, and other vehicle-dynamic parameters are negligible factors in the amount of offtracking that occurs. High-speed offtracking, as its name implies, incorporates dynamic effects and is more pronounced the higher the speed. Each type of offtracking is discussed below.

Low-Speed Offtracking

A train travels on tracks and, thus, its rear wheels precisely follow the paths of the front wheels. With vehicles that are not on tracks, such as bicycles, automobiles, and trucks, the rear wheels do not follow the front ones. During turning at low speeds, the front wheels try to drag the rear ones toward them and across the inside of the curve. The magnitude of this phenomenon is small for bicycles and automobiles and is usually ignored. For trucks, however, it can be substantial and is an important factor in the design of intersections, ramps, and other highway elements.

There are two commonly used descriptors of offtracking: one is the *offtracking amount*, defined as the radial offset between the path of the centerline of the front axle and the path of the centerline of a following axle shown in Figure 20; the other, and more important descriptor for use in highway design, is the *swept path width*, shown for a tractor-semitrailer in Figure 21 as the difference in paths between the outside front tractor tire and the inside rear trailer tire.

Offtracking increases gradually as a vehicle proceeds through a turning maneuver. This developing offtracking is termed partially-developed offtracking (sometimes referred to in the literature as nonsteady-state offtracking or transient offtracking). As the vehicle continues to move in a constant radius curve, the offtracking eventually reaches what is termed its fully-developed offtracking value (sometimes referred to in the literature as steady-state offtracking or, misleadingly, as maximum offtracking). Each is discussed more fully in the following paragraphs.

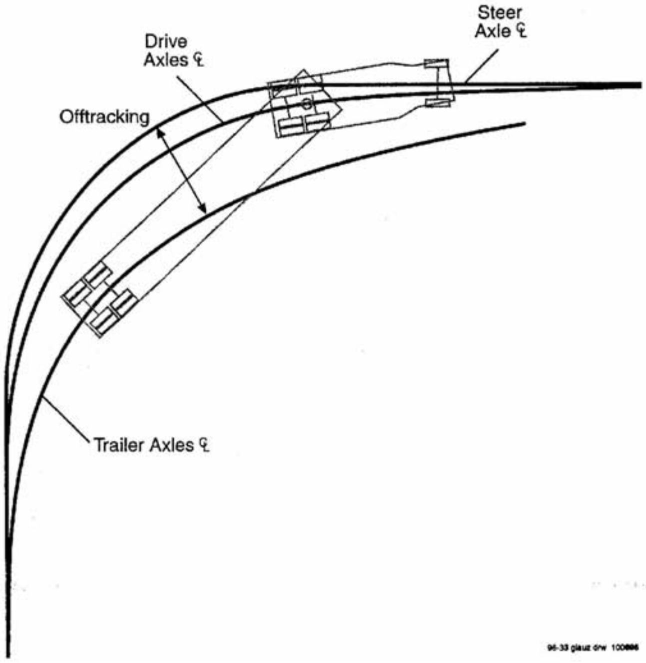


Figure 20. Illustration of truck offtracking.

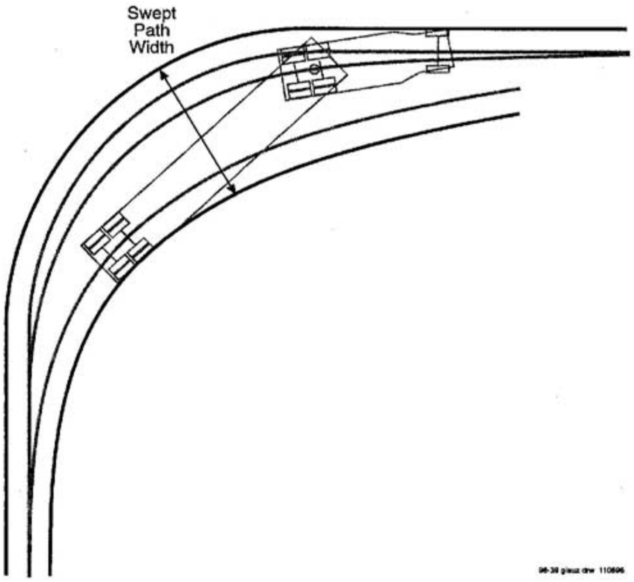


Figure 21. Illustration of swept path width.

Fully-Developed Offtracking

On longer radius turns, such as typical horizontal curves on highways or ramps, fully-developed offtracking is usually reached; once this value is attained, offtracking does not increase further as the vehicle continues around the curve. Fully-developed offtracking is considered in the geometric design of horizontal curves, especially on two-lane roads, in determining whether the roadway needs to be wider on the curve than on the normal tangent cross section. Similarly, it is considered in the design of freeway ramps. Even though such facilities are designed primarily for highway speeds (or near-highway speeds), where low-speed offtracking should not be a factor, consideration is also given to situations such as congestion, where vehicles are forced to travel at low speeds.

In performing offtracking calculations, certain equations are applied consecutively to the distances between adjacent pairs of axles or hinge points. The contribution to offtracking of each inter-axle distance is roughly proportional to the square of that distance. Thus, the dominant term for the offtracking of most tractor-semitrailers is the so-called kingpin-to-rear-axle dimension, the largest distance.

The offtracking of a vehicle with two axles, for example, may be approximated, using the Pythagorean Theorem (see Woodroofe et al. (*20*), for example) as

$$\mathrm{OT} = -\mathrm{R} + \sqrt{(\mathrm{R}^2 - \ell^2)} \qquad (1)$$

where ℓ is the distance between the two axles, R is the radius of the curve, and negative offtracking implies tracking inward toward the center of the arc. If $\ell << \mathrm{R}$, then this may be reduced to the simpler form $-0.5(\ell^2/\mathrm{R})$, which is the often used Western Highway Institute formula (*21*). Equation 1 is sufficiently accurate for most purposes, but additional effects of multiple axles (e.g., tandems and tridems), roadway superelevation, and body roll may also be included (see Glauz and Harwood (*22*)). (This formulation also assumes $\ell << \mathrm{R}$.)

As noted above, Equation 1, or its equivalent, is applied consecutively to each pair of axles or hinge points of the truck; each application gives the offtracking of the center of the following axle or hinge point relative to the center of its leader. These computed offtracking amounts are additive, except that the sign of the contribution from the center of the drive axles to the kingpin is reversed if the kingpin is moved forward (the usual case), as is the contribution from the drive axles to the pintle hook of the first trailer in a doubles combination (which swings outward rather than tracking inward).

Partially-Developed Offtracking

Partially-developed offtracking is of concern where trucks traverse shorter curves or, more importantly, curves of smaller radius. Partially-developed offtracking is of particular interest as it affects the design of intersections or other locations where vehicles are required to turn rather sharply.

In contrast to fully-developed offtracking, partially-developed offtracking cannot be determined from solving a simple equation, even for the case where the tractor travels on a simple circular path. Early attempts to estimate this type of offtracking were made using a mechanical device called a Tractrix integrator, basically a simple scale model of the truck in question. In the early 1980s, computer programs to compute offtracking and swept path width for any specified truck configuration began to be developed (*23*,*24*,*25*). A commercially available software package, known as AutoTURN, is now commonly used by highway agencies to determine partially-developed offtracking. All such computer programs operate by moving the front axle of a specified vehicle forward in small steps or increments along a specified path and then computing the resulting location of the rear axle(s).

Table 23 presents the maximum low-speed offtracking and swept path width in 90-deg turns of varying radii for selected design vehicles, including design vehicles from the 2001 *Green Book* and the proposed new or revised design vehicles presented in Chapter 4. The derivation of these offtracking and swept path width values is described in Appendix C.

The FHWA *Truck Characteristics* study (*2*,*3*) found, and the data in Table 23 developed in this research confirm, that the swept path widths for trucks the size of the WB-19 [WB-62] or larger are so great that the truck cannot make a 90-deg right turn from one two-lane road to another while remaining within a 3.6-m [12-ft] lane for turning radii of 23 m [75 ft] or less. Trucks making such turns at locations with curb return radii less than 23 m [75 ft] must either encroach on the roadway shoulder (or curbline) or on an opposing lane. This observation is borne out by the truck turning observations presented in the next section. On a turn between multilane roads, trucks with sizes up to the WB-23BD [WB-77BD] can make a 90-deg right turn while encroaching on an adjacent same-direction lane, but without encroaching on an opposing lane. Trucks with sizes greater than or equal to the WB-30D [WB-92D] are not physically capable of making a 90-deg right turn with a radius of 23 m [75 ft] or less.

Observed Low-Speed Offtracking

The above discussion of offtracking makes use of mathematical models. Although drivers may approximate those

TABLE 23 Maximum low-speed offtracking and swept path width for selected design vehicles in 90-degree turns

		Maximum offtracking (ft) for specified turn radius				Maximum swept path width (ft) for specified turn radius			
Design vehicle type	Symbol	50 ft	75 ft	100 ft	150 ft	50 ft	75 ft	100 ft	150 ft
Single-unit truck	SU	3.8	2.7	1.8	1.1	11.8	10.7	9.8	9.1
Single-unit truck (three-axle)	SU25	6.1	4.3	3.2	2.1	14.1	12.3	11.2	10.1
Interstate semitrailer	WB-62	16.8	12.8	10.1	6.9	25.0	21.1	18.4	15.1
Interstate semitrailer (revised)[a]	WB-62	17.0	13.1	10.3	7.0	25.3	21.3	18.6	15.3
Interstate semitrailer	WB-67	19.4	15.	12.1	8.3	27.6	23.4	20.3	16.6
Interstate semitrailer[b]	WB-67 (41-ft KCRT)	17.0	13.1	10.3	7.0	25.3	21.3	18.6	15.3
Long interstate semitrailer	WB-71	21.5	17.0	13.8	9.6	29.8	25.3	22.0	17.9
Long interstate semitrailer[c]	WB-71 (41-ft KCRT)	17.0	13.1	10.3	7.0	25.3	21.3	18.6	15.3
"Double-bottom"-semitrailer/trailer	WB-67D	11.5	8.3	6.3	4.2	19.7	16.6	14.6	12.5
Longer "double-bottom"-semitrailer/trailer	WB-77D	14.2	10.6	8.2	5.5	22.4	18.8	16.4	13.7
B-train double-semitrailer/semitrailer	WB-77BD	15.6	11.7	9.1	6.1	23.9	20.0	17.4	14.4
Rocky mountain double-semitrailer/trailer	WB-92D	–	–	12.7	8.7	–	–	21.0	17.0
Turnpike double-semitrailer/trailer	WB-109D	–	–	17.1	12.0	–	–	25.3	19.2
Long turnpike double-semitrailer/trailer	WB-120D	–	–	17.9	12.6	–	–	26.1	20.8

[a] Proposed revision to WB-62 design vehicle; KCRT distance increased from 40.5 to 41.0 ft.

[b] WB-67 design vehicle with axles pulled forward to obtain 41.0-ft KCRT distance.

[c] WB-71 design vehicle with axles pulled forward to obtain 41.0-ft KCRT distance.

findings, in reality there is a fair amount of dispersion in the actual paths used. DeCabooter and Solberg obtained actual offtracking paths for a number of intersections in Wisconsin *(26)*. The data were obtained using several synchronized cameras, whose photos were later analyzed and the actual paths determined by phototriangulation.

Figure 22 illustrates the results found. Although most drivers approached the intersection with the left front tire on the centerline, some were in the opposing lane. The position where they began their turns varied somewhat. And, at this particular intersection, most intruded into the opposing lane of the target intersection, and a few mounted the curb.

High-Speed Offtracking

When a vehicle moves through a curve at higher speed, the rear axles of the vehicle tend to move outward. This tendency to move outward is called high-speed offtracking. It acts in the opposite direction to low-speed offtracking, so the two phenomena tend to counteract each other. At lower speeds, low-speed offtracking predominates; as the speed increases, the net offtracking is reduced. At sufficiently high speeds, the two phenomena exactly cancel, resulting in no net offtracking, and at still higher speeds the net result is that the rear of the vehicle tracks outside of the front.

The quantification of fully-developed high-speed offtracking was initially modeled by Bernard and Vanderploeg *(27)*, and their model was later expanded by Glauz and Harwood *(22)*. The model includes the fully-developed low-speed offtracking terms discussed above, plus a speed-dependent portion, which is the high-speed contribution. It is proportional to the axle spacing, P, not to its square as is the case with low-speed offtracking. It is, however, proportional to the square of the truck speed and increases with decreasing path radius. In practice, net outward offtracking, due to the high-speed term becoming dominant, does not occur until speeds reach the neighborhood of 89 km/h [55 mph], for example, on highway entrance or exit ramps. Net outward offtracking rarely exceeds 0.6 m [2.0 ft].

Because net high-speed offtracking is usually not a significant factor in roadway design, compared with low-speed offtracking, its transient or partially-developed form has not been studied.

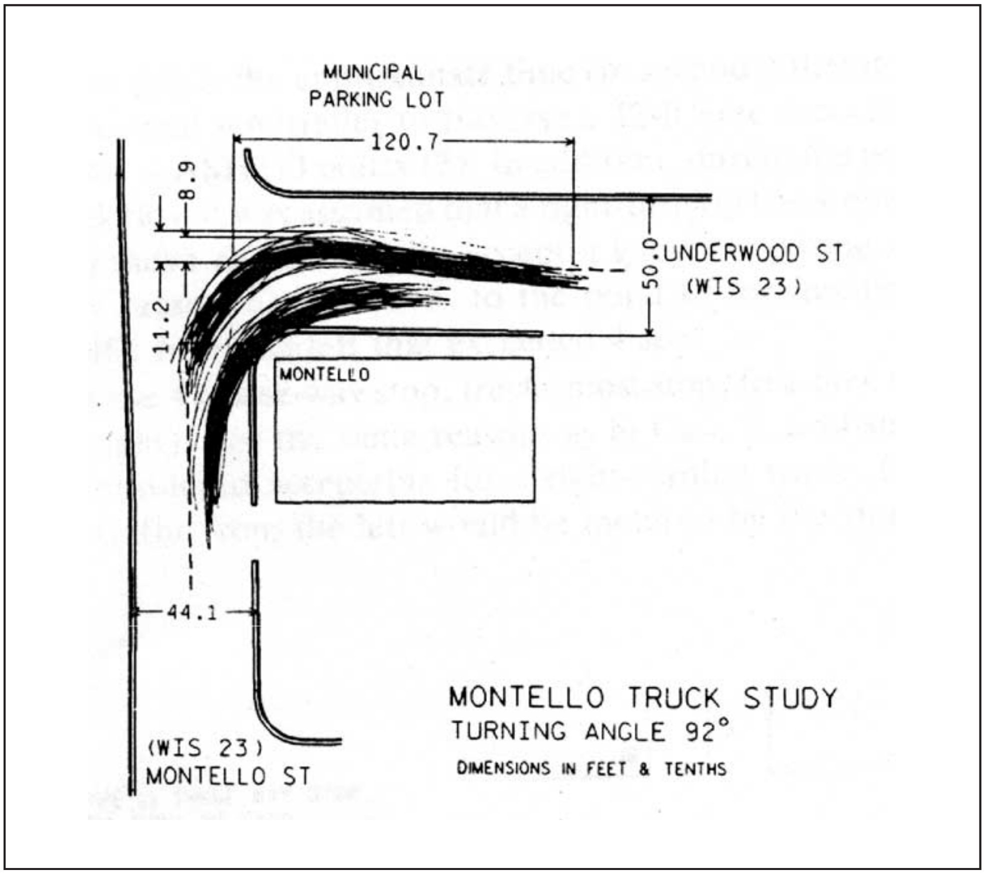


Figure 22. Observed wheelpaths for combination trucks turning right at an intersection in Montello, Wisconsin (26).

TRAILER SWINGOUT

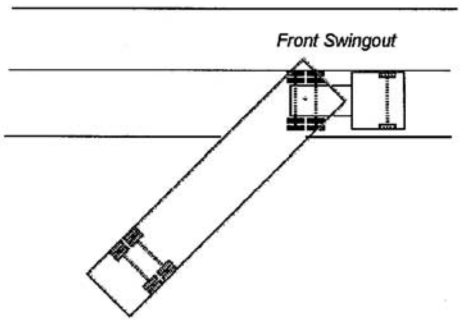
The front of a trailer is generally ahead of the front axles that support the trailer. Similarly, the rear of a trailer generally overhangs the rear axles. As a result, during a turn the front of the trailer swings to the outside of the front trailer axles (front swingout) and the rear of the trailer swings to the outside of the rear axles (rear swingout). Front and rear swingout are illustrated in Figure 23.

Swingout is (1) a function of the trailer wheelbases and other dimensions and the radius of the turn and (2) can be quantified using a modification of the low-speed offtracking programs discussed above.

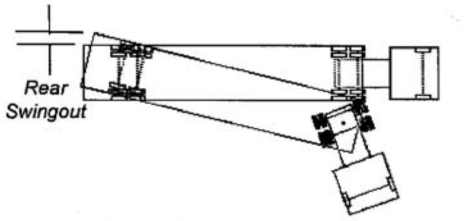
On some trailers, the consequences of front swingout are reduced by beveling or rounding the front of the trailer. Nevertheless, in practical trailer configurations, the front overhang of a trailer is only of the order of 1 m [3 ft], and front swingout persists for only a few seconds during a turn. Moreover, it is clearly visible to, and thus under the control of, the driver. For these reasons, drafters of NAFTA IAN standards have suggested a fairly liberal limitation of no more than 0.45-m [18-in] front swingout in a 90-deg turn of 14.0 m [45.9 ft].

On the other hand, rear overhang can be substantial. For example, with a 16.2-m [53-ft] semitrailer with the rear axles moved forward to satisfy a 12.5-m [41-ft] king-pin-to-rear-axle limitation, the rear overhang is typically 2.7 m [9 ft]. Although rear swingout is not as pronounced as front swingout due to the geometrics involved, it can persist for much longer periods of time during a turn and is out of view of the driver. For these reasons, the drafters of the NAFTA IAN criteria have suggested a limitation of no more than 0.2 m [8 in] of rear swingout in a 90-deg turn of 14.0-m [45.9-ft] radius.

Table 24 shows the maximum rear swingout in 90-deg turns for varying radii for selected design vehicles, including design vehicles from the 2001 Green Book and the proposed new or revised design vehicles presented in Chapter 4. The derivation of these maximum rear swingout values is described in Appendix C.



Front Swingout



Rear Swingout

Figure 23. Illustration of front and rear swingout for a tractor-trailer combination making a turn (8).

The results for 15.3-m [50-ft] turns in Table 24 indicate that most of the current and proposed Green Book design vehicles are well within the proposed NAFTA IAN criteria, with two exceptions. First, the WB-20 [WB-67] design vehicle very slightly exceeds the IAN criteria if the axles are pulled forward to obtain a 12.5-m [41-ft] KCRT distance; the modeled value is so close to the IAN criterion that it may be within the margin of error. The WB-22 [WB-71] design vehicle is in

TABLE 24 Maximum rear swingout for selected design vehicles in 90 degree turns

Design vehicle type	Symbol	Maximum rear swingout (ft) for specified turn radius			
		50 ft	75 ft	100 ft	150 ft
Single-unit truck	SU	0.35	0.24	0.18	0.12
Single-unit truck (three-axle)	SU25	1.07	0.73	0.53	0.35
Interstate semitrailer	WB-62	0.18	0.14	0.09	0.06
Interstate semitrailer (revised)[a]	WB-62	0.17	0.13	0.09	0.06
Interstate semitrailer	WB-67	0.17	0.14	0.10	0.07
Interstate semitrailer[b]	WB-67 (41-ft KCRT)	0.69	0.51	0.41	0.27
Long interstate semitrailer	WB-71	0.17	0.13	0.10	0.07
Long interstate semitrailer[c]	WB-71 (41-ft KCRT)	1.45	1.08	0.84	0.61
“Double-bottom”-semitrailer/trailer	WB-67D	0.08	0.05	0.05	0.03
Longer “double-bottom”-semitrailer/trailer	WB-77D	0.13	0.11	0.08	0.06
B-train double-semitrailer/semitrailer	WB-77BD	0.17	0.12	0.10	0.07
Rocky mountain double-semitrailer/trailer	WB-92D	–	–	0.05	0.04
Turnpike double-semitrailer/trailer	WB-109D	–	–	0.09	0.06
Long turnpike double-semitrailer/trailer	WB-120D	–	–	0.37	0.27

[a] Proposed revision to WB-62 design vehicle; KCRT distance increased from 40.5 to 41.0 ft.
[b] WB-67 design vehicle with axles pulled forward to obtain 41.0-ft KCRT distance.
[c] WB-71 design vehicle with axles pulled forward to obtain 41.0-ft KCRT distance.

compliance with the IAN criterion if the rear axles are pushed back close to the rear of the trailer, but this design vehicle is substantially out of compliance if the rear axles are pulled forward to obtain a 12.5-m [41-ft] KCRT distance. Thus, it is not possible for the possible future WB-22 [WB-71] to simultaneously satisfy the IAN rear swingout criterion and the KCRT limitations of many states.

It is important to recognize that rear swingout, like low-speed offtracking, grows as the truck proceeds through a turn. Although the outside rear corner of the trailer follows a path outside of the rear trailer wheels, it is inside of the swept path. The outside of the swept path is determined by the outside front wheel of the tractor and not by the trailer wheels. This phenomenon is illustrated by Figure C-23 in Appendix C. This finding suggests that rear swingout is rarely a concern to other vehicles, unless they are making a parallel turn.

BRAKING DISTANCE

Braking distance is defined in the Green Book as "the distance needed to stop the vehicle from the instant brake application begins." Braking distance is used in the determination of many highway design and operational criteria, including stopping sight distance, vehicle change intervals for traffic signals, and advance warning sign placement distances. Currently, all of these design and operational criteria are based on passenger car braking distances and do not consider the longer braking distances required for trucks. The process of bringing a truck to a stop requires a complex interaction between the driver, the brake system, the truck tires, the dimensions and loading characteristics of the truck, and the pavement surface characteristics. Because truck braking is much more complex than passenger car braking, it is necessary to discuss how each of these characteristics affects truck braking distances.

Tire-Pavement Friction in Braking Maneuvers

Vehicles are brought to a stop by brakes that retard the rotation of the wheels and allow tire-pavement friction forces to decelerate the vehicle. An understanding of the forces involved in tire-pavement friction is, therefore, critical to the understanding of braking distances.

For a horizontal pavement, the coefficient of braking friction (f_y) is defined as the ratio of the horizontal braking force (F_y) generated at the tire-pavement interface to the vertical load (F_z) carried by the tire. In other words

$$f_y = \frac{F_y}{F_z} \tag{2}$$

Side forces, or "cornering forces," can interact with the braking force and affect the ability to stop a vehicle in a controlled manner. If a vehicle is being steered to follow a curved path, tire-pavement friction supplies a cornering force, tending to keep the vehicle from departing its intended path. The coefficient of cornering friction (f_x) is the ratio of the cornering force (F_x) generated at the tire-pavement interface to the vertical load (F_z) carried by the tire. In other words

$$f_x = \frac{F_x}{F_z} \tag{3}$$

Figure 24 illustrates that both braking and cornering friction vary as a function of percent slip, which is the percent decrease in the angular velocity of a wheel relative to the pavement surface as a vehicle undergoes braking. A freely rolling wheel is operating at zero percent slip. A locked wheel is operating at 100 percent slip with the tire sliding across the pavement. Figure 24 shows that the coefficient of braking friction increases rapidly with percent slip to a peak

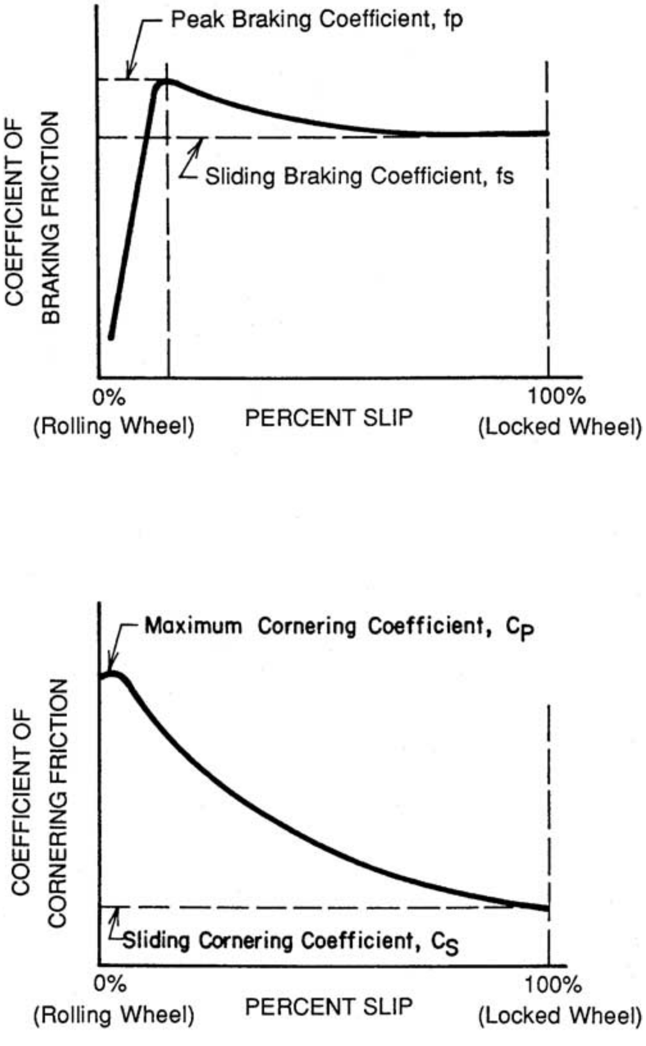


Figure 24. Variation of braking and cornering friction coefficients with percent slip.

value that typically occurs between 10 and 15 percent slip. The coefficient of braking friction then decreases as percent slip increases, reaching a level known as the coefficient of sliding friction at 100 percent slip.

The coefficient of cornering friction has its maximum value at zero percent slip and decreases to a minimum at 100 percent slip. Thus, when a braking vehicle locks its wheels, it may lose its steering capability due to a lack of cornering friction.

Locked-Wheel Braking Versus Controlled Braking

The discussion of Figure 24 implies that braking maneuvers can be performed in two general modes: locked-wheel braking and controlled braking. Locked-wheel braking occurs when the brakes grip the wheels tightly enough to cause them to stop rotating, or "lock," before the vehicle has come to a stop. Braking in this mode causes the vehicle to slide or skid over the pavement surface on its tires. Locked-wheel braking uses sliding friction (100 percent slip) represented by the right end of the graph in Figure 24, rather than rolling or peak friction. The sliding coefficient of friction takes advantage of most of the friction available from the pavement surface, but is generally less than the peak available friction. On dry pavements, the peak coefficient of friction is relatively high with very little decrease in friction at 100 percent slip. On wet pavements, the peak friction is lower, and the decrease in friction at 100 percent slip is generally larger.

The braking distance required for a vehicle to make a locked-wheel stop can be determined from the following relationship:

$$BD = \frac{V^2}{30f_s} \tag{4}$$

where

BD = braking distance (ft)
V = initial speed (mph)
f_s = coefficient of sliding friction

The coefficient of sliding friction in Equation 4 is mathematically equivalent to the deceleration rate used by the vehicle expressed as a fraction of the acceleration of gravity (g), equal to 9.8 m/s^2 [32.2 ft/s^2]. The coefficient of friction and, thus, the deceleration rate may vary as a function of speed during the stop, so f_s in Equation 4 should be understood as the average coefficient of friction or deceleration rate during the stop.

Controlled braking is the application of the brakes in such a way that the wheels continue to roll without locking up while the vehicle is decelerating. Drivers of vehicles with conventional brakes generally achieve controlled braking by "modulating" the brake pedal to vary the braking force and to avoid locking the wheels. Controlled braking distances are governed by the rolling coefficient of friction, which, for a typical vehicle, occurs at a value of percent slip to the left of the peak available friction shown in Figure 24. Due to the steep slope of the braking friction curve to the left of the peak and due to braking techniques used by drivers to avoid wheel lock up, the average rolling friction utilized by vehicles is generally less than the sliding friction coefficient. Therefore, controlled braking distances are usually longer than locked-wheel braking distances, although theoretically they would be less if the driver could use peak braking friction.

Locked-wheel braking is commonly used by passenger car drivers during emergency situations. Passenger cars can often stop in a stable manner, even with the front wheels locked. In this situation, the driver loses steering control, and the vehicle generally slides straight ahead. On a tangent section of road this is perhaps acceptable behavior, although on a horizontal curve the vehicle may leave its lane and possibly the roadway.

Combination trucks, by contrast, have much more difficulty stopping in the locked-wheel mode. Figure 25 illustrates the dynamics of a tractor-trailer truck if its wheels are locked during emergency braking (*17*). The behavior depends on which axle locks first—they usually do not all lock up simultaneously. When the steering wheels (front axle) are locked, steering control is eliminated, but the truck maintains rotational stability and it will skid straight ahead. However, if the rear wheels of the tractor are locked, that axle slides and the tractor rotates or spins, resulting in a "jackknife" loss of control. If the trailer wheels are locked, those axles will slide, and the trailer will rotate out from behind the tractor, which also leads to loss of control. Although a skilled driver can recover from the trailer swing through quick reaction, the jackknife situation is not correctable. None of these locked-wheel stopping scenarios for trucks is considered safe. Therefore, it is essential that trucks stop in a controlled braking mode and that highway geometric design criteria recognize the distances required for trucks to make a controlled stop.

The braking distance for a vehicle to make a controlled stop can be determined from the following relationship:

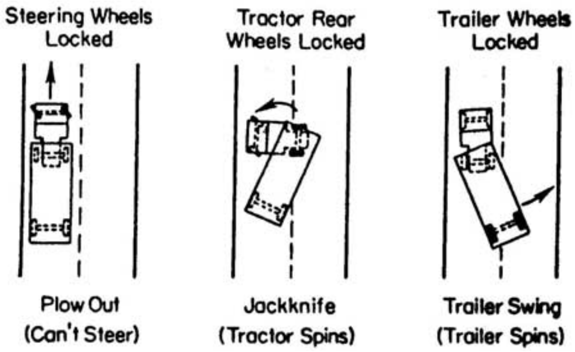


Figure 25. Tractor-trailer dynamics with locked wheels (17).

$$BD = \frac{V^2}{30f_r} \tag{5}$$

where

BD = braking distance (ft)
f_r = coefficient of rolling friction
V = initial speed (mph)

As in the case of sliding friction, the coefficient of rolling friction (f_r) in Equation 5 represents the average coefficient of friction or average deceleration rate during the entire controlled stop.

Pavement and Truck Characteristics Affecting Braking Distance

In order to stop without the risk of loss of control, trucks must use controlled braking, rather than locked-wheel braking. The deceleration rates used by trucks in making a controlled stop are represented by f_r in Equation 5. The following discussion reviews the principal individual pavement and tire characteristics that affect the value of f_r and, thus, the braking distance of a truck. Additional factors that can affect braking distance include road roughness, brake adjustment, and brake lining temperature *(2,3)*.

Pavement Properties

The shape of the braking friction curve in Figure 24 is a function of both pavement and tire properties. Highway agencies generally measure pavement friction by means of locked-wheel skid tests with a "standard" tire. These tests determine a value equivalent to f_s in Equation 4. The results of these tests are often multiplied by 100 and referred to as skid numbers rather than coefficients of friction. Although skid numbers are usually determined at 64 km/h [40 mph], a procedure is available to determine the skid number at any speed from the skid number at 64 km/h [40 mph] *(28,29,30)*. The peak coefficient of friction (f_p) can be estimated from the sliding coefficient of friction by the following relationship *(28)*:

$$f_p = 1.45 f_s \tag{6}$$

Equation 6 represents the average relationship for truck tires between peak and sliding friction; this relationship can vary markedly between pavements and for the same pavement under wet and dry conditions. Pavements generally have much lower coefficients of friction under wet conditions than under dry conditions, so highway design criteria are generally based on wet conditions.

Estimates of braking distance by Olson et al. used an assumed pavement skid number at 64 km/h [40 mph] (SN_{40}) equal to 28 *(28)*. The Green Book criteria for stopping sight distance prior to the 2001 edition were based on a pavement with SN_{40} equal to 32.

Pavement surface condition (wet versus dry) has an important bearing on braking distances. Locked-wheel braking is directly related to the tire-pavement friction coefficient, but controlled braking is less so. Trucks require greater braking distances than passenger cars on dry pavements, but NCHRP Synthesis 241 reports that the braking distances of passenger cars and trucks on wet pavements are nearly equal.

Tire Properties

Truck tires are designed primarily for wear resistance. For this reason, they tend to have somewhat lower wet friction coefficients than passenger car tires. It is generally estimated that truck tires have coefficients of friction that are about 70% of those of passenger car tires *(28)*. However, passenger car tires generally have coefficients of friction that are about 120% of the friction coefficients of the standard tires used in skid testing. Thus, the peak coefficient of friction can be estimated from skid test results with the following relationship:

$$f_p = (1.20)(0.70)(1.45)f_s = 0.0122\,SN_{40} \tag{7}$$

The coefficient of friction for truck tires decreases as the tires wear and their tread depth decreases. New truck tires have tread depths of 12 mm [$^{15}/_{32}$ in] for ribbed tires and 25 mm [$^{31}/_{32}$ in] for lug type tires. Olson et al. assumed, based on the literature, that the tread wear of truck tires has very little effect on their frictional properties until the tread depth falls below 10 mm [$^{12}/_{32}$ in] *(28,31)*. Tire tread depth has little effect on the coefficient of friction on pavements with high macrotexture, but the coefficient of friction does decrease substantially with tread depth for smooth, poorly textured pavements *(32)*. The following relationship was used by Olson et al. to estimate the reduction in friction coefficient of tires as their tread depth decreases *(28)*:

$$TF = 1 - \frac{\Delta f_p\left(1 - \sqrt{x/n}\right)}{f_p} \tag{8}$$

where

TF = adjustment factor for tire tread depth
Δf_p = difference in coefficient of friction between new and bald (completely worn) tires
x = remaining tread depth (in) (use $^{12}/_{32}$ if $x \ge {}^{12}/_{32}$)
n = minimum tread depth with coefficient of friction equivalent to a new tire (assumed: $^{12}/_{32}$ in)

Equation 8 is probably based on studies of passenger car tires, but no equivalent relationship for truck tires is currently available.

Data on the coefficients of friction for various types of truck tires are available in References 18, 32, 33, and 34.

Both References 32 and 33 indicate that the friction coefficients of truck tires decrease slightly with increasing axle load. Tire inflation pressure has very little effect on peak friction coefficient (f_p), but increasing the inflation pressure from 47 to 70 kPa [68 to 102 psi] results in a very small loss (less than 10%) in the sliding friction coefficient (f_S) *(34).*

Braking Efficiency

Conventional Braking Systems. Conventional truck braking systems are limited in their ability to take full advantage of all of the friction available at the tire-pavement interface. Fancher has estimated that the braking efficiency for single-unit trucks is between 55 and 59% of the peak available friction *(35).* Both Fancher and Olson et al. assume that this same level of braking efficiency is applicable to tractor-trailer trucks *(28,35).* A primary reason for this relatively low level of braking efficiency is that most controlled braking takes place at a value of percent slip less than the level which produces the peak braking friction coefficient. Several other vehicle-related factors that contribute to low braking efficiencies are reviewed in this section. Antilock brake systems, which enable increases in braking efficiency, are also discussed.

By way of introduction, the operation of air brakes—the usual braking system for combination trucks—is reviewed. Air brake systems use compressed air to transmit and amplify the driver's input from the brake pedal to the brakes on individual wheels. The use of air as an amplifying medium results in a slight delay in the system response due to the compressibility of air. (In contrast, hydraulic braking systems provide an almost immediate response, but are not operationally feasible for truck combinations that must be frequently disassembled and reassembled.) Once the brake pedal is released, the air in the system is expelled to the atmosphere and is replaced by air from a compressor on board the tractor. Therefore, air brakes are not "pumped," as might be done in making a controlled stop with hydraulic brakes. Pumping of air brakes will result in the rapid depletion of the compressed air supply, which in turn results in a total loss of braking ability. Rather, for an air brake system, the pressure within the system is adjusted by slightly depressing or slightly releasing the brake pedal to apply more or less braking force. This braking practice is called "modulating" the brakes. As discussed earlier in this section, "modulating" the brakes requires some experience on the part of the driver to obtain the maximum braking effect from the system without causing the wheels to lock.

Antilock Brake Systems. The purpose of antilock brakes is to take full advantage of the available tire-pavement friction capabilities without locking the wheels and losing vehicle control. Antilock brake systems try to achieve and maintain the peak coefficient of tire-pavement friction shown in Figure 24, thereby maximizing the braking effort.

Antilock brake systems operate by monitoring each wheel for impending lock up. When wheel lock up is anticipated, the system reduces brake pressure on the wheel. When the wheel begins to roll freely again, the system reapplies braking pressure. The system constantly monitors each wheel and readjusts the brake pressure until the wheel torque is no longer sufficient to lock the wheel. The antilock brake system is controlled by an onboard microprocessor.

Antilock brake systems are now required for new trucks, tractors, and trailers in accordance with Federal Motor Vehicle Safety Standard (FMVSS) 121 *(36).* Antilock brake systems have been required for air-brake-equipped tractors manufactured on or after March 1, 1997; and air-brake-equipped trailers and single-unit trucks manufactured on or after March 1, 1998. Antilock brake systems were also available as an option for some of these vehicles before those dates.

Truck tractors have a useful life of approximately 7 years. Therefore, nearly all truck tractors in the current fleet have antilock brakes or will soon be replaced by a tractor that does. Thus, the use of antilock brakes in the tractor fleet can be regarded as nearly 100%.

Truck trailers have a useful life of approximately 20 years. Thus, only about 5% of the trailer fleet is replaced each year. There has not been sufficient time since March 1, 1998, for antilock brake systems to come into use for trailers as completely as they have for tractors. A field survey at truck weigh stations conducted in three states during 2002 as part of this research, and presented in Appendix B of this report, found that approximately 43% of trailers are equipped with antilock brake systems. Based on the service life of trailers, it can be expected that within 10 years nearly all trailers will be equipped with antilock brake systems.

FMVSS 121 specifies a performance standard for truck braking distance. The required braking distances are summarized in Table 25. These criteria apply to tests of the truck service brakes on a dry pavement with a peak friction coefficient of 0.9.

Driver Control Efficiency

Most drivers, including truck drivers, have little or no practice in emergency braking situations. This lack of expertise in modulating the brakes in critical situations results in braking distances that are longer than the vehicle capability. Olson et al. evaluated the effect of driver efficiency on braking distance using both experienced test drivers and professional truck drivers without test track experience *(28).* Their study found that the driver efficiencies ranged from 62 to 100% of the vehicle capability. The braking performance of the drivers tended to improve during the testing period as the drivers gained experience in emergency stopping. Because so many drivers on the road lack experience in emergency braking, the study recommended the use of a driver efficiency of 62% in stopping sight distance design criteria. However, it should be recognized that

TABLE 25 Truck braking distances specified as performance criteria for antilock brake systems in FMVSS 121 (*36*)

Vehicle speed (mph)	Truck braking distance (ft)[a] Loaded single-unit truck	Unloaded truck tractors and single-unit trucks	Loaded truck tractors with an unbraked control trailer
20	35	38	40
25	54	59	62
30	78	84	89
35	106	114	121
40	138	149	158
45	175	189	200
50	216	233	247
55	261	281	299
60	310	335	355

[a] Braking distance for truck service brakes; separate criteria apply to truck emergency brakes.

this is a very conservative choice. The best-performance drivers can operate at efficiencies approaching 100%. Furthermore, because antilock brake systems are becoming ever more common, and will soon be the norm, the concern over driver efficiency is eliminated by providing computer-controlled modulation of the brakes to achieve minimum braking distance, equivalent to a driver efficiency of 100%.

Estimation of Braking Distances

Olson et al. have suggested a model to predict braking distance as a function of pavement surface characteristics, tire characteristics, vehicle braking performance, and driver control efficiency *(28)*. Parametrically, the model expresses the coefficient of rolling friction, f_r, as

$$f_r = f_p \times TF \times BE \times CE \qquad (9)$$

where

f_p = peak braking friction coefficient available given the pavement surface characteristics
TF = adjustment factor for tire tread depth (see Equation (8))
BE = adjustment factor for braking efficiency (the efficiency of the braking system in using the available friction, typically 0.55 to 0.59 for conventional braking systems)
CE = adjustment factor for driver control efficiency (the efficiency of the driver in modulating the brakes to obtain optimum braking performance, typically 0.62 to 1.00 for conventional braking systems)

The factors that influence each term of Equation 9 have been addressed in the preceding discussion.

Based on Equation 9, the FHWA *Truck Characteristics* study *(2,3)* estimated truck braking distances for a truck with a conventional braking system and the worst-performance driver, a truck with a conventional braking system and the best-performance driver, and a truck with an antilock brake system. Table 26 presents these braking distances along with the updated assumptions about controlled braking distance presented in the 2001 Green Book.

DRIVER EYE HEIGHT

Driver eye height is a combined driver and vehicle characteristic that is essential to the evaluation of sight distance issues. Truck drivers generally have substantially higher eye heights than passenger car drivers, which means that a truck

TABLE 26 Truck deceleration rates and braking distances

Vehicle speed (mph)	Deceleration rate (g)[a] Previous AASHTO policy[b]	Current AASHTO policy[c]	Worst-performance driver[d]	Best-performance driver[e]	Antilock brake system	Braking distance (ft)[a] Previous AASHTO policy[b]	Current AASHTO policy[c]	Worst-performance driver[d]	Best-performance driver[e]	Antilock brake system
20	0.40	0.35	0.17	0.28	0.36	33	38	77	48	37
30	0.35	0.35	0.16	0.26	0.34	86	86	186	115	88
40	0.32	0.35	0.16	0.25	0.31	186	152	344	213	172
50	0.30	0.35	0.16	0.25	0.31	278	238	538	333	269
60	0.29	0.35	0.16	0.26	0.32	414	343	744	462	375
70	0.28	0.35	0.16	0.26	0.32	583	467	1,013	628	510

[a] Based on an empty tractor-trailer truck on a wet pavement with SN_{40} = 32.
[b] Based on 1994 *Green Book*
[c] Based on 2001 *Green Book*
[d] Based on driver control efficiency of 0.62.
[e] Based on driver control efficiency of 1.00.

driver can see farther than a passenger car driver on the approach to vertical sight restrictions.

The AASHTO Green Book specifies a value of 1,080 mm [3.5 ft] for driver eye height, based on consideration of a passenger car as the design vehicle. By contrast, a value of 2,400 mm [8.0 ft] is recommended by the Green Book for truck driver eye height. This value is based on relatively recent field studies by Fambro et al. *(37)* and does not appear to be in need of updating.

TRUCK ACCELERATION CHARACTERISTICS

Two aspects of truck acceleration performance are considered in this section. The first aspect is the ability of a truck to accelerate from a full stop to clear a specified hazard zone such as an intersection or railroad-highway grade crossing. Typically, a hazard zone of this type is less than 66 m [200 ft] long; as a result, the speed attained by the truck is low. This first aspect of truck acceleration performance is, therefore, referred to as *low-speed acceleration*. The second aspect of truck acceleration is the ability of a truck to accelerate to a high speed, either from a stop or from a lower speed. This type of acceleration, referred to here as *high-speed acceleration*, is needed by trucks in passing maneuvers and in entering a high-speed facility.

Low-Speed Acceleration

The low-speed (or start-up) acceleration ability of a truck determines the time required for it to clear a relatively short hazard zone such as an intersection or railroad-highway grade crossing. The primary factors that affect the clearance times of trucks are

- Length of hazard zone,
- Length of truck,
- Truck weight-to-power ratio,
- Truck gear ratio, and
- Roadway geometry (i.e., percent grade and curvature).

State and Federal regulations require vehicles transporting passengers and hazardous materials to accelerate at railroad-highway grade crossings without shifting gears. The assumption that the truck does not shift gears is probably less realistic at intersections than at railroad-highway grade crossings. When shifting gears is allowed, a truck can reach a higher speed but, simultaneously, it loses speed during the delay when the driver is shifting gears. Therefore, the overall effect on clearance time, assuming that there is no gear shift, may be negligible unless the hazard zone is quite long.

A simplified analytical model of the low-speed acceleration of trucks has been developed by Gillespie *(38)*. The Gillespie model estimates the time required for a truck to clear a hazard zone, starting from a full stop, as

$$t_c = \frac{0.682(L_{HZ} + L_T)}{V_{mg}} + 3.0 \tag{10}$$

where

t_c = time required to clear zone (s)
L_{HZ} = length of hazard zone (ft)
L_T = length of truck (ft)
V_{mg} = maximum speed in the gear selected by the driver (mph)

Equation 10 is based on the assumption that the distance traveled by the truck during the clearance time is the length of the hazard zone plus the length of the truck, $L_{HZ} + L_T$. Neither the weight nor the weight-to-power ratio of the truck is considered explicitly in Equation 10, although it is implicitly assumed that the weight-to-power ratio would affect the driver's choice of gears. The model assumes that, when starting from a full stop, a truck rather quickly reaches the maximum speed in the gear selected by the driver and then travels at that constant speed until it clears the hazard zone. Thus, Equation 10 is essentially a constant speed model, and acceleration rates, as such, are not meaningful. On a level road, V_{mg} can be calculated as

$$V_{mg} = \frac{60}{gr} \tag{11}$$

where gr = gear ratio selected by the driver

This model of low-speed acceleration is based on the assumption that the gear design, engine speed, and tire size of the truck are such that its maximum speed in high gear without overdrive (gear ratio 1 : 1) is 97 km/h [60 mph].

The estimated clearance times for a 19.8-m [65-ft] tractor-trailer truck, obtained from Equation 10, are given in Table 27. The values of clearance times on grades are greater than those on no grade because the truck speed, V_{mg}, is lower, as illustrated in Table 27.

The Gillespie model was compared with the results of field observations of time versus distance for 77 tractor-trailer trucks crossing zero-grade intersections from a full stop *(38)*. These data are shown in Figure 26. There is no information on the weights or weight-to-power ratios of these trucks, although they probably vary widely. A line representing the clearance time predicted by Equation 10 for a level grade is also presented in the figure. Equation 10 provides a relatively conservative estimate of clearance times, given that most of the experimental points fall below the prediction.

The experimental data in Figure 26 can be bounded by two parallel lines representing the maximum and minimum observed clearance times.

Hutton collected data on the acceleration performance of 31 tractor-trailer combinations *(39)*. Most of the trucks evaluated by Hutton were cab-over-engine tractors pulling twin

TABLE 27 Clearance time (s) for low-speed acceleration by a 19.8-m [65-ft] tractor-semitrailer

Percent grade	V_{mg} (mph)	Length of hazard zone (ft)									
		30	40	50	60	70	80	90	100	110	120
0-2	8	11.1	1.9	2.8	3.7	4.5	5.4	16.2	17.1	17.9	18.8
3-5	6	13.8	14.9	16.1	17.2	18.3	19.5	20.6	21.8	22.9	24.0
6-10	5	16.0	17.3	18.7	20.0	21.4	22.8	24.1	25.5	26.9	28.2
11-13	4	19.2	20.9	22.6	24.3	26.0	27.7	29.4	31.1	32.8	34.5

8.2-m [27-ft] trailers. The engine horsepower of the trucks ranged from 170 to 283 kW [228 to 375 hp], while their gross vehicle weights ranged from 15,100 to 40,900 kg [33,250 to 89,900 lb]. Figure 27 illustrates the resulting time versus distance curves determined by Hutton for initial acceleration by trucks with weight-to-power ratios of 60, 120, 180, and 240 kg/kW [100, 200, 300, and 400 lb/hp].

The Hutton data can be used to calculate clearance times and then compared with the clearance times from the Gillespie data from Figure 26. This comparison shows that the Hutton data fall within the boundaries shown in Figure 26. Moreover, all the Hutton data fall below the predictions of Equation 10.

Based on these findings, the FHWA Truck Characteristics study recommended that the range for clearance times for trucks be revised as follows *(2)*:

$$t_{min} = -4.2 + 0.70\sqrt{36 + 1.25(L_{HZ} + L_t)} \qquad (12)$$

$$t_{max} = 10.8 + 0.075(L_{HZ} + L_T) \qquad (13)$$

Table 28 presents the estimated minimum and maximum clearance times for a 19.8-m [65-ft] truck to cross hazard zones of varying length.

Fancher compared the results of two studies to the time versus distance for low-speed acceleration from a stop specified in the Green Book and found that the *average* tested heavy vehicles performed with more acceleration than the 1984 Green Book criteria for a WB-15 [WB-50] truck *(40)*.

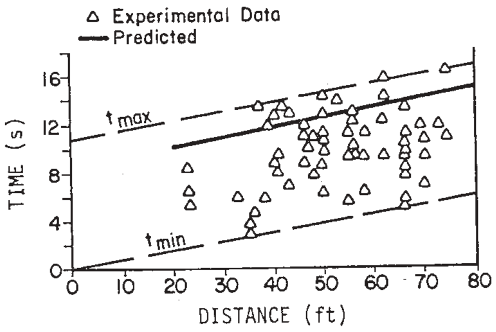


Figure 26. Field observations of times for 19.8-m [65-ft] tractor-trailer trucks to clear intersection distances after starting from a stop (2, 38).

High-Speed Acceleration

There is a substantial amount of performance data in the literature for acceleration from a stop to a high-speed. Figure 28 presents speed-versus-distance curves for acceleration to high-speeds developed in References 41, 42, 43, 44, and 45. (The values for Reference 45 are shown in Figure 28 as a range.) All of these sources are dated prior to 1990 and reflect the performance of past truck populations.

Hutton also developed acceleration data for trucks classified by weight-to-power ratio *(39)*. Although these data were collected in 1970, the fundamental relationships between weight-to-power ratio and truck performance have not changed substantially.

Figure 29 shows distance-versus-time curves for acceleration from a full-stop to higher speeds for 60, 120, 180, and 240 kg/kW [100, 200, 300, and 400 lb/hp] trucks *(38)*. These curves can be approximated by the following analytical relationships:

Weight-to-power ratio (lb/hp)	Distance-time relationship	
100	$t = -15.1 + \sqrt{229 + 1.64x}$	(14)
200	$t = -22.8 + \sqrt{523 + 2.56x}$	(15)
300	$t = -22.0 + \sqrt{480 + 2.94x}$	(16)
400	$t = -26.6 + \sqrt{708 + 3.57x}$	(17)

Figure 30 shows corresponding speed-versus-time curves for the same trucks. The average acceleration rates for acceleration to 64 km/h [40 mph] from speeds of 0, 16, 32, and 48 km/h [0, 10, 20, and 30 mph] are given in Table 29, based on the data in Figure 30. Acceleration rates of trucks at higher speeds are less than those given in Table 29. For example, the acceleration rate for a 60 kg/kW [100-lb/hp] truck to increase

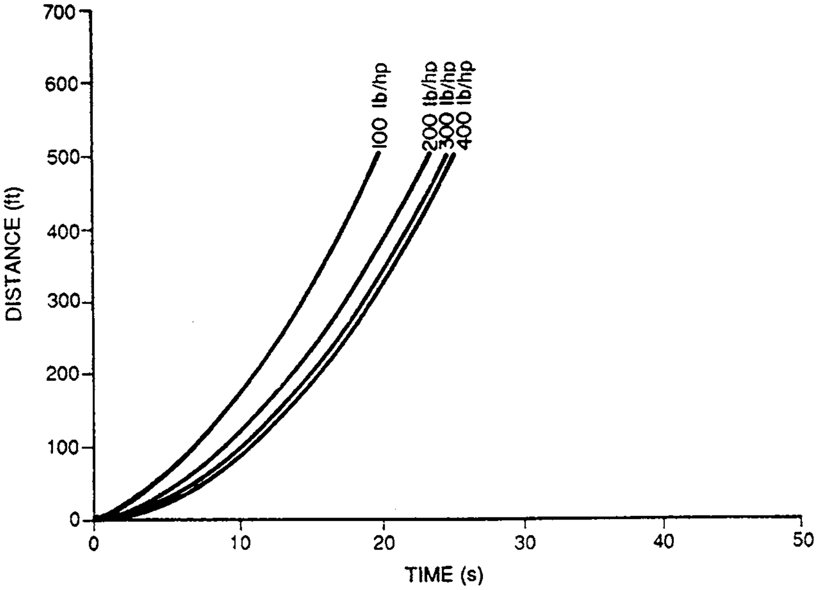


Figure 27. Observed time versus distance curves for initial acceleration from a stop by tractor-trailer trucks (2, 39).

its speed from 56 to 88 km/h [35 to 55 mph] is 0.16 m/s^2 [0.53 ft/s^2], based on the curve in Figure 30. The corresponding rate for a 120-kg/kW [200-lb/hp] truck is 0.11 m/s^2 [0.36 ft/s^2]. Figure 30 illustrates that 180- and 240-kg/kW [300- and 400-lb/hp] trucks cannot accelerate to 88 km/h [55 mph] within the time scale shown on the figure.

SPEED-MAINTENANCE CAPABILITIES ON GRADES

The primary factors that determine the ability of a truck to maintain speed on an upgrade are

- Weight-to-power ratio,
- Percent grade of roadway,
- Aerodynamic drag,
- Rolling resistance,
- Drive line efficiency,
- Length of grade,
- Tire size, and
- Transmission characteristics.

The speed of a truck on an upgrade can be approximated by the following equation:

$$m\dot{V} = P/V - F_r - F_a - mg\ \sin\alpha \qquad (18)$$

where

m = mass of truck
P = net engine power available at the drive wheels (hp)
V = speed (ft/s)
F_r = rolling resistance force (lb)
F_a = aerodynamic drag force (lb)
$\forall$ = angle of the grade (degrees)
g = acceleration of gravity (9.8 m/s^2 [32.2 ft/s^2])

The steepness of grade (α) can be expressed in the more conventional percent grade form as 100 tan $\forall$. The variable, $\dot{V}$, represents the time derivative of truck speed (dV/dt).

Equation 18 can also be written as

$$mV = \frac{mg}{(W/P)V} - F_r - F_a - mg\sin\alpha \qquad (19)$$

where W/P is weight-to-power ratio in units of lb/hp.

Another way to view truck performance on a grade is provided by Gillespie *(46)*. Figure 31 shows the factors of Equations 18 and 19, expressed as forces propelling a truck forward

TABLE 28 Minimum and maximum clearance times (s) for a 19.8-m [65-ft] tractor-trailer truck

Range of clearance times	Length of hazard zone (ft)									
	30	40	50	60	70	80	90	100	110	120
t_{min}	4.5	4.9	5.2	5.5	5.8	6.1	6.4	6.7	7.0	7.2
t_{max}	17.9	18.7	19.4	20.2	20.9	21.7	22.4	23.2	23.9	24.7

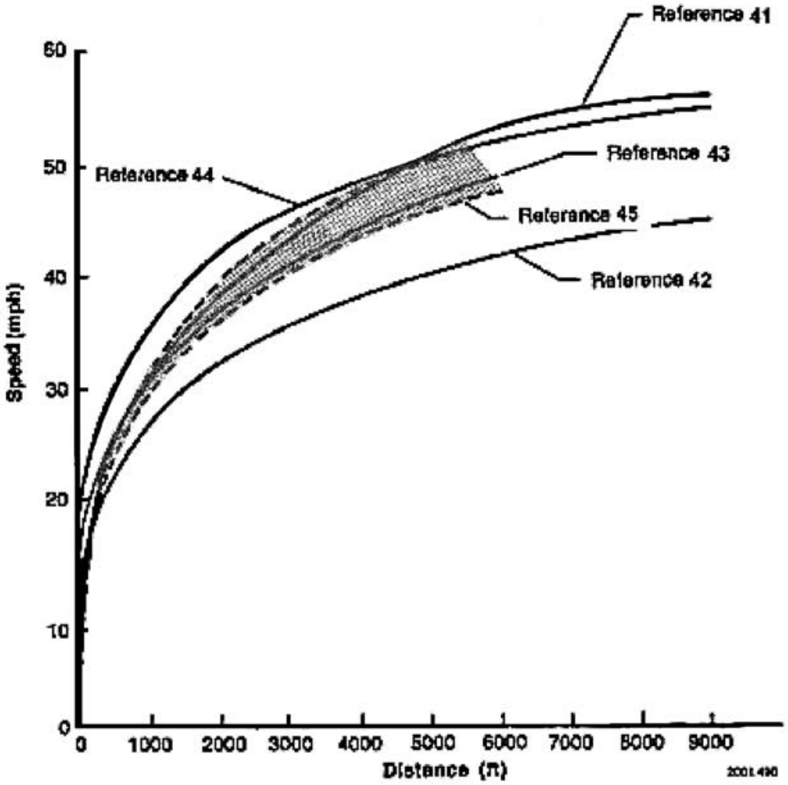


Figure 28. Speed-versus-distance curves for truck acceleration from a stop (2, 39).

or resisting its forward motion. This figure is for a very low performance truck, by today's standards, that is barely able to achieve 105 km/h [65 mph] on a level road. At that speed, the engine power limit is about 15% of the vehicle weight, but that is reduced to 13% of the vehicle weight by drive train losses. Major losses are about 5% of the vehicle weight due to rolling resistance and 8% of the vehicle weight due to aerodynamic losses. Thus, losses require all the available engine power, and no engine power is left for further acceleration. At speeds above about 80 to 89 km/h [50 to 55 mph], the aerodynamic losses dominate; at lower speeds, rolling resistance is greater.

If the truck is on a grade, overcoming the grade becomes extremely important. For this truck, even a small 1% grade requires a force equal to about 8% of the vehicle weight to overcome, so the maximum speed for this very low performance truck is reduced to about 64 km/h [40 mph].

Several of the key factors in Equations 18 and 19 are discussed below.

Literature Review

Weight-to-Power Ratio

The ability of a truck to maintain speed on an upgrade is very sensitive to its weight-to-power ratio. The weight-to-power ratios of trucks have been decreasing steadily for many years, as tractor engines have become more and more powerful. Figure 32 illustrates the long-term trends in the weight-to-power ratios of trucks. The figure shows the several lines illustrating trends in average weight-to-power ratios of trucks as a function of gross weight from 1949 to 1975. Added to the figure is a line based on the 1977 Truck Inventory and Use Survey (TIUS), predecessor of the current VIUS survey, and points representing the Gillespie data *(46,47)*. A comparison of the TIUS and Gillespie data demonstrates that the major reason for the reduced weight-to-power ratios of trucks during this period is a substantial increase in average engine horsepower. The average tractor power in the 1977 TIUS data was 170 kg/kW [282 hp], in comparison with 210 kg/kW [350 hp] in the Gillespie data of 1984. The trend toward more powerful engines for tractor-trailer combinations has continued through the 1980s and 1990s.

Table 30 presents average values of weight-to-power ratios of trucks obtained from field observations at sites located in the Eastern and Western parts of the United States in a 1985 report by Gillespie *(46)*. The table shows the average weight, power, and weight-to-power ratios of trucks by truck type and road class. The number of trucks observed for each road class is given in parentheses following the road class.

Data on truck performance on grades collected by Gillespie in 1984 are shown as triangles in Figure 32. Since the reported results did not include the explicit distribution of weight-

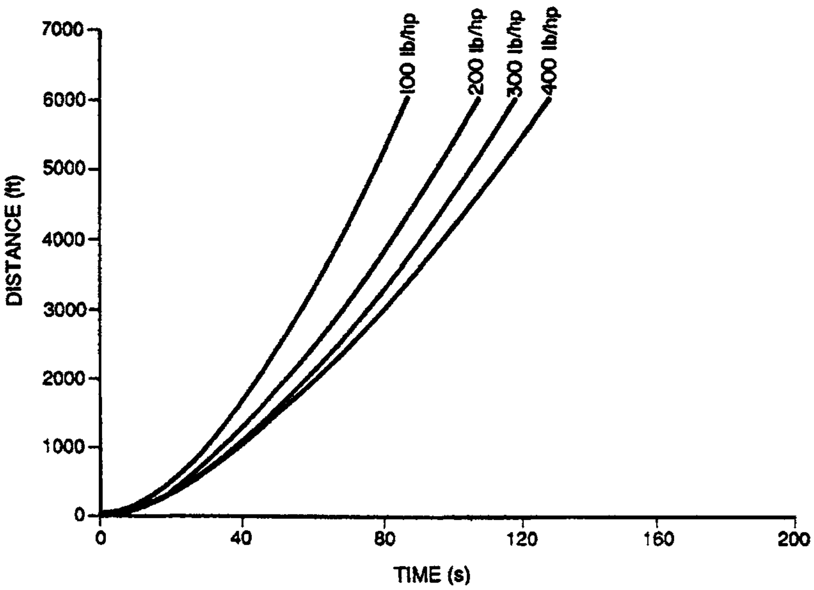


Figure 29. Observed time versus distance curves for acceleration to high speed from a stop by a tractor-trailer truck (2, 39).

to-power ratios, the database developed in that study was obtained and reanalyzed in the FHWA *Truck Characteristics* study *(2,3)*. That study presents a detailed discussion of the procedures used to derive weight-to-power ratios for over 3,000 individual trucks theoretically from their final climbing speeds and directly from the weights and rated horsepowers of a sample of approximately 500 trucks. This analysis addressed only combination trucks (tractor-trailers) and addressed several factors including aerodynamic losses that were not addressed by Gillespie. The distributions of truck weight-to-power ratio were derived indirectly from the final climbing speeds and directly from measured gross weights and rated horsepowers. These distributions showed that the median weight-to-power ratio for trucks was about 100 kg/kW [175 lb/hp], while the 87.5 percentile weight-to-power ratio was about 150 kg/kW [250 lb/hp].

There have been no data reported in the literature to indicate how truck weight-to-power ratios have changed since the

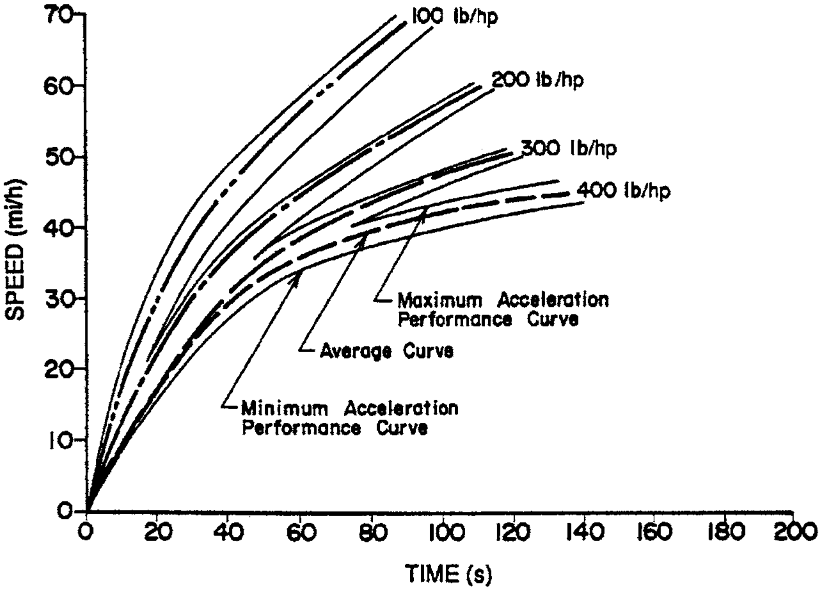


Figure 30. Observed speed-versus-time curves for acceleration by truck with various weight-to-power ratios (39).

TABLE 29 Average acceleration capabilities of trucks from specified speed to 64 km/h [40 mph] (*39*)

Weight-to-power ratio (lb/hp)	Acceleration rate (ft/s^2)			
	0 mph	10 mph	20 mph	30 mph
100	1.87	1.70	1.47	1.29
200	1.22	1.08	0.96	0.79
300	0.91	0.81	0.72	0.58
400	0.71	0.61	0.50	0.36

NOTE: Based on speed-distance curves shown in Figure 30.

mid-1980s other than the results of a field study by Harwood et al. *(49)* performed at one site on a two-lane highway in California in 1997. Furthermore, the choice of a design weight-to-power ratio should be based not on an average or median value like those reported in Table 30, but on a value representative of trucks that perform more poorly, such as the 85th percentile weight-to-power ratio. To obtain up-to-date data on the performance abilities on upgrades of the current truck fleet, field studies were conducted as part of the current research at nine sites on freeways and two-lane highways in three states: California, Colorado, and Pennsylvania. In addition, the data from the 1997 study mentioned above for one two-lane highway site in California were also included in the analysis. Tables 31 and 32 summarize the results for truck weight-to-power ratios in these three states.

Comparison of Table 30 with Tables 31 and 32 suggests that, since 1984, average truck weight-to-power ratios on freeways have improved substantially in the western states but have stayed about the same in the eastern states. No comparative data are available for two-lane highways.

Rolling Resistance

The rolling resistance of tires, F_r, is defined as the ratio of power lost due to rolling resistance to speed. F_r can be estimated using the following SAE equations:

$$F_r = 0.001(4.1 + 0.041\ V) \text{ for radial tires} \tag{20}$$

$$F_r = 0.001(5.3 + 0.044\ V) \text{ for mixed tires} \tag{21}$$

$$F_r = 0.001(6.6 + 0.046\ V) \text{ for bias-ply tires} \tag{22}$$

where V is speed in mph. Experimental rolling resistance data for selected truck tires can be found in the literature *(50)*.

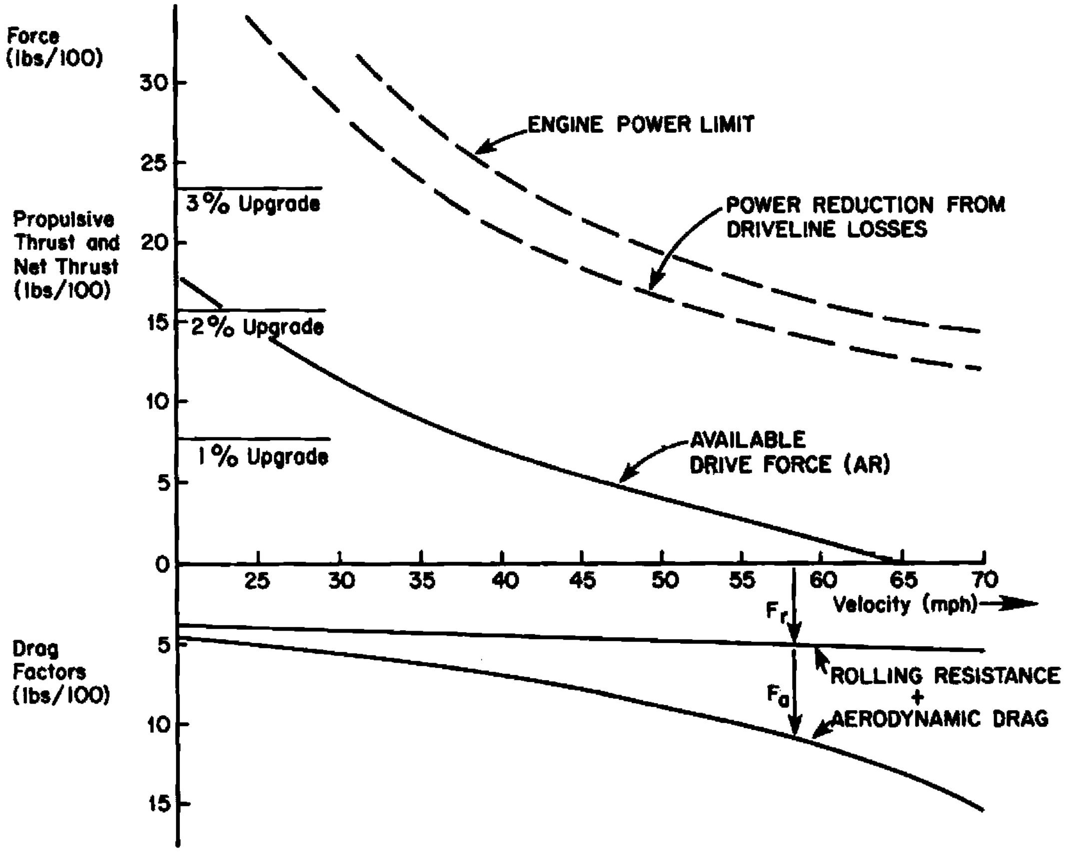


Figure 31. Forces acting on a vehicle as a function of speed (46).

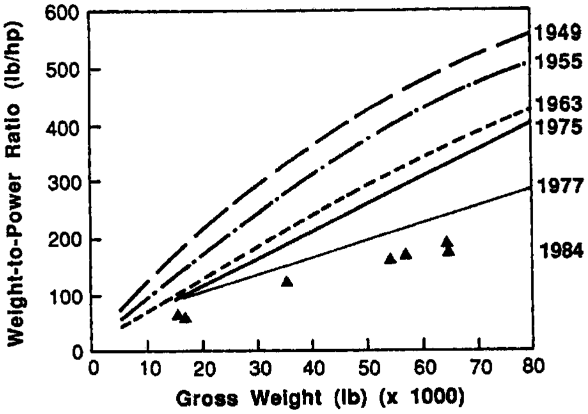


Figure 32. Trends in weight-to-power ratios of trucks from 1949 to 1984 (46, 47, 48).

Aerodynamic Drag

The aerodynamic drag force is estimated by the following relationship *(43)*:

$$F_a = 1.1 D C_D A V^2 \qquad (23)$$

where

F_a = aerodynamic drag (lb)
D = air density (lb/fa^t)
C_D = drag coefficient (0.6 with aerodynamic aids, 0.7 without)
A = truck frontal area (102 fa^t for van bodies, 75 fa^t for cab only) (fa^t)
V = truck speed (mph)

VEHICLE LENGTH

Vehicle length is addressed primarily in other sections of this report. Chapter 2 of this report addresses vehicle length limits in truck size and weight policies. Chapter 3 addresses the distribution of vehicle lengths in the current truck population. Chapter 4 addresses the lengths of the Green Book design vehicles (and their individual tractors and trailers) and their suitability for use to characterize the current truck population.

VEHICLE HEIGHT

Chapter 4 of this report addresses the heights of the Green Book design vehicles. The maximum height of any of the current design vehicles is 4.1 m [13.5 ft]. Most trucks have heights less than this. Chapter 6 addresses the relationship of vehicle height to design criteria for vertical clearance.

REARWARD AMPLIFICATION

When a combination vehicle makes a sudden lateral movement, such as to avoid an obstacle in the road, its various units undergo different lateral accelerations. The front axles and the cab exhibit a certain acceleration, but the following trailer(s) have greater accelerations. This has been experimentally verified and quantified *(51)*. The lateral acceleration of the first trailer may be twice that of the tractor, and the lateral acceleration of a second trailer may be four times as much.

The factors that contribute to increased lateral accelerations of the trailing units, the phenomenon known as rearward amplification (also called transient high-speed offtracking), include the following:

- Number of trailing units;
- Shortness of trailers (longer ones experience less amplification);
- Loose dolly connections;
- Greater loads in rearmost trailers; and
- Increased vehicle speeds.

Quantifying rearward amplification in terms of multiples of lateral acceleration may be appropriate for vehicle regulation, but is not generally relevant to highway geometric design. It has been recommended that a reasonable performance criterion would be that the physical overshoot that a following trailer exhibits during such a maneuver, relative to its final displaced lateral position, be limited to 0.8 m [2.7 ft] *(51)*.

TABLE 30 Average weights and power values for trucks (*46*)

	Weight (lb)	Power (hp)	Weight/Power
Straight trucks			
Interstate—East (14)	15,233	219	70
Interstate—West (6)	35,050	267	131
Primary—East (6)	16,575	273	75
Tractor-trailer			
Interstate—East (157)	54,452	328	166
Interstate—West (233)	64,775	370	175
Primary—East (134)	57,487	330	174
65-ft doubles			
Interstate—West (19)	64,920	331	196

TABLE 31 Summary of truck weight-to-power ratios by percentiles for freeway sites

Percentile	Weight-to-power (lb/hp) ratio California	Colorado	Pennsylvania
5th	83	69	111
25th	112	87	142
50th	141	115	168
75th	164	152	194
85th	183	169	207
90th	198	179	220
95th	224	199	251

SUSPENSION CHARACTERISTICS

This section of the report reviews the characteristics of truck suspensions. The review is based primarily on a summary of suspension characteristics from the NHTSA factbook of truck characteristics *(18)*. Other references are cited in the text as appropriate.

The suspension of a heavy vehicle affects its dynamic responses in three major ways:

- Determining dynamic loads on tires,
- Orienting the tires under dynamic loads, and
- Controlling vehicle body motions with respect to the axles.

Suspension characteristics can be categorized by eight basic mechanical properties:

- Vertical stiffness,
- Damping,
- Static load equalization,
- Dynamic inter-axle load transfer,
- Height of roll center,
- Roll stiffness,
- Roll steer coefficient, and
- Compliance steer coefficient.

These suspension characteristics are important in determining the stability of trucks on horizontal curves.

Vertical Stiffness: Dependent on Spring Stiffness

The vertical stiffness of a truck suspension is mainly determined by the spring elements. Generally these elements are either leaf springs or air springs. The vertical loads on the tandem axle of the trailer of a loaded truck can be up to four times greater than when the trailer is unloaded *(51)*. Given that the load on the suspension can vary greatly, the springs must be very stiff for a fully loaded truck and much less stiff for an unloaded truck. Air springs are particularly well suited for such a range of loadings, because the spring rate can change significantly with loading. With leaf springs, the stiffness can also change under different loadings, but not quite as much as with the air suspension. This creates a poor ride quality for unloaded conditions. The friction of leaf springs also affects its force-displacement relationship.

TABLE 32 Summary of truck weight-to-power ratios by percentiles for two-lane highway sites

Percentile	Weight-to-Power (lb/hp) Ratio California	Colorado	Pennsylvania
5th	79	68	79
25th	144	85.5	110
50th	186	107	180
75th	226	149	242
85th	246	180	280
90th	262	193	303
95th	281	214	331

The range of vertical stiffness for the various types of suspensions has been measured for a load of 4,500 kg [10,000 lb] on the front axles and 7,300 kg [16,000 lb] on the rear axles. The range of vertical stiffness per axle is given in Table 33.

Damping: Dependent on Shock Absorbers and Coulomb Friction of Leaf Springs

Suspensions that have leaf springs rely on coulomb friction for damping. Coulomb friction comes from the rubbing at the interfaces of the various leaves of the spring. Therefore, the damping is a function of mean load and displacement. Air spring suspensions need shock absorbers to provide damping.

Damping has a moderate effect on rearward amplification and the transient dynamic behavior of the vehicle. A lack of damping can create a system that is likely to oscillate and produce large dynamic loads on the axles. Damping is set so that a maximum ride quality can be achieved. Increased damping usually reduces rearward amplification of steering inputs in multitrailer combination trucks and can, thus, increase stability in emergency maneuvers. A typical range of values for damping is given in Table 34.

Static Load Equalization: Dependent on Coulomb Friction and Mechanisms Intended to Distribute Loads Evenly on Both Axles of a Tandem Set

Static load equalization results because the design of tandem-axle suspensions tends to distribute the load equally between the two axles of the tandem. This type of load equal-

TABLE 33 Typical range of vertical stiffness per axle for truck suspensions (*18*)

Type of suspension	Range of vertical stiffness (lb/in)
Front suspension	2,000 - 2,750
Air suspension	1,000 - 7,000
Four-spring	8,000 - 21,000
Walking beam	10,000 - 21,000
Single-axle leaf spring	8,500 - 13,750

TABLE 34 Typical range of damping for truck suspension (*18*)

Type of suspension	Range of damping (lb)
Front suspension	800 - 1,250
Air suspension	550 - 1,200
Four-spring	1,200 - 2,700
Walking beam	700 - 2,000
Single-axle leaf spring	1,800 - 2,400

TABLE 35 Typical range of inter-axle load transfer for truck suspension (*18*)

Type of suspension	Range of inter-axle load transfer (lb/lb)
Air suspension	0.035 - (–0.018)
Four-spring	(–0.10) - (–0.185)
Walking beam	0.010 - (–0.030)

ization is a static quantity; dynamic inter-axle load transfers are discussed in the next section.

Typically, most tandem axles are very good at distributing the load evenly between the axles. Static measurements on tandem axles have shown that the largest variation is on the order of about 5% more weight on one axle than on the other.

Dynamic Inter-Axle Load Transfer: Dependent on Coulomb Friction and Mechanisms Intended to Distribute Loads Evenly on Both Axles of a Tandem Set

Inter-axle load transfer can occur in dynamic situations, such as during braking or acceleration. Unfortunately, the mechanisms that are used to create good static load equalization have just the opposite effect on dynamic load transfers. When a braking (or accelerating) force is applied on a tandem axle, there is often a load transfer between the axles of a tandem set. Inter-axle load transfers can be a problem during braking, because the more lightly loaded axle will tend to lock up before the other. If the lockup occurs on the lead axle, then the directional stability is reduced; directional stability can be completely lost if lockup occurs on the trailing axle. Another unwanted result of poor load transfer is that the system can produce an under-damped mode. Occasionally, this can result in "tandem hop," which can cause a partial degradation of braking and handling performance.

Dynamic inter-axle load transfer is measured in pounds of load transferred per pound of brake force. The transfer is positive if it is toward the leading axle. A typical range of values is given in Table 35.

Roll Center Height: Dependent on the Line of Action of the Lateral Suspension Forces

When the chassis of a truck rolls (tilts sideways as when rounding a horizontal curve), it tends to roll about a theoretical point, called the roll center. With a four-spring suspension, the leaf springs will determine the roll center location. Special links can be added to provide lateral forces on walking-beam suspensions and air suspensions; these links affect the roll center height. Roll center heights are measured from the ground. Typical values are given in Table 36.

Roll Stiffness: Dependent on Spring Stiffness, Lateral Spacing, Roll Center Height, and Auxiliary Mechanisms Such as Anti-Sway Bars

Roll stiffness is a measure of a suspension system's resistance to rolling. As a truck body rolls, the vertical springs deform to cause a resisting moment. This moment is dependent on the vertical spring constants and lateral spacing of the springs.

The height of the roll center plays an important part in the rolling tendency of a vehicle, as illustrated in Figure 33. As a truck goes around a horizontal curve, the centrifugal force causes the truck body to roll about its roll center. This will also cause the center of gravity to produce a moment about the roll center, due to its shift in position. The higher the roll center (i.e., the closer it is to the center of gravity), the shorter the moment arm and the smaller the moment that is produced.

Ideally, the roll stiffness at each axle should be proportional to the weight on that axle, which means that the roll stiffness of the trailer axles should be about the same as that of the tractor's rear axles. However, this is not usually the case. More typically, the trailer has a harder suspension than the tractor.

The range of roll stiffnesses for the various suspensions has been measured with a load of 5,500 kg [12,000 lb] on the front axles and 7,300 kg [16,000 lb] on the rear axles. A typical range of roll stiffnesses on a per axle basis is given in Table 37.

Roll Steer Coefficient: Dependent on the Layout of Links That Restrain the Axles

Nonsteering axles can deflect slightly to create a steering effect as a result of vehicle roll. As the truck body rolls, one side of the axle moves forward while the other side moves

TABLE 36 Typical range of roll center heights for truck suspension (*18*)

Type of suspension	Range of roll center height (in)
Front suspension	8.5 - 20
Air suspension	24 - 29.5
Four-spring	23 - 31
Walking beam	21.5 - 23
Single-axle leaf spring	25 - 28

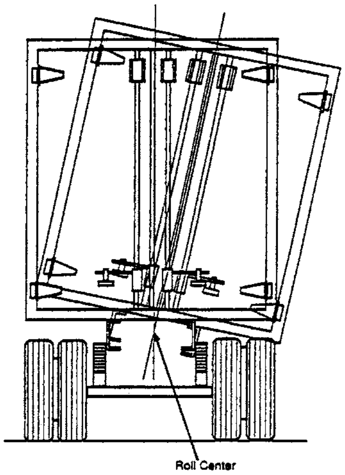


Figure 33. Diagram of roll by trailer body illustrating location of roll center (18).

aft. This unintentional steering is created by the suspension and tire forces. The tendency to steer in a roll is measured with respect to the amount of vehicle roll present. This steering can greatly affect truck handling, particularly in a turn.

The units used in measuring the roll steer coefficient are degrees of steer per degree of roll. A positive roll steer coefficient means that the axle will steer toward the outside of the turn; a negative coefficient means that the axle will steer toward the inside of the turn. A typical range of values is given in Table 38 on a per-axle basis.

LOAD TRANSFER RATIO

The extent to which vertical load is transferred from the tires on one side of a vehicle to those on the other side is called the *load transfer ratio*. Load is transferred when a vehicle is stationary on a lateral incline, when rounding a curve, and when making a steering maneuver such as to avoid an obstacle. It is calculated as follows:

$$\text{Load Transfer Ratio} = \text{Sum}(F_L - F_R)/\text{Sum}(F_L + F_R) \qquad (24)$$

where F_L and F_R are the tire loads on the left and right sides, respectively.

TABLE 37 Typical range of roll stiffness for truck suspension (*18*)

Type of suspension	Range of roll stiffness (in-lb/deg)
Front suspension	0.017 - 0.025
Air suspension	0.025 - 0.090
Four-spring	0.065 - 0.140
Walking beam	0.070 - 0.160
Single-axle leaf spring	0.052 - 0.089

TABLE 38 Typical range of roll steer coefficients for truck suspension (*18*)

Type of suspension	Range of roll steer (deg steer)/(deg roll)
Air suspension	0.01 - 0.23
Four-spring	–0.04 - 0.23
Walking beam	0.16 - 0.21
Single-axle leaf spring	0.0 - 0.07

The load transfer ratio has a value of 0.0 when the loads on the two sides are equal and ±1.0 when all the load is transferred to one side or the other. When the latter situation is just reached, the unloaded side is about to lift off from the pavement, and rollover is imminent. The load transfer ratio for an automobile or a single-unit truck is, for most practical purposes, a single number. For a combination vehicle, it can be computed separately for each unit; the unit with the greatest ratio is usually the most likely to come on the verge of rolling over. The truck properties affected by the load transfer ratio, other than impending rollover, include handling response time, roll steer, and rearward amplification.

ROLLOVER THRESHOLD

A vehicle’s resistance to rollover is measured by the maximum lateral acceleration that can be achieved without causing rollover. This maximum acceleration, measured in units of the acceleration of gravity (g), is known as the rollover threshold. Gillespie *(52)* reports the following typical values of rollover threshold:

Low-slung sports car	1.7 g
Normal passenger car	1.1-1.5 g
Pickup trucks and vans	0.8-1.1 g
Heavy trucks	0.4-0.6 g

A typical passenger car tracking a horizontal curve or making a turn at too high a speed will likely skid off the road because of inadequate tire-pavement friction long before its rollover threshold is reached. Trucks, on the other hand, generally have rollover thresholds that are less than the available tire-pavement friction on dry pavements. Indeed, Navin *(53)* states that “data conclusively show that fully laden heavy trucks, if involved in an accident on a curve, will most likely have rolled over.”

Truck rollovers are caused by high lateral accelerations in a turning maneuver. As lateral acceleration increases, the load transfer ratio approaches ±1.0, and the wheels on the inside of the turn begin to lift off the pavement. Generally, because of uneven load distribution and uneven suspension, tire, and structural stiffness, all of the wheels will not begin to lift off the pavement at the same time. Typically, the rear trailer wheels will be the first to lift off. It is possible for some wheels of a truck to lift off the pavement without producing a rollover; however, this is a very unstable situation and could ultimately lead to a rollover.

Earlier research, largely based on modeling, indicated that an extreme rollover threshold as low as 0.24 was possible *(50, 54)*. However, that work was based on older trucks that had widths of 2.4 m [8 ft] and incorporated a very unusual loading condition. But, beginning with the passage of the Surface Transportation Assistance Act (STAA) of 1982, truck widths increased to 2.6 m [8.5 ft]. This has a net effect of increasing the rollover threshold by 15 to 18%, as will be indicated shortly. Also, experimental data *(51, 55)* show that actual rollover thresholds tend to be 0.03 to 0.04 g higher than modeled values. Thus, a worst-case rollover threshold is now about 0.31 g.

The rollover threshold of a truck is largely a function of its loading configuration. The following parameters of a truck's loading configuration affect its rollover threshold:

- Center of gravity (CG) height,
- Overall weight,
- Longitudinal weight distribution, and
- Lateral weight distribution.

The sensitivity of truck rollover threshold to these parameters is reviewed below, based largely on results reported in a 1986 FHWA study *(55),* which have been confirmed by computer simulation analyses reported in the FHWA *Truck Characteristics* study *(2, 3).* These findings include

- For the baseline case of a 36,400-kg [80,000-lb] semitrailer truck, with medium density (34 lb/ft^3) cargo, loaded evenly left to right and fore and aft on a 2.4-m [8-ft] wide trailer (a pre-STAA trailer), the computed rollover threshold is 0.35 g.
- If the trailer and tractor are widened to 2.6 m [8.5 ft], and the tire spacing and spring spacing are widened accordingly, the rollover threshold is increased by 15 to 18%.
- If the cargo is less dense, it will fill more of the trailer and its CG height will be increased. The rollover threshold is reduced by about 0.005 g for every inch the CG is raised. Typical less-than-truckload (LTL) cargo is less dense, but is not of uniform density. Such cargo is normally loaded with the denser cargo on the bottom, and the lighter cargo on top. A "typical" fully loaded LTL trailer will have a CG height of 2.4 m [7.9 ft]. The worst-case scenario is a truck with maximum gross weight with the trailer filled to the roof ("cubed out") with uniform density cargo. The cargo density would be about 18.7 lb/ft^3, and its CG height would be about 2.7 m [8.8 ft]. Recent research found a rollover threshold of 0.34 g for a truck loaded with LTL freight (*56*).
- Adding weight to the truck by adding more of the same cargo on top of the existing load raises the CG and lowers the rollover threshold. The effect is a reduction of about 0.01 g per added ton.
- If the load is not centered left to right in the truck, its rollover threshold is raised on turns in the direction to which the load is offset and reduced in turns in the opposite direction. The effect can be quite large—about 10% for each 76 mm [3 in] of offset. This amount would be realized, for example, if pallets designed for 2.4-m [8.0-ft] wide trailers were loaded along one side of a 2.6-m [8.5-ft] wide trailer.
- For the same width, weight, and CG height, double-trailer trucks consistently have rollover thresholds 0.03 to 0.05 g higher than semitrailers. Thus, semitrailers are the vehicles of most concern relative to rollover threshold.
- Rearward amplification in doubles caused by sudden maneuvers, such as obstacle avoidance, can lead to rollover of the rear trailer. However, this is more of a concern in emergency maneuvers than in normal tracking of a curve or turn, which is the basis of geometric design.
- Trailer length, per se, has no appreciable effect on rollover threshold, provided that the axle loads are the same for longer and shorter trailers. Conversely, if the load on a shorter trailer is placed in a longer trailer, the CG would be lowered and the rollover threshold would be increased.
- The 1986 FHWA study analyzed accident data representing 9,000 single-vehicle accidents involving 5-axle semis (*51*). Of these, 2,000 resulted in a rollover. Using the reported gross vehicle weight, the authors of said study assumed medium-density freight (and a 2.4-m [8.0-ft] width, the standard at that time). With these assumptions, the CG height was calculated, along with the resulting rollover threshold. The distribution shown in Figure 34 was obtained. The lowest rollover threshold obtained was about 0.39 g. Of course, this represents an average of the actual minimum rollover thresholds because the actual cargo densities would have varied

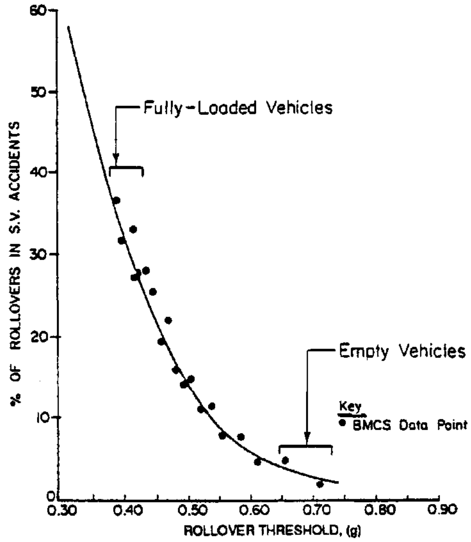


Figure 34. Percent of single-truck accidents in which rollover occurs as a function of rollover threshold (51).

about the assumed medium density. No data on cargo density were available, however.

- Most researchers suggest that a reasonable value for a minimum rollover threshold for loaded trucks is in the range from 0.35 to 0.40. In an appendix to the *U. S. Comprehensive Truck Size and Weight Study* (*57*), it is stated that fatal accident data show so few cases with rollover thresholds less than 0.35 that rates cannot be calculated. The authors of the study suggest this is because there are so few such vehicles on the road. Indeed, they go on to state that requiring a threshold of 0.38 g would make future fleets comparable with the current fleet with the exception of the very few trucks currently under the threshold.

CHAPTER 6

HIGHWAY GEOMETRIC DESIGN CRITERIA AND THEIR RELATIONSHIP TO TRUCK CHARACTERISTICS

This chapter provides a review of the appropriateness of individual highway geometric design criteria to accommodate trucks. The review includes the following highway geometric design criteria:

- Stopping sight distance,
- Passing sight distance and passing/no-passing zones on two-lane highways,
- Decision sight distance,
- Intersection sight distance,
- Railroad-highway grade-crossing sight distance,
- Intersection and channelization geometrics,
- Critical length of grade,
- Downgrades,
- Acceleration lanes,
- Deceleration lanes,
- Lane width,
- Horizontal curve radius and superelevation,
- Pavement widening on horizontal curves,
- Cross-slope breaks, and
- Vertical clearance.

Recommended changes in these geometric design criteria are presented in Appendix F.

The review of each individual highway geometric design criterion includes a discussion of the criterion or policy currently used by highway agencies, typically based on the *Green Book*, and a critique of that criterion based on available data or recent research concerning truck characteristics or concerning the traffic operational and safety effects of the criterion. These findings have been used to develop recommendations concerning the need to revise existing highway design policies to better accommodate trucks.

The starting point for many of the geometric design reviews presented below is the FHWA *Truck Characteristics* report *(2,3)*. This report reviewed all those design criteria in the 1984 Green Book and all those operational criteria in the 1988 MUTCD that were based on a passenger vehicle and assessed whether those criteria were adequate to accommodate trucks. In some cases, the analyses presented in that report are still valid and are presented here. In other cases, changes in geometric design policy or in truck characteristics in the intervening years make the previous evaluation obsolete; a new review, based on up-to-date information, has been performed in these cases. Each highway geometric design criterion is discussed below.

STOPPING SIGHT DISTANCE

Current Geometric Design Criteria

Sight distance is the length of roadway ahead that is visible to the driver. The minimum sight distance available on the roadway should be long enough to enable a vehicle traveling at the design speed to stop before reaching a stationary object in its path. This minimum sight distance, known as stopping sight distance, is the basis for design criteria for crest vertical curve length and minimum offsets to horizontal sight obstructions. Not only is stopping sight distance needed at every point on the roadway, but stopping sight distance also forms the basis for a number of additional highway design criteria, including intersection sight distance and railroad-highway grade-crossing sight distance.

Stopping Sight Distance Criteria

Stopping sight distance is determined as the summation of two terms: brake reaction distance and braking distance. The brake reaction distance is the distance traveled by the vehicle from when the driver first sights an object necessitating a stop to the instant the brakes are applied. The braking distance is the distance required to bring the vehicle to a stop once the brakes are applied.

Stopping sight distance criteria in the Green Book have undergone a thorough recent review and have been revised in the 2001 edition based on research by Fambro et al. *(37)*. Design values for stopping sight distance are based on the following model, which is based on Green Book Equation 3-2:

Metric	US Customary
$\mathrm{SSD} = 0.278\mathrm{Vt} + 0.039\dfrac{\mathrm{V}^2}{\mathrm{a}}$	$\mathrm{SSD} = 1.47\mathrm{Vt} + 1.075\dfrac{\mathrm{V}^2}{\mathrm{a}}$ (25)
where SSD = stopping sight distance, m t = brake reaction time, s; V = design speed, km/h; a = deceleration rate, m/s^2	where SSD = stopping sight distance, ft t = brake reaction time, s; V = design speed, mph; a = deceleration rate, ft/s^2

The first term in Equation 25 represents the brake reaction distance and the second term represents the braking distance. Equation 25 is not conceptually different from the stopping sight distance models used in previous editions of the Green Book, but the parameters of the model are now defined in ways that more realistically represent traffic situations encountered in emergency maneuvers.

The design values for stopping sight distance are presented in Table 39, based on Green Book Exhibit 3-1.

Correction of Stopping Sight Distance Criteria for Grades

Stopping sight distance is also affected by roadway grade because longer braking distance is required on a downgrade and shorter braking distance is required on an upgrade. The Green Book criteria for grade effects on stopping sight distance are derived with the following equation:

Metric	US Customary
$SSD = \dfrac{V^2}{254\left(\left(\dfrac{a}{9.81}\right) \pm G\right)}$	$SSD = \dfrac{V^2}{30\left(\left(\dfrac{a}{32.2}\right) \pm G\right)}$ (26)

In this equation, G is the percent of grade divided by 100, and the other terms are as previously stated. The stopping distances needed on upgrades are shorter than on level roadways; those needed on downgrades are longer.

On nearly all roads and streets, the grade is traversed by traffic in both directions of travel, but the sight distance at any point on the highway generally is different in each direction, particularly on straight roads in rolling terrain. As a general rule, the sight distance available on downgrades is larger than on upgrades, more or less automatically providing the appropriate corrections for grade. This may explain why designers do not adjust stopping sight distance because of grade. Exceptions are one-way roads or streets, as on divided highways with independent design profiles for the two roadways. For these separate roadways, adjustments for grade may be needed.

Application of Stopping Sight Distance Criteria to Crest Vertical Curves

Vertical crests limit the sight distance of the driver. Crest vertical curves designed in accordance with the AASHTO Green Book criteria should provide stopping sight distance at least equal to the design values in Table 39 at all points along the curve. The minimum length, L, of a crest vertical curve as a function of stopping sight distance is calculated based on Green Book Equations 3-43 and 3-44, as

Metric	US Customary
When SSD is less than L, $L = \dfrac{A(SSD)^2}{658}$	When SSD is less than L, $L = \dfrac{A(SSD)^2}{2158}$ (27)
When SSD is greater than L, $L = 2(SSD) - \dfrac{658}{A}$	When SSD is greater than L, $L = 2(SSD) - \dfrac{2158}{A}$ (28)
where A = algebraic difference in grade	

Equations 27 and 28 are based on the mathematical properties of a parabolic curve. The Green Book suggests that it is typical practice to use a minimum vertical curve length that is at least three times the value of the design speed (expressed in mph). For stopping sight distance, the driver eye height (h_1) used by AASHTO is 1,080 mm [3.5 ft] and the object height (h_2) used is 600 mm [2.0 ft]. Table 40 presents the minimum vertical curve lengths to attain the desirable stopping sight distance criteria in Table 39 as a function of design speed.

TABLE 39 Design values for stopping sight distance (*1*)

Metric					US Customary				
Design speed (km/h)	Brake reaction distance (m)	Braking distance on level (m)	Stopping sight distance Calculated (m)	Design (m)	Design speed (mph)	Brake reaction distance (ft)	Braking distance on level (ft)	Stopping sight distance Calculated (ft)	Design (ft)
20	13.9	4.6	18.5	20	15	55.1	21.6	76.7	80
30	20.9	10.3	31.2	35	20	73.5	38.4	111.9	115
40	27.8	18.4	46.2	50	25	91.9	60.0	151.9	155
50	34.8	28.7	63.5	65	30	110.3	86.4	196.7	200
60	41.7	41.3	83.0	85	35	128.6	117.6	246.2	250
70	48.7	56.2	104.9	105	40	147.0	153.6	300.6	305
80	55.6	73.4	129.0	130	45	165.4	194.4	359.8	360
90	62.6	92.9	155.5	160	50	183.8	240.0	423.8	425
100	69.5	114.7	184.2	185	55	202.1	290.3	492.4	495
110	76.5	138.8	215.3	220	60	220.5	345.5	566.0	570
120	83.4	165.2	248.6	250	65	238.9	405.5	644.4	645
130	90.4	193.8	284.2	285	70	257.3	470.3	727.6	730
					75	275.6	539.9	815.5	820
					80	294.0	614.3	908.3	910

NOTE: Brake reaction distance predicated on a time of 2.5 s; deceleration rate of 3.4 m/s^2 [11.2 ft/s^2] used to determine calculated sight distance.

TABLE 40 Design controls for stopping sight distance and for rate of vertical curvature (*1*)

Metric				US Customary			
Design speed (km/h)	Stopping sight distance (m)	Rate of vertical curvature, K[a]		Design speed (mph)	Stopping sight distance (ft)	Rate of vertical curvature, K[a]	
		Calculated	Design			Calculated	Design
20	20	0.6	1	15	80	3.0	3
30	35	1.9	2	20	115	6.1	7
40	50	3.8	4	25	155	11.1	12
50	65	6.4	7	30	200	18.5	19
60	85	11.0	11	35	250	29.0	29
70	105	16.8	17	40	305	43.1	44
80	130	25.7	26	45	360	60.1	61
90	160	38.9	39	50	425	83.7	84
100	185	52.0	52	55	495	113.5	114
110	220	73.6	74	60	570	150.6	151
120	250	95.0	95	65	645	192.8	193
130	285	123.4	124	70	730	246.9	247
				75	820	311.6	312
				80	910	383.7	384

[a] Rate of vertical curvature, K, is the length of curve per percent algebraic difference in intersecting grades (A). K = L/A

Application of Stopping Sight Distance Criteria to Horizontal Curves

Sight distance can also be limited by obstructions on the inside of horizontal curves, such as trees, buildings, retaining walls, and embankments. Horizontal curves designed in accordance with the Green Book should provide sight distance at least equal to the design values in Table 39 along the entire length of the curve. For a circular horizontal curve, the line of sight is a chord of that curve and the sight distance is measured along the centerline of the inside lane (see Figure 35). The minimum offset to a horizontal sight obstruction at the center of the curve (known as the middle ordinate of the curve) is computed in accordance with the following equation:

Metric	US Customary
$M = R\left[\left(1 - \cos\frac{28.65\mathrm{SSD}}{R}\right)\right]$	$M = R\left[\left(1 - \cos\frac{28.65\mathrm{SSD}}{R}\right)\right]$ (29)
where R = Radius of curve, m; M = Middle ordinate, m	where R = Radius of curve, ft; M = Middle ordinate, ft

Critique of Geometric Design Criteria

This section reviews the recent literature relevant to stopping sight distance criteria and their application to crest vertical curves and horizontal curves. The criteria are based on consideration of the passenger car as the design vehicle. The critique calls attention to differences between passenger cars and trucks that are relevant to stopping sight distance design.

Specific Aspects of Stopping Sight Distance

The critique that follows addresses the following aspects of stopping sight distance criteria:

- Assumed speed for design,
- Brake reaction time,
- Deceleration rate (or coefficient of tire-pavement friction) and braking distance,
- Driver eye height, and
- Object height.

In addition, the critique addresses horizontal sight. Each of these factors is discussed below.

Assumed Speed for Design. Prior to the 2001 Green Book, stopping sight distance was based on an assumed range of speeds, from the average running speed of traffic to the design speed, which resulted in a range of design values for stopping sight distance. The rationale for using this range of speeds was the assumption that drivers travel more slowly on wet pavements than on dry pavements; however, recent data have shown that drivers travel at about the same speeds on both wet and dry pavements. Therefore, the 2001 Green Book assumes that the initial speed of the vehicle prior to braking should be equal to the design speed of the roadway. This assumption appears to be as applicable to truck drivers as to passenger car drivers.

Brake Reaction Time. The brake reaction time (t) is set equal to 2.5 s in the 2001 Green Book, as in past design policies. This choice for brake reaction time has been confirmed

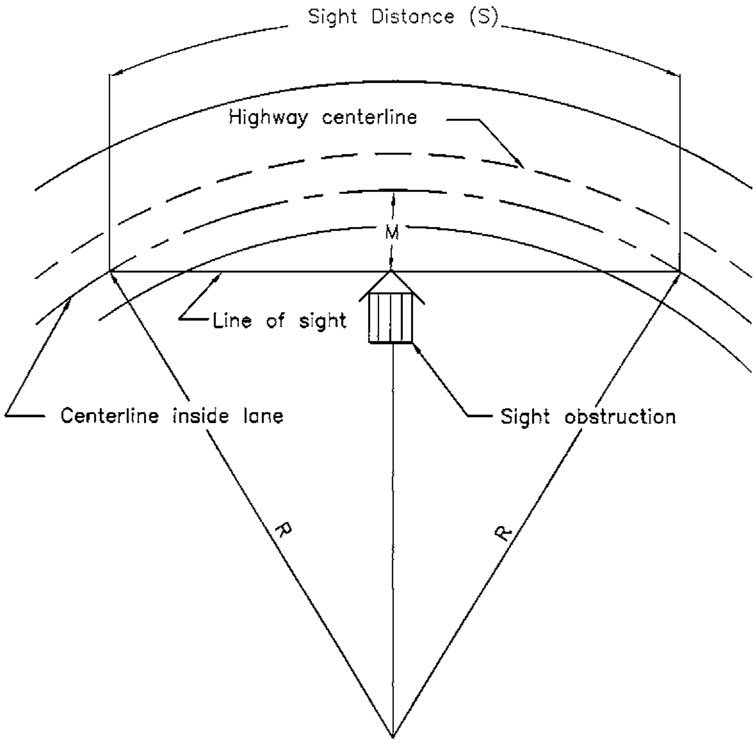


Figure 35. Diagram illustrating components for determining horizontal sight distance.

as appropriate for most drivers in several older studies *(28, 58)*. Recent research by Fambro et al. *(37)* has confirmed that 2.5 s represents the 90th percentile of brake reaction time for all drivers.

The brake reaction time is a driver characteristic and is assumed to be applicable to truck drivers as well as passenger car drivers. In fact, experienced professional truck drivers could reasonably be expected to have shorter brake reaction times than the driver population as a whole. On the other hand, the air brake systems historically used in tractor-trailer combination trucks have an inherent delay of approximately 0.5 s in brake application *(18)*. It appears to be a reasonable assumption that the factors offset one another and that the 2.5-s brake reaction time is appropriate for both passenger car and truck drivers.

Deceleration Rate and Braking Distance. The deceleration rate, *a*, in Equation 25 is set equal to 3.4 m/s^2 [11.2 ft/s^2] in the 2001 *Green Book*. This value was found by Fambro et al. *(37)* to represent the 10th percentile deceleration rate of passenger car drivers. This deceleration rate represents a comfortable value for controlled braking by a passenger car and is within the driver's capability to stay within his or her lane and maintain steering control during braking maneuvers on wet surfaces. Previous design policies were based on friction levels for locked-wheel braking, which carried with it a potential for loss of control of the vehicle. Thus, the 2001 *Green Book* criteria are based on an assumed maneuver that is more appropriate for trucks than previous editions of the *Green Book*.

The review of braking distances in Chapter 5 of the report indicates that trucks equipped with antilock brakes can achieve deceleration rates in controlled braking nearly equal to the rate used for passenger car drivers in the *Green Book*. Thus, as antilock brakes come into widespread use, braking distances and deceleration rates for passenger cars and trucks should come closer together. *NCHRP Synthesis 241 (19)* noted that braking distances for passenger cars and trucks differ on dry pavement, but are nearly the same on wet pavements; wet pavements are, of course, the most critical situation for stopping sight distance.

Appendix B discusses data collection activities undertaken to document the distribution of trailers with antilock brake systems in the current vehicle fleet. Results of the field studies show that approximately 42 percent of trailers are equipped with antilock brake systems. As a comparison, Vehicle Inventory and Use Survey (VIUS) data from 1997 show that approximately 21 percent of trucks were equipped with antilock brake systems at that time. Thus, the percentage of trailers equipped with antilock brake systems has approximately doubled from 1997 to 2002. It is expected that, within 10 years, nearly all trailers will be equipped with antilock brake systems. Thus, there is good reason to expect that, within 10 years, most trucks will be able to stop on wet pavements in the same distances as passenger cars. In addition, nearly all truck tractors are equipped with antilock brake systems.

Driver Eye Height. The minimum crest vertical curve criteria for stopping sight distance in Table 40 are based on a driver eye height for passenger cars of 1,080 mm [3.5 ft]. The driver eye heights for trucks are much higher than for passenger cars, which may partially or completely offset their longer braking distances on crest vertical curves. However, the higher eye heights of truck drivers provide no comparable advantage at sight obstructions on horizontal curves unless the truck driver is able to see over the obstruction. The Green Book uses a value of 2,400 mm [8.0 ft] for truck driver eye height. Because this value is based on the results of recent research by Fambro et al. *(37)*, it does not appear to be in need of updating.

Object Height. The object height used in the 2001 Green Book to determine crest vertical curve lengths is 600 mm [2.0 ft], which was chosen as a conservative value to represent the taillight height of a passenger car. Previous editions of the Green Book used object heights of 100 and 150 mm [4 and 6 in.]. These lower object heights represented an arbitrary rationalization of possible hazardous objects that could be found in the roadway. Some researchers maintain that, historically, these lower object heights represented a subjective tradeoff of the cost of providing sight distance to the pavement and did not represent any particular hazard *(59)*. An accident study by Fambro et al. *(37)* found that virtually no accidents occur involving objects in the 100- to 150-mm [4- to 6-in.] range. Most collisions involve objects at least 600 mm [2 ft] high including, predominantly, other vehicles and, to a lesser extent, pedestrians, bicyclists, and animals. The choice of the 600-mm [2-ft] object, representing vehicle taillights, for use in the Green Book, was based on the work of Fambro et al.

Horizontal Sight Obstructions

Increased eye height provides truck drivers no advantage over passenger car drivers at a horizontal sight obstruction, unless the truck driver can see over the obstruction. However, Olson et al. indicate that the minimum offset to a horizontal sight obstruction, represented by the middle ordinate of the curve computed with Equation 29, is normally required only near the center of a horizontal curve *(28)*. Figure 36 illustrates a sight distance envelope or *clear sight zone* within which horizontal sight obstructions should not be present. The figure illustrates that less offset to horizontal sight obstructions is required within a distance to the ends of the curve equal to one-half the stopping sight distance.

Another problem associated with stopping sight distance on horizontal curves is that the tire-pavement friction available for braking is reduced by the portion of the available tire-pavement friction that is required for cornering *(28, 60)*. Olson et al. expressed the available friction for braking on a horizontal curve as *(28)*:

$$f^2 = f_t^2 - \left(\frac{V^2}{15R} - e\right)^2 \qquad (30)$$

where

f = coefficient of friction available for braking
f_t = total available coefficient of friction
V = vehicle speed (mph)
R = radius of curvature (ft)
e = superelevation rate (ft/ft)

Equation 30 implies that the required stopping sight distances on horizontal curves should be longer than on tangents.

Truck Considerations

A sensitivity analysis conducted for the 1990 FHWA *Truck Characteristics* study *(2, 3)* concluded the following:

- The 1984 Green Book stopping sight distance criteria were adequate for trucks with antilock brake systems.

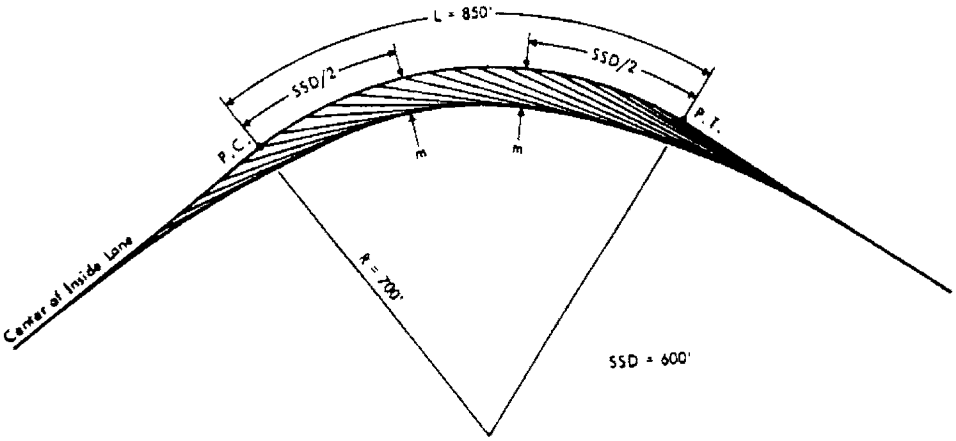


Figure 36. Example sight obstruction envelope on horizontal curves for condition where the stopping sight distance is less than the length of the curve (28).

- The 1984 Green Book stopping sight distance criteria were adequate for trucks with conventional brake systems and the best-performance driver at vertical sight restrictions and were nearly adequate at horizontal sight restrictions.
- The 1984 Green Book stopping sight distance criteria were not adequate to accommodate trucks with conventional brake systems and poor-performance drivers, but changes in stopping sight distance criteria to accommodate poor-performance drivers would only be cost-effective for new construction or major reconstruction projects on rural two-lane highways that carry more than 800 trucks per day and rural freeways that carry more than 4,000 trucks per day.

Given that antilock braking systems for trucks are coming into widespread use, these results suggest that changes to stopping sight distance policies to accommodate trucks should not be needed.

The recommended stopping sight distances in the Green Book are based on passenger car operation and do not explicitly consider design for truck operation. However, it does appear that the introduction of antilock brake systems on trucks minimizes any concern about stopping sight distance criteria for trucks in the long term.

One situation in the Green Book indicates that every effort should be made to provide stopping sight distances greater than the design values in Table 39: Where horizontal sight restrictions occur on downgrades, particularly at the ends of long downgrades where truck speeds closely approach or exceed those of passenger cars, the greater height of eye of the truck driver is of little value, even when the horizontal sight obstruction is a cut slope. Although the average truck driver tends to be more experienced than the average passenger car driver and quicker to recognize potential risks, the Green Book states that it is desirable under such conditions to provide stopping sight distance that exceeds the values in Table 39 or the values derived from Equation 26.

There is no indication in the literature whether the Green Book hypothesis that stopping sight distance for trucks is especially critical at the end of long downgrades is correct. Further research on this issue would be desirable. Such research could be performed using a computer simulation model. The most critical situation for consideration in such research would appear to be the combination of a downgrade and a superelevated horizontal curve.

PASSING SIGHT DISTANCE AND PASSING/ NO-PASSING ZONES ON TWO-LANE HIGHWAYS

Current Geometric Design and Marking Criteria

Two major aspects of geometric design criteria for passing and no-passing zones on two-lane highways are addressed in this section: passing sight distance and minimum passing zone length. This discussion addresses the *Green Book* criteria for passing sight distance, but also, for completeness, compares and contrasts these criteria with the criteria for passing sight distance and passing zone length in the FHWA *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) *(61)*.

Passing Sight Distance

Passing sight distance is needed where passing is permitted on two-lane, two-way highways to ensure that passing vehicles using the lane normally used by opposing traffic have a clear view ahead for a distance sufficient to minimize the possibility of collision with an opposing vehicle.

Geometric Design Criteria. The current design criteria for passing sight distance on two-lane highways set forth in the 2001 Green Book are essentially unchanged from the criteria in the 1965 AASHTO policy and are based on the results of field studies conducted between 1938 and 1941 and validated by another study conducted in 1958 *(62, 63, 64)*. Based on these studies, the Green Book policy defines the minimum passing sight distance as the sum of the following four distances:

- d_1 = distance traveled during perception and reaction time and during initial acceleration to the point of encroachment on the left lane,
- d_2 = distance traveled while the passing vehicle occupies the left lane,
- d_3 = distance between passing vehicle and opposing vehicle at the end of the passing maneuver (i.e., clearance distance), and
- d_4 = distance traveled by an opposing vehicle for two-thirds of the time the passing vehicle occupies the left lane, or $^2/_3$ of d_2.

Design values for the four distances described above were developed using the field data and the following assumptions stated in the Green Book:

- The passed vehicle travels at uniform speed.
- The passing vehicle reduces speed and trails the passed vehicle as it enters the passing section. (This is called a delayed pass.)
- When the passing section is reached, the passing driver requires a short period of time to perceive the clear passing section and to begin to accelerate.
- Passing is accomplished under what may be termed a delayed start and a hurried return in the face of opposing traffic. The passing vehicle accelerates during the maneuver, and its average speed during the occupancy

of the left lane is 16 km/h [10 mph] higher than that of the passed vehicle.

- When the passing vehicle returns to its lane, there is a suitable clearance length between it and any oncoming vehicle in the other lane.

The design values for the four components of passing sight distance are shown in Figure 37, based on Green Book Exhibit 3-4. Table 41, Figure 38, and Table 42 illustrate the development of the design values for passing sight distance. The columns in Table 41 not headed by a value of design speed represent field data from the sources cited above for the four components of the passing maneuver identified above.

Figure 38 illustrates the distances for these four components of the passing maneuver graphically, as well as the total passing sight distance, which is the sum of d_1 through d_4. Table 42 presents the design values of passing sight distance for design speeds from 30 to 130 km/h [20 to 80 mph].

In Table 42, the speeds used to compute the design values for passing sight distance differ from the design speed of the highway. The speed of the passed vehicle is assumed to represent the average running speed of traffic. The speed of the passed vehicle is up to 36 km/h [22 mph] less than the design speed of the highway. The speed of the passing vehicle is assumed to be 15 km/h [10 mph] higher than the speed of the passed vehicle.

The distance traveled during the initial maneuver period (d_1) is computed in the Green Book as follows:

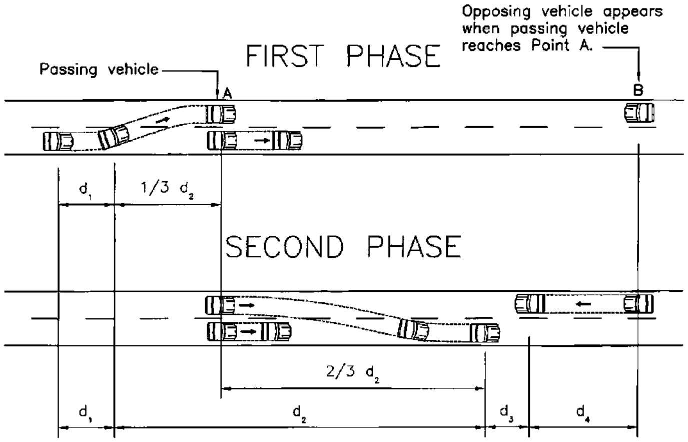


Figure 37. Elements of passing sight distance for two-lane highways (1).

TABLE 41 Elements of safe passing sight distance for design of two-lane highways (*1*)

	Metric				US Customary			
Component of passing maneuver	Speed range (km/h)				Speed range (mph)			
	50-65	66-80	81-95	96-110	30-40	40-50	50-60	60-70
	Average passing speed (km/h)				Average passing speed (mph)			
	56.2	70.0	84.5	99.8	34.9	43.8	52.6	62.0
Initial maneuver:								
a = average acceleration[a]	2.25	2.30	2.37	2.41	1.40	1.43	1.47	1.50
t_1 = time (sec)[a]	3.6	4.0	4.3	4.5	3.6	4.0	4.3	4.5
d_1 = distance traveled	45	66	89	113	145	216	289	366
Occupation of left lane:								
t_2 = time (sec)[a]	9.3	10.0	10.7	11.3	9.3	10.0	10.7	11.3
d_2 = distance traveled	145	195	251	314	477	643	827	1030
Clearance length:								
d_3 = distance traveled[a]	30	55	75	90	100	180	250	300
Opposing vehicle:								
d_4 = distance traveled	97	130	168	209	318	429	552	687
Total distance, $d_1 + d_2 + d_3 + d_4$	317	446	583	726	1040	1468	1918	2383

[a] For consistent speed relation, observed values adjusted slightly.

NOTE: In the metric portion of the table, speed values are in km/h, acceleration rates in km/h/s, and distances are in meters. In the U.S. customary portion of the table, speed values are in mph, acceleration rates in mph/sec, and distances are in feet.

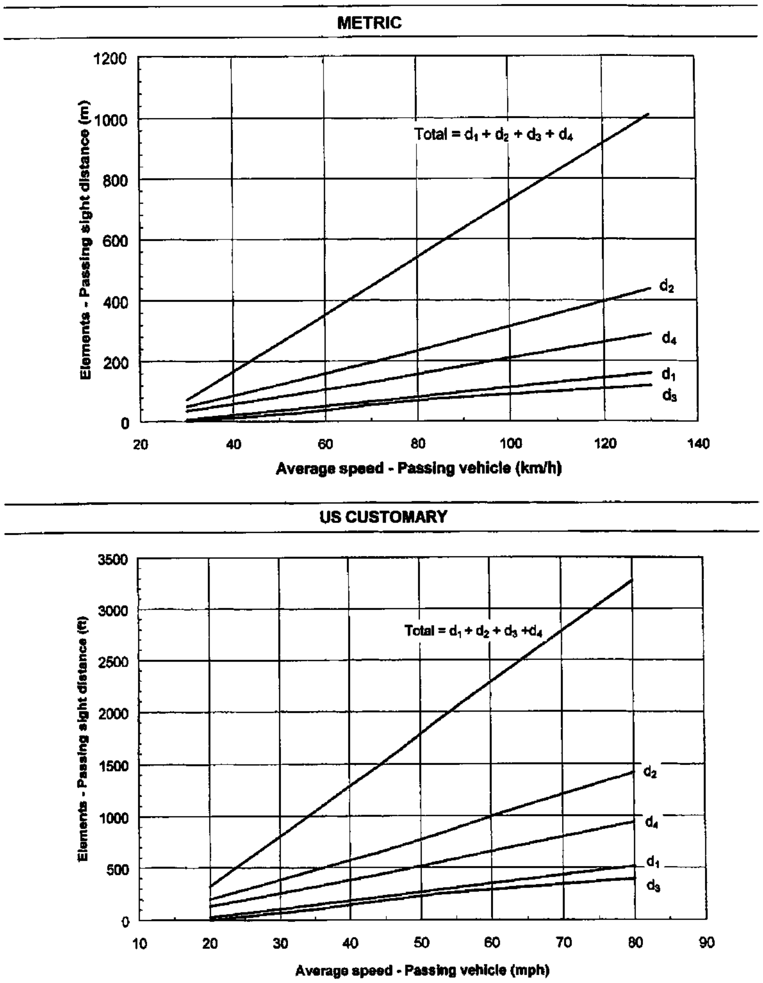


Figure 38. Total passing sight distance and its components—two-lane highway (1).

Metric	US Customary
$d_1 = 0.278t_i\left(v - m + \frac{at_i}{2}\right)$	$d_1 = 0.47t_i\left(v - m + \frac{at_i}{2}\right)$ (31)
where t_i = time of initial maneuver, s; a = average acceleration, km/h/s; v = average speed of passing vehicle, km/h; m = difference in speed of passed vehicle and passing vehicle, km/h	where t_i = time of initial maneuver, s; a = average acceleration, mph/s; v = average speed of passing vehicle, mph; m = difference in speed of passed vehicle and passing vehicle, mph

The Green Book policy estimates the time for the initial maneuver (t_1) as within the 3.6 to 4.5 s range, based on field data. Similarly, the average acceleration rate during the initial maneuver ranges from 2.22 to 2.43 km/h/s [1.38 to 1.51 mph/s].

The distance traveled by the passing vehicle while occupying the left lane (d_2) is estimated in the Green Book from the following equation:

Metric	US Customary
$d_2 = 0.278vt_2$	$d_2 = 1.47vt_2$ (32)
where t_2 = time passing vehicle occupies the left lane, s; v = average speed of passing vehicle, km/h	where t_2 = time passing vehicle occupies the left lane, s; v = average speed of passing vehicle, mph

Based on field data, the Green Book assumes that the time the passing vehicle occupies the left lane ranges from 9.3 to 11.3 s for speed ranges from 50 to 110 km/h [30 to 70 mph].

The clearance distance (d_3) is estimated in the Green Book to range from 30 to 90 m [100 to 300 ft], depending on speed.

The distance traveled by an opposing vehicle (d_4) is estimated as two-thirds of the distance traveled by the passing vehicle in the left lane. Conservatively, the distances d_2 and d_4 should be equal, but the Green Book assumes that the passing vehicle could abort its pass and return to the right lane if an opposing vehicle should appear early in the passing maneuver.

TABLE 42 Passing sight distance for design of two-lane highways (*1*)

Metric					US Customary				
	Assumed speeds (km/h)		Passing sight distance (m)			Assumed speeds (mph)		Passing sight distance (ft)	
Design speed (km/h)	Passed vehicle	Passing vehicle	Calculated	Rounded for design	Design speed (mph)	Passed vehicle	Passing vehicle	Calculated	Rounded for design
30	29	44	200	200	20	18	28	706	710
40	36	51	266	270	25	22	32	897	900
50	44	59	341	345	30	26	36	1088	1090
60	51	66	407	410	35	30	40	1279	1280
70	59	74	482	485	40	34	44	1470	1470
80	65	80	538	540	45	37	47	1625	1625
90	73	88	613	615	50	41	51	1832	1835
100	79	94	670	670	55	44	54	1984	1985
110	85	100	727	730	60	47	57	2133	2135
120	90	105	774	775	65	50	60	2281	2285
130	94	109	812	815	70	54	64	2479	2480
					75	56	66	2578	2580
					80	58	68	2677	2680

Table 41 illustrates the derivation of the Green Book passing sight distance criteria, representing the sum of the distances d_1 through d_4 for specific speed ranges. Table 42 presents the Green Book passing sight distance criteria for specific design speeds. These design values range from 200 to 815 m [710 to 2,680 ft] for design speeds from 30 to 130 km [20 to 80 mph]. The Green Book criteria are used in highway design to determine if a particular highway project has sufficient length with passing sight distance to ensure an adequate level of service on the completed highway. The acceptable level of service for a particular project is considered to be a design decision and is not specified in the Green Book. The Green Book criteria for passing sight distance are not used in the marking of passing and no-passing zones.

Marking Criteria. The criteria for marking passing and no-passing zones on two-lane highways are set by the MUTCD. Passing zones are not marked directly. Rather, the warrants for no-passing zones are established by the MUTCD, and passing zones merely happen where no-passing zones are not warranted. Table 43 presents the MUTCD passing sight distance warrants for no-passing zones. These criteria are based on prevailing off-peak 85th-percentile speeds rather than design speeds.

The MUTCD passing sight distance warrants are substantially less than the Green Book passing sight distance design criteria. For example, at a speed of 100 km/h [60 mph], the AASHTO and MUTCD passing sight distance criteria are 670 m [2,135 ft] and 320 m [1,000 ft], respectively.

The rationale for the MUTCD passing sight distance criteria is not stated in the MUTCD. However, the MUTCD warrants are identical to those presented in the 1940 AASHTO policy on marking no-passing zones *(65)*. These earlier AASHTO warrants represent a subjective compromise between distances computed for flying passes and distances computed for delayed passes. As such, they do not represent any particular passing situation. Table 44 presents the basic assumptions and data used to derive the MUTCD passing sight distance warrants.

TABLE 43 Minimum passing sight distance for marking passing and no-passing zones on two-lane highways (*61*)

Metric		U.S. Customary	
85th percentile speed or posted or statutory speed limit (km/h)	Minimum passing sight distance (m)	85th percentile speed or posted or statutory speed limit (mph)	Minimum passing sight distance (ft)
40	140	25	450
50	160	30	500
60	180	35	550
70	210	40	600
80	245	45	700
90	280	50	800
100	320	55	900
110	355	60	1,000
120	395	65	1,100
		70	1,200

TABLE 44 Derivation of MUTCD passing sight distance warrants (based on 1940 AASHTO policy) (*65*)

	Speed of passing vehicle (mph)				
	30	40	50	60	70
Assumed speed differential between passing and passed vehicles (mph)	10	12	15	20	25
Assumed speed of opposing vehicle (mph)	25	32	40	46	55
Required sight distance for flying pass (ft)	440	550	660	660	660
Required sight distance for delayed pass (ft)	510	760	1,090	1,380	1,780
Recommended minimum sight distance (ft)	500	600	800	1,000	1,200

Minimum Passing Zone Length

Another consideration in the marking of passing and no-passing zones on two-lane highways is the minimum length of a passing zone. The Green Book does not address passing zone lengths at all. The MUTCD indirectly sets a minimum passing zone length of 120 m [400 ft] by stating that, when two no-passing zones come within 120 m [400 ft] of one another, the no-passing barrier stripe should be continued between them.

Critique of Geometric Design and Marking Criteria

Passing Sight Distance

Clearly, the AASHTO and MUTCD passing sight distance criteria are incompatible. The design values for the individual component distances in the Green Book criteria are questionable because, at high speeds, they are based on vehicle speeds less than the design speed of the highway. On the other hand, the definition of passing sight distance as the sum of the four distance elements (d_1 through d_4) is extremely conservative, because it assumes that very early in the passing maneuver, the passing driver is committed to complete the pass. In fact, observation of two-lane highway operations shows that passing drivers frequently abort passing maneuvers.

The MUTCD passing sight distance criteria are based on a questionable premise, given that they represent a compromise between delayed passes and flying passes. A delayed pass is a maneuver in which the passing vehicle slows to the speed of the passed vehicle before initiating the passing maneuver. A flying pass is a maneuver in which the passing vehicle comes up behind the passed vehicle at a speed higher than the passed vehicle and initiates the passing maneuver without slowing down to the speed of the passed vehicle. Furthermore, both the AASHTO and MUTCD criteria are based on field data collected nearly 50 years ago. These field studies considered only passenger cars, not passing maneuvers involving longer and less powerful vehicles such as trucks. Neither the AASHTO nor MUTCD models for passing sight distance contain a vehicle length term that could be used to examine the differences between passing sight distance requirements for trucks and passenger cars. Over the last three decades, researchers have recognized the inconsistencies between the AASHTO and MUTCD policies and have investigated alternative formulations of passing sight distance criteria. A total of 13 studies published since 1970 have questioned the premises of the AASHTO and MUTCD models and/or suggested revisions to those models *(66–78)*. In the early 1970s, two studies independently recognized that a key stage of a passing maneuver occurs at the point where the passing driver can no longer safely abort the pass and is, therefore, committed to complete it. One study called this the *point of no return* and another called it the *critical position (66, 67)*. A 1976 paper added the insight that the critical position is the point at which the sight distances required to abort the pass and to complete the pass are equal *(68)*. Until the critical position is reached, the passing vehicle can abort the pass and return to the right lane behind the passed vehicle. Beyond the critical position, the driver is committed to complete the pass, because the sight distance required to abort the pass is greater than the sight distance required to complete the pass. The critical position concept has also been incorporated in research on passing sight distance requirements published in 1982, 1984, 1988, and 1989 *(69, 70, 75, 76)*.

Several of the studies cited above formulated passing sight distance models based on the critical position concept. However, each of these models contained one or more logical flaws that made the model invalid. In 1988, however, Glennon formulated a new passing sight distance model that accounts for the kinematic relationships between the passing, passed, and opposing vehicles *(75)*. The location of the critical position is determined as follows:

$$\Delta_C = L_P + 1.47\,m\left[\frac{(2.93\,m + L_I + L_P)}{1.47(2V - m)} - \frac{\sqrt{4V(2.93\,m + L_I + L_P)}}{d(2V - m)}\right] \quad (33)$$

where

Δ_C = critical separation (distance from front of passing vehicle to front of passed vehicle at critical position) (ft)
V = speed of passing vehicle and opposing vehicle (mph)
m = speed difference between passed vehicle and passing vehicle (mph)
d = deceleration rate used in aborting a passing maneuver (ft/s^2)
L_P = length of passing vehicle (ft)
L_I = length of passed vehicle (ft)

When the location of the critical position is known, the critical passing sight distance can be computed as follows:

$$PSD_C = 2V\left[2.93 + \frac{L_P - \Delta_C}{1.47m}\right] \qquad (34)$$

The assumptions of the Glennon model are as follows:

- The maximum sight distance during a passing maneuver is required at the critical position at which the sight distances required to complete the pass or to abort the pass are equal.
- The speeds of the passing vehicle and opposing vehicle are equal.
- The passing vehicle has sufficient acceleration capability to attain the specified speed difference relative to the passed vehicle by the time it reaches the critical position.
- If the passing vehicle completes its pass, it returns to its normal lane with a 1-s gap in front of the passed vehicle.
- If the passing vehicle aborts its pass, it returns to its normal lane with a 1-s gap behind the passed vehicle.
- The minimum clearance time between the passing vehicle and an opposing vehicle is 1 s.

The derivation of the Glennon model, as given in Equations 33 and 34, is presented in the literature and will not be repeated here *(75)*.

The Glennon model combined with accepted enforcement practices provides a very safety-conservative approach for marking passing and no-passing zones on two-lane highways. If the passing sight distance determined from Equation 34 is available throughout a passing zone, then it is ensured that a passing driver in the critical position at any point within that zone (even at the very end) has sufficient sight distance to complete the passing maneuver safely. In most terrain, passing sight distance substantially greater than the minimum will be available throughout most of the passing zone. It must always be recognized that some drivers will illegally start a passing maneuver before the beginning of a passing zone (jumping) or complete it beyond the end of the zone (clipping). However, given that the sight distance requirements of passing drivers are lower in the early and later stages of a passing maneuver than at the critical position, the model provides assurance that jumping and clipping drivers are unlikely to be greatly at risk of collision with an opposing vehicle. Finally, it should be recognized that the assumptions for a critical passing situation given above (e.g., passing and opposing vehicles traveling at the design speed of the highway, 1-s clearance time to an opposing vehicle, and so forth) represent an *extremely* rare combination of events that does not occur often on two-lane highways.

An advantage of the Glennon model is that the lengths of the passing and passed vehicles appear explicitly so that the sensitivity of the required passing sight distance to vehicle length can be examined.

Minimum Passing Zone Length

The MUTCD minimum passing zone length of 120 m [400 ft] is clearly inadequate for high-speed passes. A 1970 study evaluated several very short passing zones *(79)*. In two passing zones with lengths of 120 and 200 m [400 and 640 ft], it was found that very few passing opportunities were accepted in such short zones and, of those that were accepted, more than 70 percent resulted in a slightly forced or very forced return to the right lane in the face of opposing traffic.

A 1971 study recommended that the minimum length of a passing zone should be the sum of the perception-reaction distance (d_1) and the distance traveled while occupying the left lane (d_2) *(67)*. Table 45 illustrates several alternative criteria

TABLE 45 Alternative criteria for minimum length of passing zones on two-lane highways (*2,3*)

	Minimum length of passing zone (ft)		
Design speed (mph)	Based on MUTCD criteria	Based on $d_1 + d_2$ from AASHTO policy	Based on 85th percentile $d_1 + d_2$ observed in field studies*(65)*
20	400	505	–
30	400	650	–
40	400	865	–
50	400	1,065	–
55	400	1,155	885
60	400	1,245	–
65	400	1,340	1,185
70	400	1,455	1,335

that could be used for the minimum length of a passing zone, including the implicit MUTCD criteria, the sum of distances d_1 and d_2 based on the assumptions in Green Book policy, and the 85th percentile value of the sum of distances d_1 and d_2 based on field observations *(2,3)*.

Sensitivity Analyses Based on Truck Characteristics

The design criteria for minimum passing sight distance and minimum passing zone length are sensitive to three major vehicle characteristics: vehicle length, acceleration/deceleration capabilities, and driver eye height. Sensitivity analyses of these variables are presented below. These sensitivity analyses are based on the 1990 FHWA *Truck Characteristics* study *(2,3)*, but have been updated to account for changes in truck characteristics and changes in Green Book and MUTCD criteria since those original sensitivity analyses were performed.

Passing Sight Distance

The existing design and marking criteria for minimum passing sight distance are based on consideration of passenger cars as both the passing and passed vehicles. The sensitivity analysis presented below considers three other passing scenarios: a passenger car passing a truck, a truck passing a passenger car, and a truck passing another truck.

Passenger Car Passing Truck. Neither the AASHTO nor the MUTCD models can be used to examine the sensitivity of passing sight distance requirements to vehicle length. However, a major advantage of the Glennon model is that the lengths of the passing and passed vehicles appear explicitly in the model. Therefore, this model has been used to compare the passing sight distance requirements for passenger cars and trucks.

The lengths of the vehicles in the sensitivity analyses that follow are based on the length of the AASHTO passenger car design vehicle (6 m [19 ft]) and the length of a relatively long truck (23 m [75 ft]).

In computing passing sight distance requirements with the Glennon model, presented above in Equations 33 and 34, the deceleration rate, d, used by a passenger car in aborting a pass is assumed to be 2.4 m/s^2 [8 ft/s^2]. This is a relatively conservative deceleration rate for a passenger car on a dry pavement, but it approaches a maximum deceleration rate in braking on a poor, wet road.

The sensitivity analysis considered two alternative sets of assumptions concerning the speeds of the passing and passed vehicles. The first set consists of the standard AASHTO assumptions that the passed vehicle travels at the average running speed of the highway (see Table 41) and that the speed differential, *m*, between the passing and passed vehicles is a constant 16 km/h (10 mph) at all design speeds. The second set of assumptions was that proposed by Glennon, based on field data *(67, 75)*. Glennon proposed that the passing vehicle should be assumed to travel at the design speed of the highway, but that the speed differential, *m*, between the passing and passed vehicles should be a function of design speed as shown in Table 46.

Table 47 presents the passing sight distance requirements for a passenger car passing a truck using the Glennon model and Glennon's assumptions concerning vehicle speeds, presented above. (An alternative analysis with the standard AASHTO assumptions concerning vehicle speeds yielded very similar results.) For comparative purposes, the passing sight distance requirements for a passenger car passing another passenger car are presented in three different ways: (1) based on AASHTO policy, (2) based on the MUTCD warrants, and (3) based on the Glennon model.

Table 47 shows that the passing sight distance requirements for passenger cars obtained from the Glennon model are very similar to the MUTCD criteria. The passing sight distance requirements for a passenger car passing a truck are 8 to 76 m [25 to 250 ft] higher than for a passenger car passing a passenger car, depending on speed. The Green Book sight distance requirements are much longer than any of the other criteria, because of their very conservative assumptions.

Truck Passing Passenger Car. The passing sight distance requirements for a truck passing a passenger car can be addressed through a slight modification of the Glennon model. It is unlikely that a truck would be able to sustain a speed difference as large as a passenger car in performing a passing maneuver. No data are available on the speed differences actually used by trucks in passing, but, for purposes of this analysis, it will be assumed that trucks can maintain only one-half of the speed difference used by passenger cars. This assumption has been implemented in the following analysis by keeping the speed of the passed and opposing vehicles constant and decreasing the speed of the passing vehicle. Given that the speeds of the passing and opposing vehicles are no longer equal, a revised version of the Glennon model was derived and used for this analysis. This revised model for passing maneuvers by trucks is equivalent to Equations 33 and 34 with $0.5\,(V_p + V_o)$ substituted for the V term, where

V_p = speed of the passing vehicle (mph)

V_o = speed of the opposing vehicle (mph)

TABLE 46 Speed differentials between passing and passed vehicles for particular design speeds (*75*)

Design speed (mph)	Speed differential (mph)
30	12
40	11
50	10
60	9
70	8

TABLE 47 Sight distance requirements for passing by passenger cars based on Glennon model (*75*)

Design or prevailing speed (mph)	AASHTO policy	MUTCD criteria	Required passing sight distance (ft)	
			Passenger car passing passenger car	Passenger car passing truck
20	800	–	325	350
30	1,100	500	525	575
40	1,500	600	700	800
50	1,800	800	875	1,025
60	2,100	1,000	1,025	1,250
70	2,500	1,200	1,200	1,450

A truck is also not likely to use a deceleration rate as high as 2.4 m/s^2 [0.25 g or 8 ft/s^2] in aborting a pass except in an emergency situation. Therefore, a deceleration rate of 1.5 m/s^2 [0.15 g or 5 ft/s^2], which would be a comfortable deceleration rate on a dry pavement, has been assumed.

Table 48 presents the passing sight distance requirements for a 23-m [75-ft] truck passing a 6-m [19-ft] passenger car under the assumptions discussed above. The passing sight distance requirements for a truck passing a passenger car are 8 to 130 m [25 to 425 ft] more than for a passenger car passing a passenger car, depending on speed.

Truck Passing Truck. The passing sight distance requirements for a truck passing a truck have also been examined and are also presented in Table 48. Both vehicles are assumed to be 23 m [75 ft] in length. The passing sight distance requirements for a truck passing another truck were found to be 8 to 206 m [25 to 675 ft] longer than for a passenger car passing a passenger car, depending on speed.

Comparison of Results. Figure 39 compares the passing sight distance requirements determined in the sensitivity analysis with the current AASHTO and MUTCD policies.

TABLE 48 Sight distance requirements for passing by trucks based on revised Glennon model

Design or prevailing speed (mph)	AASHTO policy	MUTCD criteria	Required passing sight distance (ft)	
			Truck passing passenger car	Truck passing truck
20	800	–	350	350
30	1,100	500	600	675
40	1,500	600	875	975
50	1,800	800	1,125	1,275
60	2,100	1,000	1,375	1,575
70	2,500	1,200	1,625	1,875

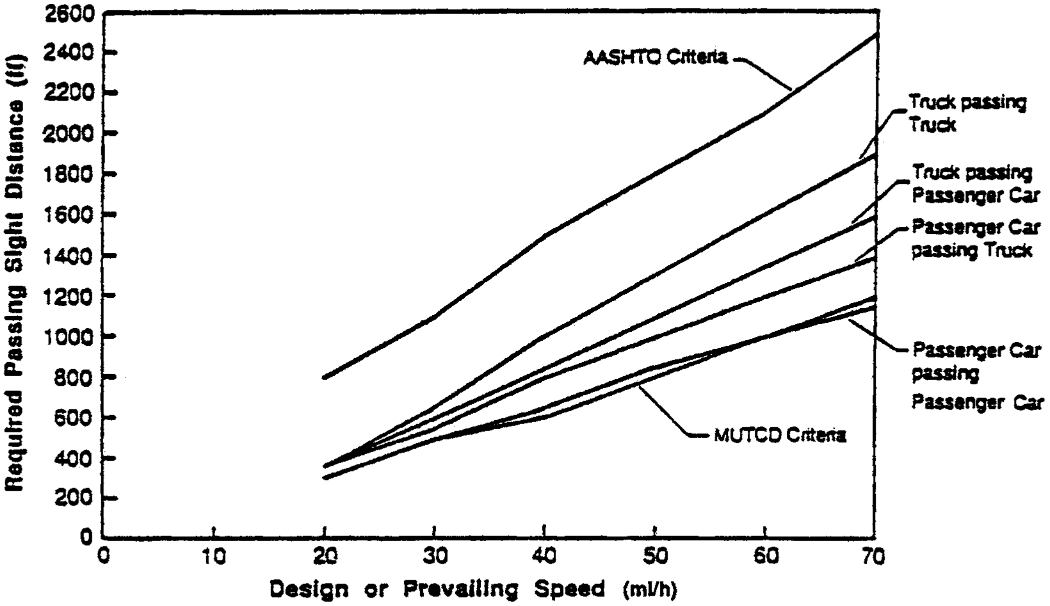


Figure 39. Required passing sight distance for passenger cars and trucks in comparison with current criteria (2,3).

The figure indicates that the MUTCD criteria are in good agreement with the requirements for a passenger car passing another passenger car. The other passing scenarios—passenger car passing truck, truck passing passenger car, and truck passing truck—each require progressively more sight distance, but all are substantially less than the current AASHTO Green Book criteria. Figure 40 compares the minimum passing zone lengths for the same scenarios. The development and interpretation of these curves is addressed in the discussion of minimum passing zone length that follows.

Effect of Driver Eye Height at Crest Vertical Curves. Where passing sight distance is restricted by a vertical curve, the truck driver has an advantage over a passenger car driver due to greater eye height. However, as in the case of stopping sight distance, the truck driver has no such advantage where passing sight distance is restricted by a horizontal sight obstruction.

Table 49 presents the required minimum vertical curve lengths to maintain passing sight distance over a crest as determined in the FHWA *Truck Characteristics* study *(2, 3)* for the four passing scenarios addressed in Tables 47 and 48. Table 49 has been updated to use eye heights of 1,080 mm [3.5 ft] for a passenger car driver and 2,330 mm [7.6 ft] for a truck driver based on the design recommendations of the 2001 Green Book.

Table 49 indicates that increased driver eye height partially, but not completely, offsets the greater passing sight distance requirements of trucks. At all speeds above 48 km/h [30 mph], a longer minimum vertical curve length is required to maintain adequate passing sight distance for passing maneuvers involving trucks than for a passenger car passing another passenger car. However, except at high speeds and large algebraic differences in grades (e.g., sharp crests), a truck can safely pass a passenger car on any vertical curve where a passenger car can safely pass a truck.

Minimum Passing Zone Length

There are currently no design or operational criteria for minimum passing zone length, other than the default 120-m [400-ft] guideline set by the MUTCD. One possible criterion for minimum passing zone length is the distance required for a vehicle traveling at or near the design speed of the highway to pass a slower vehicle. Recent debate over the role of trucks in passing sight distance criteria has largely ignored the longer passing distances and, thus, longer passing zone lengths required for passing maneuvers involving trucks.

A sensitivity analysis of passing distances has been conducted based on the following assumptions:

- The distance required to complete a pass is the sum of the initial maneuver distance (d_1) and the distance traveled in the left lane (d_2).
- The passing driver does not begin to accelerate in preparation for the passing maneuver until the beginning of the passing zone is reached.
- The initial maneuver distance (d_1) for passes by both passenger cars and trucks can be determined using the AASHTO relationship presented in Equation 31. The

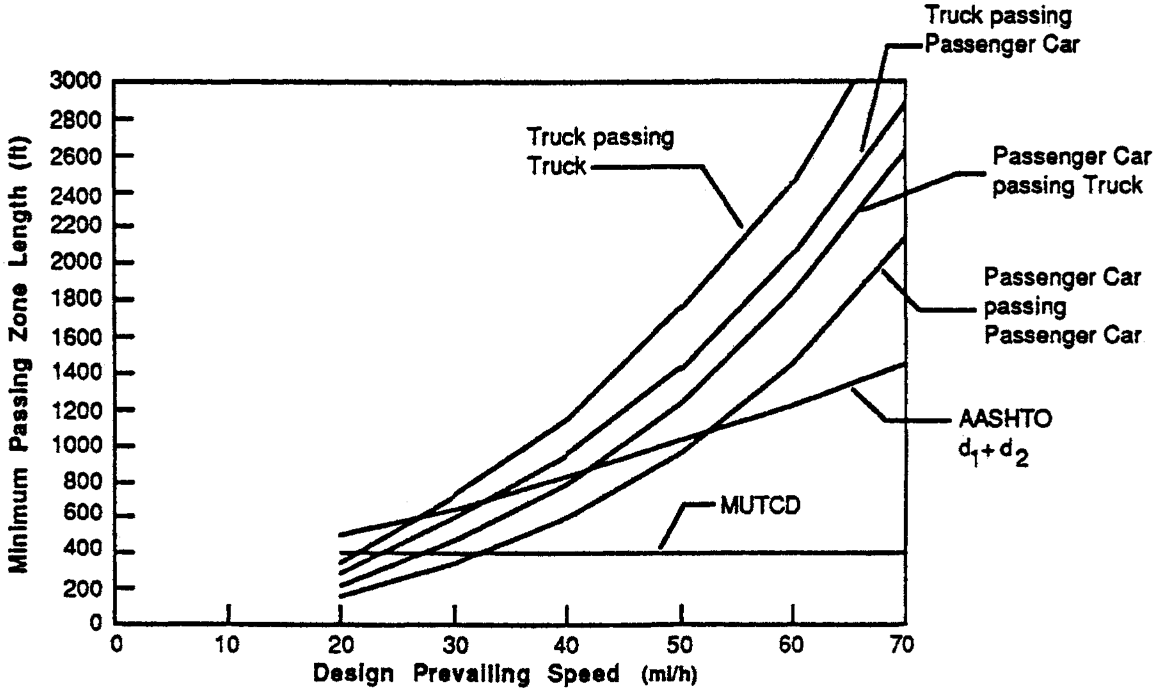


Figure 40. Required passing zone length to complete a pass at or near the highway design speed.

TABLE 49 Minimum vertical curve length (ft) to maintain required passing sight distance

Algebraic difference in grade (%)	Design speed (mph)					
	20	30	40	50	60	70
Passenger car passing passenger car[a]						
2	80	200	350	550	760	1,030
4	160	400	700	1,100	1,510	2,060
6	230	600	1,050	1,650	2,260	3,090
8	310	790	1,400	2,190	3,010	4,120
10	380	990	1,750	2,740	3,760	5,150
Passenger car passing truck[a]						
2	90	240	460	760	1,120	1,510
4	180	480	920	1,510	2,240	3,010
6	270	710	1,380	2,260	3,350	4,510
8	350	950	1,830	3,010	4,470	6,010
10	440	1,190	2,290	3,760	5,590	7,510
Truck passing passenger car[b]						
2	60	170	360	600	890	1,240
4	120	340	720	1,190	1,770	2,470
6	180	510	1,080	1,780	2,650	3,700
8	230	680	1,430	2,370	3,540	4,940
10	290	850	1,790	2,960	4,420	6,170
Truck passing truck[b]						
2	60	220	450	760	1,160	1,650
4	120	430	890	1,520	2,320	3,290
6	180	640	1,340	2,280	3,480	4,930
8	230	860	1,780	3,040	4,640	6,570
10	290	1,070	2,220	3,800	5,800	8,210

[a] Based on sight distance requirements from Table 47 for passenger car driver eye height of 1,080 mm [3.5 ft].

[b] Based on sight distance requirements from Table 48 for truck driver eye height of 2,330 mm [7.6 ft].

passing vehicle is assumed to accelerate at a constant rate, a, until the desired speed differential, m, relative to the passed vehicle is reached. Thus, t_l can be calculated as m/a.

- The acceleration rate, a, and initial maneuver time, t_1, for passes by passenger cars as a function of design speed can be approximated by the AASHTO estimates in Table 41. Due to the lower performance capabilities of trucks, their acceleration rates during the initial maneuver are assumed to be one-half of those used by passenger cars.
- The distance traveled in the left lane (d_2) can be estimated as follows:

$$d_2 = V\left(\frac{2.93(V - m) + L_P + L_I - \dfrac{0.73m^2}{a}}{m}\right) \qquad (35)$$

This relationship is used in preference to the AASHTO expression for d_2 because it explicitly contains the lengths of the passing and passed vehicles (L_p and L_I) and the speed difference between the vehicles, m. It would be desirable to calibrate Equation 35 with field data.

- Equation 35 is based on the premise that the passing vehicle initially trails the passed vehicle by a 1-s gap and returns to its normal lane leading the passed vehicle by a 1-s gap. The passing vehicle is assumed to maintain an average speed differential equal to *m* during its occupancy of the left lane; the latter assumption is consistent with AASHTO policy, but is more restrictive than the Glennon model, which assumes only that a speed differential equal to m is reached before the passing vehicle reaches the critical position (*75*).
- Passenger cars are assumed to accelerate when passing and to maintain an average speed equal to the design speed of the highway and maintain the same average speed differences used to derive Table 47. When passing, trucks are assumed to maintain only one-half of the speed difference of passenger cars, consistent with the assumptions used to derive Table 48.
- The assumed lengths of passenger cars and trucks are 6 and 23 m [19 and 75 ft], respectively.

The sensitivity analysis results for the distance required to complete a pass are presented in Table 50 for the four passing scenarios considered previously—passenger car passing passenger car, passenger car passing truck, truck passing passenger car, and truck passing truck. The required passing distances for these four scenarios are illustrated in Figure 24. Except at very low speeds, all of the passing distances are very much larger than the MUTCD minimum passing zone length of 122 m [400 ft].

Table 50 and Figure 40 show that, in order to complete a passing maneuver at speeds of 100 km/h [60 mph] or more

TABLE 50 Passing zone length required to complete a pass for various passing scenarios (*2,3*)

Design speed (mph)	Passing vehicle speed (V) (mph)	Speed difference (mph) used by passing vehicle: Passenger car	Speed difference (mph) used by passing vehicle: Truck	Minimum length of passing zone (ft): Passenger car passing passenger car	Minimum length of passing zone (ft): Passenger car passing truck	Minimum length of passing zone (ft): Truck passing passenger car	Minimum length of passing zone (ft): Truck passing truck
20	20	13	6.5	150	225	275	350
30	30	12	6	350	475	600	724
40	40	11	5.5	600	825	975	1,175
50	50	10	5	975	1,250	1,450	1,750
60	60	9	4.5	1,475	1,850	2,025	2,450
70	70	8	4	2,175	2,650	2,900	3,400

under the stated assumptions, trucks require passing zones at least 610 m [2,000 ft] long. There are relatively few such passing zones on two-lane highways and, yet, trucks regularly make passing maneuvers. The explanation of this apparent paradox is that, given that there are very few locations where a truck can safely make a delayed pass, truck drivers seldom attempt them. Most passing maneuvers by trucks on two-lane highways are flying passes that require less passing sight distance and less passing zone length than delayed passes. Thus, there may be no need to change current passing sight distance criteria to accommodate a truck passing a passenger car or a truck passing a truck as shown in Table 48. It makes little sense to provide enough passing sight distance for delayed passes by trucks when passing zones are not generally long enough to permit such maneuvers.

Summary of Findings

The review and sensitivity analysis conducted for the FHWA *Truck Characteristics* study found that there is very close agreement between the current MUTCD criteria for passing sight distance and the sight distance requirements for a passenger car passing another passenger car based on an analytical model recently developed by Glennon *(75)*. Application of the Glennon model indicates that successively longer passing sight distances are required for a passenger car passing a truck, a truck passing a passenger car, and a truck passing a truck. There is no general agreement as to which of these passing situations is the most reasonable basis for designing and operating two-lane highways. All of the passing sight distance criteria derived here are shorter than the Green Book design criteria, which are based on very conservative assumptions.

The analysis results indicate that, if a passenger car passing a passenger car is retained as the design situation, only minor modifications are needed to the MUTCD passing sight distance criteria. If a more critical design situation is selected (e.g., a passenger car passing a truck), passing sight distances up to 76 m [250 ft] longer than the current MUTCD criteria would be required. It is important to recognize that such a change in passing zone marking criteria would completely eliminate some existing passing zones and shorten others, even though passenger cars can safely pass other passenger cars in those zones. Clearly, this would reduce the level of service on two-lane highways.

The increased driver eye height of trucks partially, but not completely, offsets the increased passing sight distance requirements when the truck is the passing vehicle. However, except at very sharp crests on high-speed highways, a truck can safely pass a passenger car on any crest where a passenger car can safely pass a truck.

No cost-effectiveness analysis of the potential for revising passing sight distance criteria to accommodate trucks was conducted in the *Truck Characteristics* study because of the lack of data on the operational effects of implementing the revised criteria. The criteria, presented in Tables 47 and 48, address design situations involving a passenger car passing a truck, a truck passing a passenger car, and a truck passing a truck, in contrast to the current criteria, which are based on a passenger car passing a passenger car. Adoption of any of these alternative passing sight distance criteria for marking passing and no-passing zones on two-lane highways would be premature without an operational analysis of the extent to which the revised criteria would degrade the level of service for passenger cars.

There are no current criteria for passing zone lengths, except for the default 120-m [400-ft] guideline set by the MUTCD. For all design speeds above 48 km/h [30 mph], the distance required for one vehicle to pass another at or near that design speed is substantially longer than 120 m [400 ft], indicating a need for longer passing zones. The required passing distances and passing zone lengths are increased substantially when the passing vehicle, the passed vehicle, or both, are trucks. However, this analysis is based on assumptions appropriate for delayed passing maneuvers, which are seldom made by trucks.

DECISION SIGHT DISTANCE

Current Geometric Design Criteria

Decision sight distance is the distance required for a driver to detect an unexpected or otherwise difficult-to-perceive information source or hazard in a roadway environment that may be visually cluttered, recognize the hazard or its threat potential, select an appropriate speed and path, and initiate and complete the selected maneuver safely and efficiently *(1)*. Decision sight distance is intended to give drivers an additional margin for error and to provide them sufficient length to complete their selected maneuver at the same or reduced speed, rather than to stop. Therefore, the recommended values of decision sight distance are substantially greater than the recommended stopping sight distance criteria. Locations where it may be desirable to provide decision sight distance include interchanges and intersection locations where unusual or unexpected maneuvers are required; changes in cross section, such as toll plazas and lane drops; and areas of “visual noise” where multiple sources of information, such as roadway elements, traffic, traffic control devices, and advertising signs, compete for the driver’s attention.

The concept of decision sight distance was first introduced in the 1984 Green Book based on research by McGee et al. *(80)*. The original decision sight distance concept considered only a single maneuver, a lane change to avoid an obstacle, such as a vehicle or a traffic queue, on the roadway ahead. The decision sight distance design values were defined empirically from estimates of the premaneuver (i.e., detection and recognition and decision and response initiation) and maneuver times required to make a lane change at various speeds. The decision sight distance was changed in the 1990 Green Book to include multiple scenarios that might be encountered by a driver approaching a decision point. Specifically, decision sight distance criteria are now defined for five traffic scenarios or avoidance maneuvers. These are as follows:

- Avoidance Maneuver A: Stop on rural road;
- Avoidance Maneuver B: Stop on urban road;
- Avoidance Maneuver C: Speed/path/direction change on rural road;
- Avoidance Maneuver D: Speed/path/direction change on suburban road; and
- Avoidance Maneuver E: Speed/path/direction change on urban road.

The decision sight distances for avoidance maneuvers A and B are determined as follows:

Metric	US Customary
$d = 0.278Vt + 0.039\dfrac{V^2}{a}$	$d = 1.47Vt + 1.075\dfrac{V^2}{a}$ (36)
where t = pre-maneuver time, s; V = design speed, km/h; a = driver deceleration, m/s^2	where t = pre-maneuver time, s; V = design speed, mph; a = driver deceleration, ft/s^2

Equation 36 is the same model used in the Green Book for stopping sight distance (see Equation 25). However, in application to decision sight distance, the first term (premaneuver time) is increased above the brake reaction time used for stopping sight distance to allow the driver additional time to detect and recognize the roadway or traffic situation and initiate a response. For a stop on a rural road (Avoidance Maneuver A), the estimated premaneuver time is 3.0 s. For the more complex situation represented by a stop on an urban road (Avoidance Maneuver B), the estimated premaneuver time is 9.1 s.

The decision sight distances for Avoidance Maneuvers C, D, and E are determined as follows:

Metric	US Customary
$d = 0.278Vt$	$d = 1.47Vt$ (37)
where t = total pre-maneuver and maneuver time, s; V = design speed, km/h	where t = total pre-maneuver and maneuver time, s; V = design speed, mph

Equation 37 is based on the assumption that in making a path or direction change, the driver will be traveling at the design speed of the roadway for a specified premaneuver and maneuver time. There is no explicit consideration of the possibility that the appropriate maneuver might be a speed change but, if the maneuver appropriate to the traffic situation is a reduction in speed, then the decision sight distances provided by Equation 37 will be conservative.

In Equation 37, the parameter, t, represents the total premaneuver-plus-maneuver time. The total premaneuver-plus-maneuver time varies between 10.2 and 11.2 s for rural roads, between 12.1 and 12.9 s for suburban roads, and between 14.0 and 14.5 s for urban roads, with lower values used at higher speeds. The Green Book does not specify the allocation of time between the premaneuver and maneuver periods and also does not specify any particular maneuver to be made. Rather, it is presumed that the values of t used are sufficient for whatever maneuver may be required.

The decision sight distance criteria recommended in the Green Book are presented in Table 51.

Vertical curve lengths to provide these levels of decision sight distance are based on a 1,080-mm [3.5-ft] driver eye height and a 600-mm [2-ft] object height, just as for stopping sight distance.

The Green Book decision sight distance criteria are meant to be guidelines rather than absolute requirements. The Green Book emphasizes the importance of traffic control devices, such as advance signing, where the full decision sight distance cannot be provided.

Critique of Geometric Design Policy

The Green Book criteria for decision sight distance are based primarily on consideration of passenger cars and do not explicitly consider trucks. However, the premaneuver and maneuver times considered are sufficiently long that it is

TABLE 51 Design values for decision sight distance (*1*)

Metric						US Customary					
Design speed (km/h)	Decision sight distance (m)					Design speed (mph)	Decision sight distance (ft)				
	Avoidance maneuver						Avoidance maneuver				
	A	B	C	D	E		A	B	C	D	E
50	70	155	145	170	195	30	220	490	450	535	620
60	95	195	170	205	235	35	275	590	525	625	720
70	115	235	200	235	275	40	330	690	600	715	825
80	140	280	230	270	315	45	395	800	675	800	930
90	170	325	270	315	360	50	465	910	750	890	1030
100	200	370	315	355	400	55	535	1030	865	980	1135
110	235	420	330	380	430	60	610	1150	990	1125	1280
120	265	470	360	415	470	65	695	1275	1050	1220	1365
130	305	525	390	450	510	70	780	1410	1105	1275	1445
						75	875	1545	1180	1365	1545
						80	970	1685	1260	1455	1650

Avoidance Maneuver A: Stop on rural road—t = 3.0 s.
Avoidance Maneuver B: Stop on urban road—t = 9.1 s.
Avoidance Maneuver C: Speed/path/direction change on rural road—t varies between 10.2 and 11.2 s.
Avoidance Maneuver D: Speed/path/direction change on suburban road—t varies between 12.1 and 12.9 s.
Avoidance Maneuver E: Speed/path/direction change on urban road—t varies between 14.0 and 14.5 s.

likely that these criteria may accommodate trucks as well as passenger cars.

For Avoidance Maneuvers A and B, the model used for decision sight distance is the same as that used for stopping sight distance. The premaneuver portion of the design sight distance criteria provides more reaction time than the stopping sight distance criteria. This should accommodate truck, as well as passenger car, drivers, especially given that truck drivers have an eye height advantage that lets them see stop conditions hidden by crest vertical curves before passenger car drivers.

The deceleration rate used in determining the decision sight distance criteria for Avoidance Maneuvers A and B is the same value used in determining stopping sight distance criteria.

A formal sensitivity analysis of decision sight distance requirements to accommodate trucks for Avoidance Maneuvers C, D, and E will be difficult because the Green Book does not distinguish explicitly between premaneuver and maneuver time and because the specific maneuvers to be accommodated are not specified. Given that Avoidance Maneuvers C, D, and E involve speed/path/direction changes, rather than braking to a stop, the longer braking distances of trucks may be less of an issue than for situations where a stop is required. On the other hand, trucks are substantially larger and less maneuverable than passenger cars and may require more maneuver time in some situations (e.g., lane changes). The greater eye height of truck drivers is a potential advantage for Avoidance Maneuvers C, D, and E because a truck driver may be able to see over the vehicle immediately ahead and may be able to perceive traffic situations requiring an avoidance maneuver before a passenger car driver would.

The FHWA *Truck Characteristics* study included a cost-effectiveness analysis of potential changes to the decision sight distance policy in the 1984 Green Book to better accommodate trucks. This analysis concluded that such changes would not be cost-effective. A similar analysis indicates that changes to the decision sight distance criteria in the 2001 Green Book to better accommodate trucks would still not be cost-effective.

INTERSECTION SIGHT DISTANCE

Current Geometric Design Criteria

Intersection sight distance is provided to allow drivers at, or on the approach to, an intersection to perceive the presence of potentially conflicting vehicles. This should occur in sufficient time for motorists to stop or adjust speed, as appropriate, to avoid colliding in the intersection. The methods for determining the sight distances needed by drivers approaching intersections are based on the same principles as stopping sight distance, but incorporate modified assumptions based on observed driver behavior at intersections.

The driver of a vehicle approaching an intersection should have an unobstructed view of the entire intersection, including any traffic control devices, and sufficient lengths along the intersecting highway to permit the driver to anticipate and avoid potential collisions. The sight distance needed under various assumptions of physical conditions and driver behavior is directly related to vehicle speeds and to the resultant distances traversed during perception-reaction time and braking.

Sight distance is also provided at intersections to allow the drivers of stopped vehicles a sufficient view of the intersecting highway to decide when to enter the intersecting highway or to cross it. If the available sight distance for an entering or crossing vehicle is at least equal to the appropriate stopping sight distance for the major road, then drivers have sufficient sight distance to anticipate and avoid collisions. However, in some cases, this may require a major-road vehicle to stop or slow to accommodate the maneuver by a minor-road vehicle. To enhance traffic operations, intersection sight distances that exceed stopping sight distances are desirable along the major road.

Prior to the 2001 Green Book, intersection sight distance policies were presented based on a kinematic or acceleration-deceleration model. Research by Harwood et al. *(81)* documented conceptual inconsistencies in these models and formulated a revised approach to intersection sight distance criteria based on gap acceptance. A gap-acceptance model, calibrated with field data, was used for all intersection sight distance cases, except for intersections with no traffic control on any of the approaches (Case A).

Sight Triangles

Two types of clear sight triangles are considered in intersection design: approach sight triangles and departure sight triangles.

Approach Sight Triangles

Each quadrant of an intersection should contain a triangular area free of obstructions that might block an approaching driver's view of potentially conflicting vehicles. The length of the legs of this triangular area, along both intersecting roadways, should be such that the drivers can see any potentially conflicting vehicles in sufficient time to slow or stop before colliding within the intersection. Figure 41a shows typical clear sight triangles to the left and to the right for a vehicle approaching an uncontrolled or yield-controlled intersection.

Departure Sight Triangles

A second type of clear sight triangle provides sight distance sufficient for a stopped driver on a minor-road approach to depart from the intersection and enter or cross the major road. Figure 41b shows typical departure sight triangles to the left and to the right of the location of a stopped vehicle on the minor road. Departure sight triangles should be provided in each quadrant of each intersection approach controlled by stop or yield signs and for some signalized intersection approaches.

Identification of Sight Obstructions Within Sight Triangles

The profiles of the intersecting roadways should be designed to provide the recommended sight distances for drivers on the intersection approaches. Within a sight triangle, any object at a height above the elevation of the adjacent roadways that would obstruct the driver's view should be removed or lowered, if practical. Such objects may include buildings, parked vehicles, highway structures, roadside hardware, hedges, trees, bushes, unmowed grass, tall crops, walls, fences, and the terrain itself. Particular attention should be given to the evaluation of clear sight triangles at interchange ramp/crossroad intersections where features such as bridge railings, piers, and abutments are potential sight obstructions.

The determination of whether an object constitutes a sight obstruction should consider both the horizontal and vertical alignment of both intersecting roadways, as well as the height and position of the object. In making this determination, it should be assumed that the driver's eye is 1,080 mm [3.5 ft] above the roadway surface and that the object to be seen is 1,080 mm [3.5 ft] above the surface of the intersecting road.

This object height is based on a vehicle height of 1,330 mm [4.35 ft], which represents the 15th percentile of vehicle heights in the current passenger car population less an allowance of 250 mm [10 in]. This allowance represents a near-maximum value for the portion of a passenger car height that needs to be visible for another driver to recognize it as the object. The use of an object height equal to the driver eye height makes intersection sight distances reciprocal (i.e., if one driver can see another vehicle, then the driver of that vehicle can also see the first vehicle).

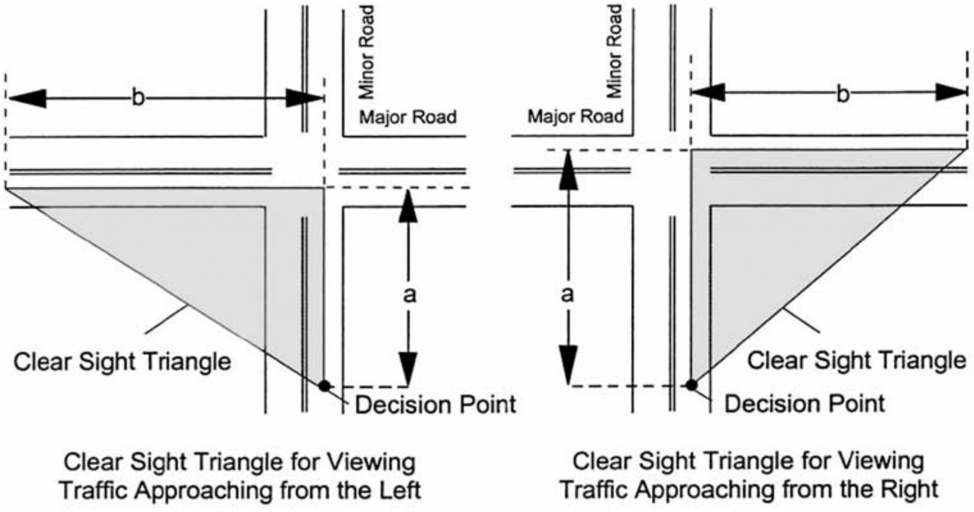
Where the sight-distance value used in design is based on a single-unit or combination truck as the design vehicle, it is also appropriate to use the eye height of a truck driver in checking sight obstructions. The value for a truck driver's eye height recommended in the Green Book is 2,330 mm [7.6 ft] above the roadway surface.

Intersection Sight Distance Cases

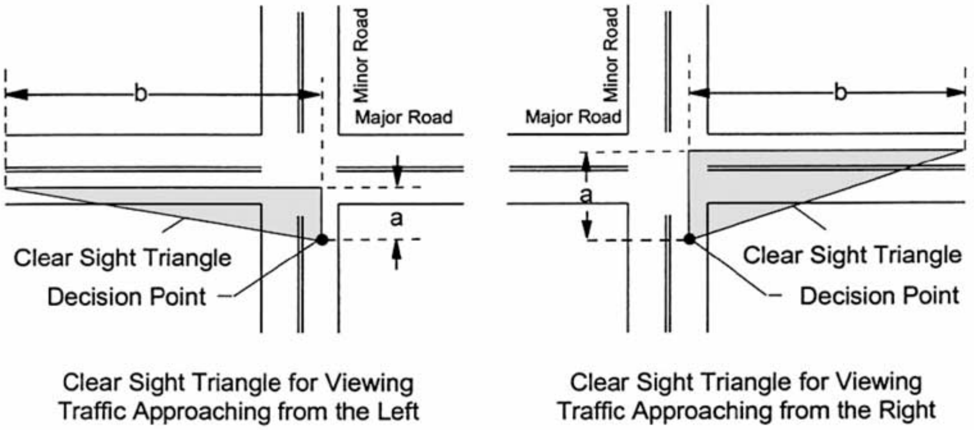
The recommended dimensions of the sight triangles vary with the type of traffic control used at an intersection because different types of control impose different legal constraints on drivers and, therefore, result in different driver behavior. Procedures to determine sight distances at intersections are provided in the Green Book for the following cases:

- Case A—Intersections with no control;
- Case B—Intersections with stop control on the minor road;
- Case B1—Left turn from the minor road;
- Case B2—Right turn from the minor road;
- Case B3—Crossing maneuver from the minor road;
- Case C—Intersections with yield control on the minor road;
- Case C1—Crossing maneuver from the minor road;
- Case C2—Left or right turn from the minor road;
- Case D—Intersections with traffic signal control;
- Case E—Intersections with all-way stop control; and
- Case F—Left turns from the major road.

The following discussion addresses Cases B, C, D, E, and F. Case A is omitted because it is applicable only to very



A -- Approach Sight Triangles



B -- Departure Sight Triangles

Figure 41. Intersection sight triangles.

low-volume intersections at which the appropriate design vehicle is unlikely to be a truck.

Case B—Intersections With Stop Control on the Minor Road

Departure sight triangles for intersections with stop control on the minor road are considered for three situations:

- Case B1—Left turns from the minor road;
- Case B2—Right turns from the minor road; and
- Case B3—Crossing the major road from a minor-road approach.

Intersection sight distance criteria for stop-controlled intersections are longer than stopping sight distance to ensure that the intersection operates smoothly. Minor-road vehicle operators can wait until they can proceed safely without forcing a major-road vehicle to stop.

Case B1—Left Turn From the Minor Road

The Green Book states that departure sight triangles for traffic approaching from either the right or the left, like those shown in Figure 41b, should be provided for left turns from the minor road onto the major road for all stop-controlled approaches. The length of the leg of the departure sight triangle along the major road in both directions is the recommended intersection sight distance for Case B1.

The vertex (decision point) of the departure sight triangle on the minor road should be 4.4 m [14.4 ft] from the edge of the major-road traveled way. This represents the typical position of the minor-road driver's eye when a vehicle is stopped relatively close to the major road. Field observations of vehicle stopping positions found that, where necessary, drivers will stop with the front of their vehicles 2.0 m [6.5 ft] or less from the edge of the major-road traveled way. Measurements of passenger cars indicate that the distance from the front of the vehicle to the driver's eye for the current U.S. passenger car population is nearly always 2.4 m [8 ft] or less *(81)*. The Green Book states that, where practical, it is desirable to increase the distance from the edge of the major-road traveled way to the vertex of the clear sight triangle from 4.4 m to 5.4 m [14.4 to 17.8 ft]. This increase allows 3.0 m [10 ft] from the edge of the major-road traveled way to the front of the stopped vehicle, providing a larger sight triangle. The length of the sight triangle along the minor road (distance "a" in Figure 41b) is the sum of the distance from the major road plus one-half of the lane width for vehicles approaching from the left, or one-and-one-half lane width for vehicles approaching from the right.

Field observations of the gaps in major-road traffic actually accepted by drivers turning onto the major road have shown that the values in Table 52 provide sufficient time for the minor-road vehicle to accelerate from a stop and complete a left turn without unduly interfering with major-road traffic operations. The time gap acceptance time does not vary with approach speed on the major road. Studies have indicated that a constant value of time gap, independent of approach speed, can be used as a basis for intersection sight distance determinations. Observations have also shown that major-road drivers will reduce their speed to some extent when minor-road vehicles turn onto the major road. Where the time gap acceptance values in Table 52 are used to determine the length of the leg of the departure sight triangle, most major-road drivers should not need to reduce speed to less than 70 percent of their initial speeds *(81)*.

The intersection sight distance in both directions should be equal to the distance traveled at the design speed of the major road during a period of time equal to the time gap. In applying Table 52, it is usually assumed that the minor-road vehicle is a passenger car. However, where substantial volumes of heavy vehicles enter the major road, such as from a ramp terminal, tabulated values for single-unit or combination trucks are provided. Table 52 includes appropriate adjustments to the gap times for the number of lanes on the major road and for the approach grade of the minor road.

The Green Book states that the intersection sight distance along the major road (dimension b in Figure 41b) is determined by the following:

Metric	US Customary
$ISD = 0.278\, V_{major}\, t_g$	$ISD = 1.47\, V_{major}\, t_g \qquad (38)$
where ISD = intersection sight distance (length of the leg of sight triangle along the major road) (m) V_{major} = design speed of major road (km/h) t_g = time gap for minor road vehicle to enter the major road (s)	where ISD = intersection sight distance (length of the leg of sight triangle along the major road) (ft) V_{major} = design speed of major road (mph) t_g = time gap for minor road vehicle to enter the major road (s)

The Green Book recommends that sight distance design for left turns at divided-highway intersections should consider multiple design vehicles and median width. If the design vehicle used to determine sight distance for a divided-highway intersection is larger than a passenger car, then sight distance for left turns will need to be checked for that selected design vehicle and for smaller design vehicles as well. If the divided-highway median is wide enough to store the design vehicle with a clearance to the through lanes of approximately 1 m [3 ft] at both ends of the vehicle, no separate analysis for the departure sight triangle for left turns is needed on the minor-road approach for the near roadway to the left. In most cases, the departure sight triangle for right turns (Case B2) will

TABLE 52 Time gap for Case B1—left turn from stop (*1*)

Design vehicle	Time gap (s) at design speed of major road (tg)
Passenger car	7.5
Single-unit truck	9.5
Combination truck	11.5

NOTE: Time gaps are for a stopped vehicle to turn right or left onto a two-lane highway with no median and grades 3 percent or less. The table values require adjustment as follows:

For multilane highways: For left turns onto two-way highways with more than two lanes, add 0.5 seconds for passenger cars or 0.7 seconds for trucks for each additional lane, from the left, in excess of one, to be crossed by the turning vehicle.

For minor road approach grades: If the approach grade is an upgrade that exceeds 3 percent; add 0.2 seconds for each percent grade for left turns.

provide sufficient sight distance for a passenger car to cross the near roadway to reach the median. Possible exceptions are addressed in the discussion of Case B3.

If the design vehicle can be stored in the median with adequate clearance to the through lanes, a departure sight triangle to the right for left turns should be provided for that design vehicle turning left from the median roadway. Where the median is not wide enough to store the design vehicle, a departure sight triangle should be provided for that design vehicle to turn left from the minor-road approach.

The median width should be considered in determining the number of lanes to be crossed. The median width should be converted to equivalent lanes. For example, a 7.2-m [24-ft] median should be considered as two additional lanes to be crossed in applying the multilane highway adjustment for time gaps in Table 52. Furthermore, a departure sight triangle for left turns from the median roadway should be provided for the largest design vehicle that can be stored on the median roadway with adequate clearance to the through lanes. If a divided highway intersection has a 12-m [40-ft] median width and the design vehicle for sight distance is a 22-m [74-ft] combination truck, departure sight triangles should be provided for the combination truck turning left from the minor-road approach and through the median. In addition, a departure sight triangle should also be provided to the right for a 9-m [30-ft] single-unit truck turning left from a stopped position in the median.

Figure 42 compares the intersection sight distances by type of design vehicle for Case B1.

Case B2—Right Turns from the Minor Road

The Green Book states that a departure sight triangle for traffic approaching from the left like that shown in Figure 41b should be provided for right turns from the minor road

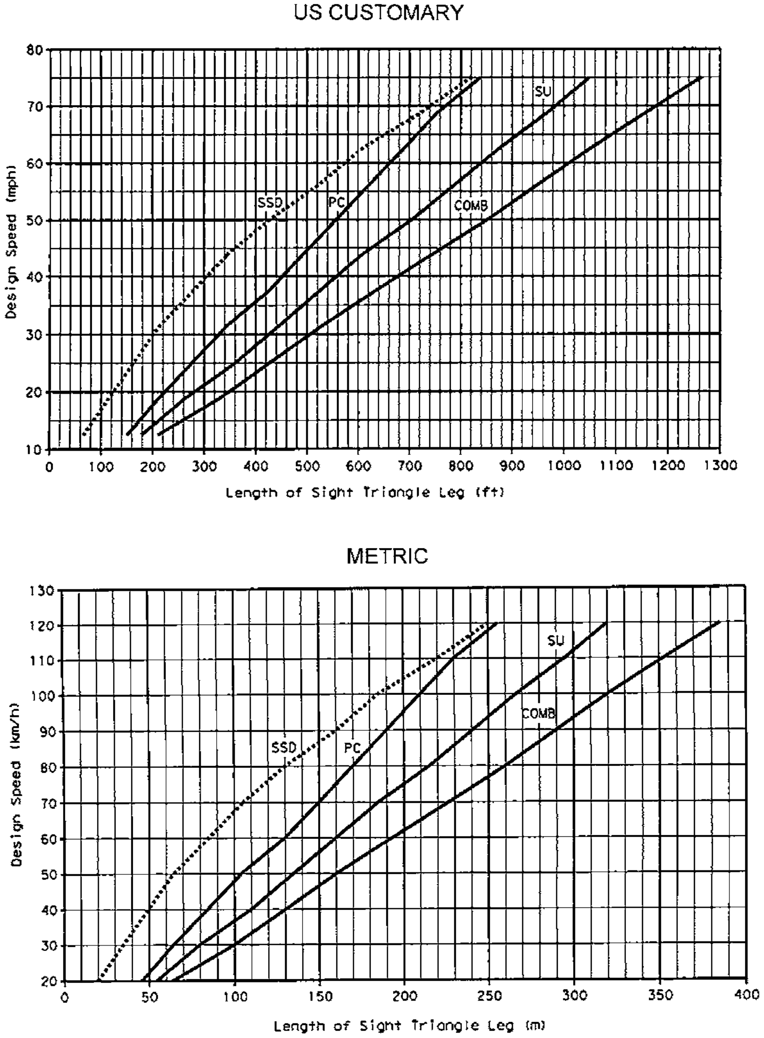


Figure 42. Intersection sight distance—Case B1—left turn from stop (1).

onto the major road. The intersection sight distance for right turns is determined in the same manner as for Case B1, except that the time gaps (t_g) in Table 52 are adjusted. Field observations indicate that, in making right turns, drivers generally accept gaps that are slightly shorter than those accepted in making left turns *(81)*. The time gaps in Table 52 can be decreased by 1.0 s for right-turn maneuvers without undue interference with major-road traffic. These adjusted time gaps for the right turn from the minor road are shown in Table 53. Figure 43 compares the design values for the design vehicles for each of the time gaps in Table 53. When the minimum recommended sight distance for a right-turn maneuver cannot be provided, even with the reduction of 1.0 s from the values in Table 53, the Green Book recommends that consideration should be given to installing regulatory speed signing or other traffic control devices on the major-road approaches.

Case B3—Crossing Maneuver from the Minor Road

In most cases, the departure sight triangles for left and right turns onto the major road, as described for Cases B1 and B2, will also provide more than adequate sight distance for minor-road vehicles to cross the major road. However, the Green Book notes that, in the following situations, it is advisable to check the availability of sight distance for crossing maneuvers:

- Where left and/or right turns are not permitted from a particular approach and the crossing maneuver is the only legal maneuver;
- Where the crossing vehicle would cross the equivalent width of more than six lanes; or
- Where substantial volumes of heavy vehicles cross the highway and steep grades that might slow the vehicle while its back portion is still in the intersection are present on the departure roadway on the far side of the intersection.

The formula for intersection sight distance in Case B1 is used again for the crossing maneuver except that time gaps (t_g) are obtained from Table 53. At divided highway intersections, depending on the relative magnitudes of the median width and the length of the design vehicle, intersection sight distance may need to be considered for crossing both roadways of the divided highway or for crossing the near lanes only and stopping in the median before proceeding. The application of adjustment factors for median width and grade are discussed under Case B1.

TABLE 53 Time gap for Case B2—right turn from stop and Case B3—crossing maneuver (*1*)

Design vehicle	Time gap (s) at design speed of major road (t_g)
Passenger car	6.5
Single-unit truck	8.5
Combination truck	10.5

NOTE: Time gaps are for a stopped vehicle to turn right onto or cross a two-lane highway with no median and grades 3 percent or less. The table values require adjustment as follows:

For multilane highways:
For crossing a major road with more than two lanes, add 0.5 seconds for passenger cars and 0.7 seconds for trucks for each additional lane to be crossed and for narrow medians that cannot store the design vehicle.
For minor road approach grades: If the approach grade is an upgrade that exceeds 3 percent, add 0.1 seconds for each percent grade.

Case C—Intersections With Yield Control on the Minor Road

Drivers approaching yield signs are permitted to enter or cross the major road without stopping, if there are no potentially conflicting vehicles on the major road. The sight distances needed by drivers on yield-controlled approaches exceed those for stop-controlled approaches.

For four-leg intersections with yield control on the minor road, two separate pairs of approach sight triangles like those shown in Figure 41a should be provided. One set of approach sight triangles is needed to accommodate crossing the major road and a separate set of sight triangles is needed to accommodate left and right turns onto the major road. Both sets of sight triangles should be checked for potential sight obstructions.

For three-leg intersections with yield control on the minor road, only the approach sight triangles to accommodate left- and right-turn maneuvers need be considered, because the crossing maneuver does not exist.

Case C1—Crossing Maneuver From the Minor Road

The Green Book design values for the length of the leg of the approach sight triangle along the minor road to accommodate the crossing maneuver from a yield-controlled approach (distance “a” in Figure 41a) is given in Table 54. The distances in Table 54 are based on the same assumptions as those for Case A except that, based on field observations, minor-road vehicles that do not stop are assumed to decelerate to 60 percent of the minor-road design speed, rather than 50 percent.

Sufficient travel time for the major-road vehicle should be provided to allow the minor-road vehicle: (1) to travel from the decision point to the intersection, while decelerating at the rate of 1.5 m/s^2 [5 ft/s^2] to 60 percent of the minor-road design speed; and then (2) to cross and clear the intersection at that same speed. The intersection sight distance along

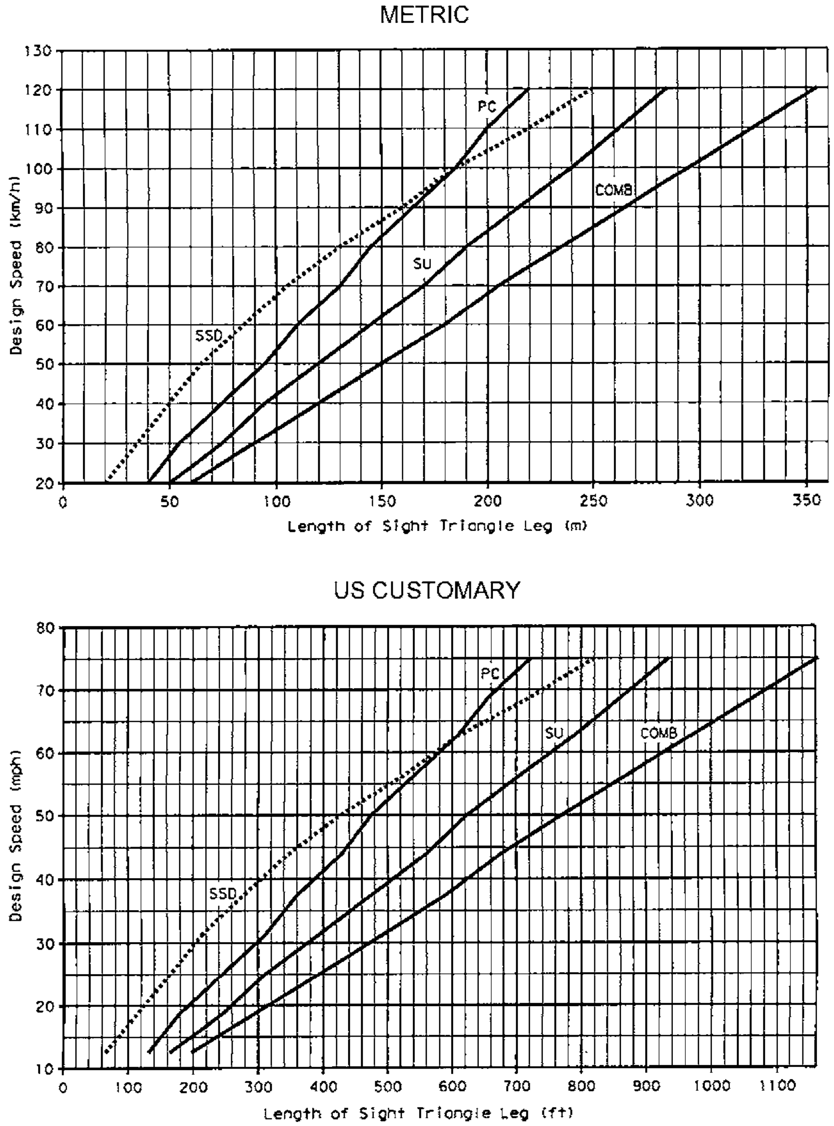


Figure 43. Intersection sight distance—Case B2—right turn from stop and Case B3—crossing maneuver (1).

the major road to accommodate the crossing maneuver (distance *b* in Figure 41a) should be computed with Equation 39.

The value of t_g should equal or exceed the appropriate travel time for crossing the major road from a stop-controlled approach, as shown in Table 53. The design values for the time gap (t_g) shown in Table 54 incorporate these crossing times for two-lane highways and are used to develop the length of the leg of the sight triangle along the major road in Table 55.

Case C2—Left or Right Turn from the Minor Road

The Green Book states that length of the leg of the approach sight triangle along the minor road to accommodate left and right turns without stopping (distance *a* in Figure 41a) should be 25 m [82 ft]. This distance is based on the assumption that drivers making left and right turns without stopping will slow to a turning speed of 16 km/h [10 mph].

The leg of the approach sight triangle along the major road (distance *b* in Figure 41a) is similar to the major-road leg of the departure sight triangle for stop-controlled intersections in Cases B1 and B2. However, the Green Book states that the time gaps in Table 52 should be increased by 0.5 s to the values shown in Table 56. The appropriate lengths of the sight triangle leg are shown in Figure 44 for the various design vehicle categories. The minor-road vehicle needs 3.5 s to travel from the decision point to the intersection. This represents additional travel time that is needed at a yield-controlled

TABLE 54 Case C1—crossing maneuvers from yield-controlled approaches—length of minor-road leg and travel times (*1*)

Metric					US Customary				
	Minor-road approach		Travel time (t_g) (seconds)			Minor-road approach		Travel time (t_g) (seconds)	
Design speed (km/h)	Length of leg[1] (m)	Travel time t_a[1,2] (seconds)	Calculated value	Design value[3,4]	Design speed (mph)	Length of leg[1] (ft)	Travel time t_a[1,2] (seconds)	Calculated value	Design value[3,4]
20	20	3.2	7.1	7.1	15	75	3.4	6.7	6.7
30	30	3.6	6.2	6.5	20	100	3.7	6.1	6.5
40	40	4.0	6.0	6.5	25	130	4.0	6.0	6.5
50	55	4.4	6.0	6.5	30	160	4.3	5.9	6.5
60	65	4.8	6.1	6.5	35	195	4.6	6.0	6.5
70	80	5.1	6.2	6.5	40	235	4.9	6.1	6.5
80	100	5.5	6.5	6.5	45	275	5.2	6.3	6.5
90	115	5.9	6.8	6.8	50	320	5.5	6.5	6.5
100	135	6.3	7.1	7.1	55	370	5.8	6.7	6.7
110	155	6.7	7.4	7.4	60	420	6.1	6.9	6.9
120	180	7.0	7.7	7.7	65	470	6.4	7.2	7.2
130	205	7.4	8.0	8.0	70	530	6.7	7.4	7.4
					75	590	7.0	7.7	7.7
					80	660	7.3	7.9	7.9

[1] For minor-road approach grades that exceed 3 percent, multiply the distance or the time in this table by the appropriate adjustment factor from Green Book Exhibit 9-53.

[2] Travel time applies to a vehicle that slows before crossing the intersection but does not stop.

[3] The value of t_g should equal or exceed the appropriate time gap for crossing the major road from a stop-controlled approach.

[4] Values shown are for a passenger car crossing a two-lane highway with no median and grades 3 percent or less.

intersection, but is not needed at a stop-controlled intersection (Case B).

Metric	US Customary
$t_g = t_a + \dfrac{w + L_a}{0.167 V_{\text{minor}}}$ $b = 0.278 V_{\text{major}} t_g$	$t_g = t_a + \dfrac{w + L_a}{0.88 V_{\text{minor}}}$ $b = 1.47 V_{\text{major}} t_g$ (39)
where t_g = travel time to reach and clear the major road (s) b = length of leg of sight triangle along the major road (m) t_a = travel time to reach the major road from the decision point for a vehicle that does not stop (s) (use appropriate value for the minor-road design speed from Exhibit 9-60 adjusted for approach grade, where appropriate) w = width of intersection to be crossed (m) L_a = length of design vehicle (m) V_{minor} = design speed of minor road (km/h) V_{major} = design speed of major road (km/h)	where t_g = travel time to reach and clear the major road (s) b = length of leg of sight triangle along the major road (ft) t_a = travel time to reach the major road from the decision point for a vehicle that does not stop (s) (use appropriate value for the minor-road design speed from Exhibit 9-60 adjusted for approach grade, where appropriate) w = width of intersection to be crossed (ft) L_a = length of design vehicle (ft) V_{minor} = design speed of minor road (mph) V_{major} = design speed of major road (mph)

However, the acceleration time after entering the major road is 3.0 s less for a yield sign than for a stop sign because the turning vehicle accelerates from 16 km/h (10 mph) rather than from a stop condition. The net 0.5-s increase in travel time for a vehicle turning from a yield-controlled approach is the difference between the 3.5-s increase in travel time and the 3.0-s reduction in travel time.

The Green Book states that departure sight triangles like those provided for stop-controlled approaches (see Cases B1, B2, and B3) should also be provided for yield-controlled approaches to accommodate minor-road vehicles that stop at the yield sign to avoid conflicts with major-road vehicles. However, given that approach sight triangles for turning maneuvers at yield-controlled approaches are larger than the departure sight triangles used at stop-controlled intersections, no specific check of departure sight triangles at yield-controlled intersections should be needed.

Yield-controlled approaches generally need greater sight distance than stop-controlled approaches, especially at four-leg yield-controlled intersections where the sight distance needs of the crossing maneuver should be considered. If sight distance sufficient for yield control is not available, use of a stop sign instead of a yield sign should be considered. In addition, at locations where the recommended sight distance cannot be provided, consideration should be given to installing regulatory speed signing or other traffic control devices at the intersection on the major road to reduce the speeds of approaching vehicles.

Case D—Intersections with Traffic Signal Control

At signalized intersections, the first vehicle stopped on one approach should be visible to the driver of the first vehicle

TABLE 55 Length of sight triangle leg along major road—Case C1—crossing maneuver at yield-controlled intersections (*1*)

Metric									US Customary									
		Minor-road design speed (km/h)									Minor-road design speed (mph)							
Major road design speed (km/h)	Stopping sight distance (m)	20	30-80	90	100	110	120	130	Major road design speed (mph)	Stopping sight distance (ft)	15	20-50	55	60	65	70	75	80
		Design values (m)									Design values (ft)							
20	20	40	40	40	40	45	45	45	15	80	150	145	150	155	160	165	170	175
30	35	60	55	60	60	65	65	70	20	115	200	195	200	205	215	220	230	235
40	50	80	75	80	80	85	90	90	25	155	250	240	250	255	265	275	285	295
50	65	100	95	95	100	105	110	115	30	200	300	290	300	305	320	330	340	350
60	85	120	110	115	120	125	130	135	35	250	345	335	345	360	375	385	400	410
70	105	140	130	135	140	145	150	160	40	305	395	385	395	410	425	440	455	465
80	130	160	145	155	160	165	175	180	45	360	445	430	445	460	480	490	510	525
90	160	180	165	175	180	190	195	205	50	425	495	480	495	510	530	545	570	585
100	185	200	185	190	200	210	215	225	55	495	545	530	545	560	585	600	625	640
110	220	220	200	210	220	230	240	245	60	570	595	575	595	610	640	655	680	700
120	250	240	220	230	240	250	260	270	65	645	645	625	645	660	690	710	740	755
130	285	260	235	250	260	270	280	290	70	730	690	670	690	715	745	765	795	815
									75	820	740	720	740	765	795	820	850	875
									80	910	790	765	790	815	850	875	910	930

TABLE 56 Time gap for Case C2—left or right turn (*1*)

Design vehicle	Time gap (t_g) seconds
Passenger car	8.0
Single-unit truck	10.0
Combination truck	12.0

NOTE: Time gaps are for a vehicle to turn right or left onto a two-lane highway with no median. The table values require adjustments for multilane highways as follows:

For left turns onto two-way highways with more than two lanes, add 0.5 seconds for passenger cars or 0.7 seconds for trucks for each additional lane, from the left, in excess of one, to be crossed by the turning vehicle.

For right turns, no adjustment is necessary.

stopped on each of the other approaches. Left-turning vehicles should have sufficient sight distance to select gaps in oncoming traffic and complete left turns. Apart from these sight conditions, the Green Book states that generally there are no other approach or departure sight triangles needed for signalized intersections. Signalization may be an appropriate crash countermeasure for higher volume intersections with restricted sight distance that have experienced a pattern of sight-distance related crashes.

However, if the traffic signal is to be placed on two-way flashing operation (i.e., flashing yellow on the major-road approaches and flashing red on the minor-road approaches) under off-peak or nighttime conditions, then the appropriate departure sight triangles for Case B, both to the left and to the right, should be provided for the minor-road approaches. In addition, if right turns on a red signal are to be permitted from any approach, then the appropriate departure sight triangle to the left for Case B2 should be provided to accommodate right turns from that approach.

The Green Book criteria for intersection sight distance Case D reflect the differences between passenger cars and trucks in that those differences are considered explicitly in Case B.

Case E—Intersections with All-Way Stop Control

At intersections with all-way stop control, the Green Book states that the first stopped vehicle on one approach should be visible to the drivers of the first stopped vehicles on each of the other approaches. There are no other sight distance criteria applicable to intersections with all-way stop control and, indeed, all-way stop control may be the best option at a limited number of intersections where sight distance for other control types cannot be attained. There are no differences between passenger cars and trucks in the intersection sight distance criteria for Case E.

Case F—Left Turns From the Major Road

All locations along a major highway from which vehicles are permitted to turn left across opposing traffic, including intersections and driveways, should have sufficient sight distance to accommodate the left-turn maneuver. Left-turning drivers need sufficient sight distance to decide when it is safe to turn left across the lane(s) used by opposing traffic. Sight distance design should be based on a left turn by a stopped

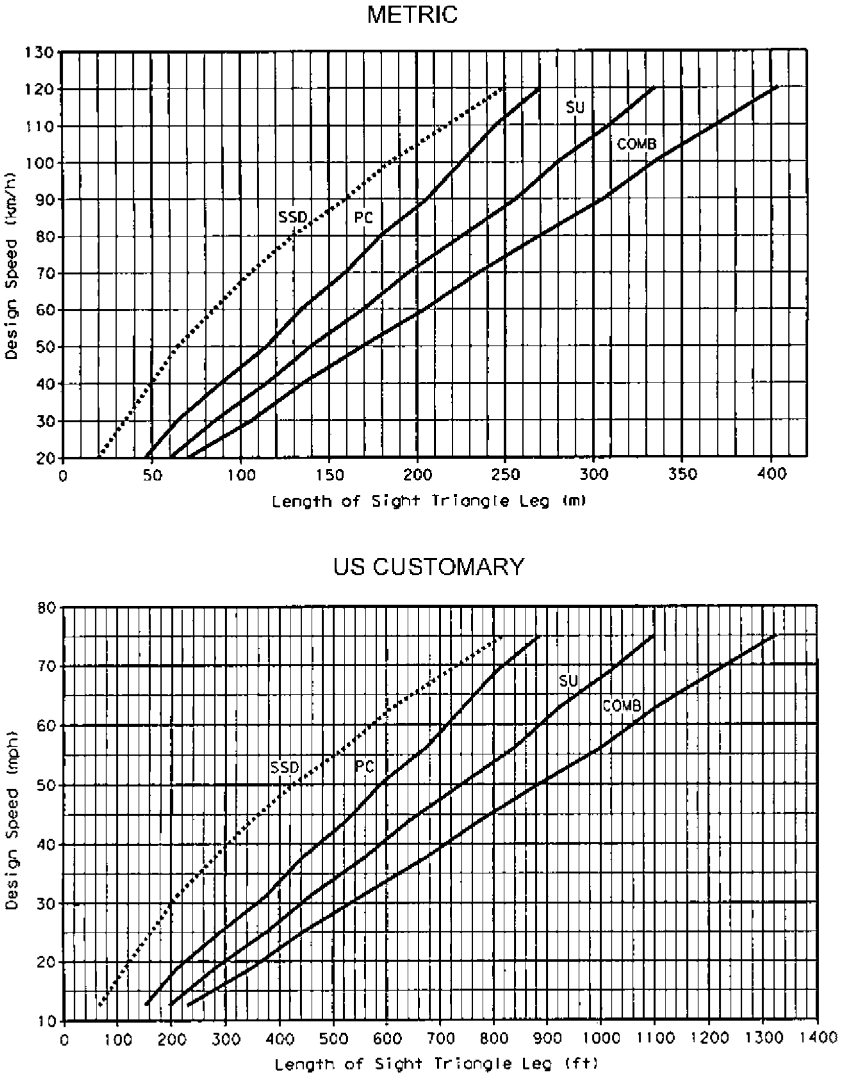


Figure 44. Intersection sight distance—Case C2—yield-controlled left or right turn (1).

vehicle, because a vehicle that turns left without stopping would need less sight distance. The Green Book criteria for sight distance along the major road to accommodate left turns is the distance traversed at the design speed of the major road in the travel time for the design vehicle as shown in Table 57.

Critique of Geometric Design Criteria

Because the intersection sight distance criteria in the 2001 Green Book are based on relatively recent research that explicitly considered the sight distance needs of trucks, there does not appear to be any need to reevaluate the conceptual or theoretical basis of these criteria at this time. These criteria should be reevaluated in the future to reflect highway agency experience with their implementation.

RAILROAD-HIGHWAY GRADE CROSSING SIGHT DISTANCE

Current Geometric Design Criteria

Sight distance is provided at railroad-highway grade crossings to accommodate two specific scenarios:

- Case A—sight distance for a moving vehicle approaching the grade crossing on the highway and
- Case B—sight distance for a vehicle stopped on the highway approach.

These cases are equivalent to the approach and departure sight triangles for intersections shown in Figure 41 and are of primary interest at railroad-highway grade crossings without train-activated warning devices. Sight distance design

TABLE 57 Time gap for Case F—left turns from the major road (*1*)

Design vehicle	Time gap (s) at design speed of major road (t_g)
Passenger car	5.5
Single-unit truck	6.5
Combination truck	7.5

Adjustment for multilane highways:
For left-turning vehicles that cross more than one opposing lane, add 0.5 seconds for passenger cars and 0.7 seconds for trucks for each additional lane to be crossed.

criteria for these cases are presented in the Green Book, but have been adapted from two other publications *(82, 83)*.

As in the case of a highway intersection, several events can occur at a railroad-highway grade intersection without train-activated warning devices. Two of these events, which relate to determining the sight distance in the Case A scenario, are as follows:

- The vehicle operator can observe the approaching train in a sight line that will allow the vehicle to pass through the grade crossing prior to the train's arrival at the crossing.
- The vehicle operator can observe the approaching train in a sight line that will permit the vehicle to be brought to a stop prior to encroachment in the crossing area.

Both of these maneuvers for Case A are shown in Figure 45, based on Green Book Exhibit 9-103. The sight triangle consists of the two major legs (i.e., the sight distance, d_H, along the highway and the sight distance, d_T, along the railroad tracks). Case A of Table 58, based on Green Book Exhibit 9-104, indicates values of the sight distances for various speeds of the vehicle and the train. These distances are developed from Equation 40. This equation incorporates a driver deceleration of 3.4 m/s^2 [11.2 ft/s^2] for consistency with the revised stopping sight distance criteria in the 2001 Green Book.

Metric

$$d_H = AV_vt + \frac{BV_v^2}{a} + D + d_e$$

$$d_T = \frac{V_T}{V_v}\left[(A)V_vt + \frac{BV_v^2}{a} + 2D + L + W\right]$$

where

A = constant = 0.278
B = constant = 0.039
d_H = sight-distance leg along the highway allows a vehicle proceeding to speed V_v to cross tracks even though a train is observed at a distance d_T from the crossing or to stop the vehicle without encroachment of the crossing area (m)
d_T = sight-distance leg along the railroad tracks to permit the maneuvers described as for d_H (m)
V_v = speed of the vehicle (km/h)
V_T = speed of the train (km/h)
t = perception/reaction time, which is assumed to be 2.5 s (This is the same value used in Chapter 3 to determine the stopping sight distance.)
a = driver deceleration, which is assumed to be 3.4 m/s^2 (This is the same value used in Chapter 3 to determine stopping sight distance.)
D = distance from the stop line or front of the vehicle to the nearest rail, which is assumed to be 4.5 m
d_e = distance from the driver to the front of the vehicle, which is assumed to be 3.0 m
L = length of vehicle, which is assumed to be 20 m
W = distance between outer rails (for a single track, this value is 1.5 m)

US Customary

$$d_H = AV_vt + \frac{BV_v^2}{a} + D + d_e$$

$$d_T = \frac{V_T}{V_v}\left[(A)V_vt + \frac{BV_v^2}{a} + 2D + L + W\right] \qquad (40)$$

where

A = constant = 1.47
B = constant = 1.075
d_H = sight-distance leg along the highway allows a vehicle proceeding to speed V_v to cross tracks even though a train is observed at a distance d_T from the crossing or to stop the vehicle without encroachment of the crossing area (ft)
d_T = sight-distance leg along the railroad tracks to permit the maneuvers described as for d_H (ft)
V_v = speed of the vehicle (mph)
V_T = speed of the train (mph)
t = perception/reaction time, which is assumed to be 2.5 s (This is the same value used in Chapter 3 to determine the stopping sight distance.)
a = driver deceleration, which is assumed to be 11.2 ft/s^2. (This is the same value used in Chapter 3 to determine stopping sight distance.)
D = distance from the stop line or front of the vehicle to the nearest rail, which is assumed to be 15 ft
d_e = distance from the driver to the front of the vehicle, which is assumed to be 10 ft
L = length of vehicle, which is assumed to be 65 ft
W = distance between outer rails (for a single track, this value is 5 ft)

The Green Book states that corrections should be made for skew crossings and highway grades that are other than flat.

Case B in Table 58 contains various values of departure sight distance for a range of train speeds. When a vehicle has stopped at a railroad crossing, the next maneuver is to depart from the stopped position. The vehicle operator should have sufficient sight distance along the tracks to accelerate the vehicle and clear the crossing prior to the arrival of a train, even if the train comes into view just as the vehicle starts, as shown in Figure 46, based on Green Book Exhibit 9-105. These values are obtained from the following equation:

Metric	US Customary
$d_T = AV_T \left[\frac{V_G}{a_1} + \frac{L + 2D + W - d_a}{V_G} + J\right]$	$d_T = AV_T \left[\frac{V_G}{a_1} + \frac{L + 2D + W - d_a}{V_G} + J\right]$ (41)
where A = constant = 0.278 d_T = sight distance leg along railroad tracks to permit the maneuvers described as for d_H (m) V_T = speed of train (km/h) V_G = maximum speed of vehicle in first gear, which is assumed to be 2.7 m/s a_1 = acceleration of vehicle in first gear, which is assumed to be 0.45 m/s^2 L = length of vehicle, which is assumed to be 20 m D = distance from stop line to nearest rail, which is assumed to be 4.5 m J = sum of perception and time to activate clutch or automatic shift, which is assumed to be 2.0 s W = distance between outer rails for a single track, this value is 1.5 m $d_a = \frac{V_G^2}{2a_1}$ or distance vehicle travels while accelerating to maximum speed in first gear $\left[\frac{V_G^2}{2a_1} = \frac{(2.7)^2}{(2)(0.45)} = 8.1\text{ m}\right]$	where A = constant = 1.47 d_T = sight distance leg along railroad tracks to permit the maneuvers described as for d_H (ft) V_T = speed of train (mph) V_G = maximum speed of vehicle in first gear, which is assumed to be 8.8 fps a_1 = acceleration of vehicle in first gear, which is assumed to be 1.47 ft/s^2 L = length of vehicle, which is assumed to be 65 ft D = distance from stop line to nearest rail, which is assumed to be 15 ft J = sum of perception and time to activate clutch or automatic shift, which is assumed to be 2.0 s W = distance between outer rails for a single track, this value is 5 ft $d_a = \frac{V_G^2}{2a_1}$ or distance vehicle travels while accelerating to maximum speed in first gear $\left[\frac{V_G^2}{2a_1} = \frac{(8.8)^2}{(2)(1.47)} = 26.3\text{ ft}\right]$

The Green Book states that corrections should be made for skewed crossings and for highway grades other than flat.

The Green Book states that sight distances of the order shown in Table 58 are desirable at any railroad grade crossing not controlled by active warning devices, but that their attainment is difficult and often impractical, except in flat, open terrain.

In other than flat terrain, the Green Book states that it may be appropriate to rely on speed control signs and devices and to predicate sight distance on a reduced vehicle speed of operation. Where sight obstructions are present, it may be appropriate to install active traffic control devices that will bring all highway traffic to a stop before crossing the tracks and will warn drivers automatically in time for an approaching train.

The Green Book states that the driver of a stopped vehicle at a crossing should see enough of the railroad track to be able to cross it before a train reaches the crossing, even though the train may come into view immediately after the vehicle starts to cross. The length of the railroad track in view on each side of the crossing should be greater than the product of the train speed and the time needed for the stopped vehicle to start and cross the railroad. The sight distance along the railroad track may be determined in the same manner as it is for a stopped vehicle crossing a preference highway, which is covered previously in this chapter. In order for vehicles to cross two tracks from a stopped position, with the front of the vehicle 4.5 m [15 ft] from the closest rail, sight distances along the railroad should be determined from Equation 41 with a proper adjustment for the *W* value.

Critique of Geometric Design Criteria

Since the sight distance criteria for highway-railroad grade crossings have been revised in the 2001 Green Book to reflect the revised stopping sight distance criteria, the sensitivity analysis performed in the FHWA *Truck Characteristics* study is no longer current and a new sensitivity analysis has been performed. This sensitivity analysis was performed to compare the sight distance requirements based on the 2001 Green Book criteria and sight distances derived for trucks with antilock braking systems. This sensitivity analysis considered only the Case A scenario (i.e., sight distance for a moving vehicle approaching the grade crossing on the highway). Sight distances were derived for three vehicle lengths. Results of the analysis are provided in Table 59. In general, the sight distances derived for vehicles with antilock braking systems are slightly higher than the sight distances derived from the current stopping sight distance criteria, but the differences are small. Thus, the current sight distance criteria for railroad-highway grade crossings appear to sufficiently accommodate trucks, so there is no need to update these criteria at this time.

INTERSECTION AND CHANNELIZATION GEOMETRICS

Current Geometric Design Criteria

A key control in the design of at-grade intersections and ramp terminals is the turning radius and path of a selected design vehicle. The following portions of the Green Book incorporate design criteria for intersections and turning roadways that are tied directly to the turning ability of selected design vehicles:

- Curvature of turning roadways and curvature at intersections (Green Book Chapter 3, p. 203)
- Widths of turning roadways at intersections (Chapter 3, p. 223–226)
- Design of roundabouts (Chapter 9, p. 581)
- Minimum edge-of-traveled-way designs for turning roadways (Chapter 9, p. 587–614)
- Curb return radii (Chapter 9, p. 623–625)

METRIC

$$d_H = 0.278 V_v t + \frac{Vv^2}{254f} + D + de$$

$$d_T = \frac{V_T}{V_v}\left[0.278 V_{vt} + \frac{Vv^2}{254f} + 2D + L + W\right]$$

d_H = Sight distance along highway
d_T = Sight distance along railroad tracks
V_v = Velocity of vehicle
t = Perception/reaction time (assumed 2.5 s)
f = Coefficient of friction time (see Exhibit 3-1)
D = Distance from stop line to near rail (assumed 4.5 m)
W = Distance between outer rails (single track W = 1.5 m)
L = Length of vehicle (assumed 20 m)
V_T = Velocity of train
de = Distance from driver to front of vehicle (assumed 3 m)

Adjustments must be made for skewed crossings.
Assumed flat highway grades adjacent to and at crossings.

US CUSTOMARY

$$d_H = 1.47 V_v t + \frac{Vv^2}{30f} + D + de$$

$$d_T = \frac{V_T}{V_v}\left(1.47 V_v t + \frac{Vv^2}{30f} + 2D + L + W\right)$$

d_H = Sight distance along highway
d_T = Sight distance along railroad tracks
V_v = Velocity of vehicle
t = Perception/reaction time (assumed 2.5 s)
f = Coefficient of friction (see Exhibit 3-1)
D = Distance form stop line to near rail (assumed 15 ft)
W = Distance between outer rails (single track W = 5 ft)
L = Length of vehicle (assumed 65 ft)
V_T = Velocity of train
de = Distance from driver to front of vehicle (assumed 10 ft)

Adjustments must be made for skewed crossings.
Assumed flat highway grades adjacent to and at crossings.

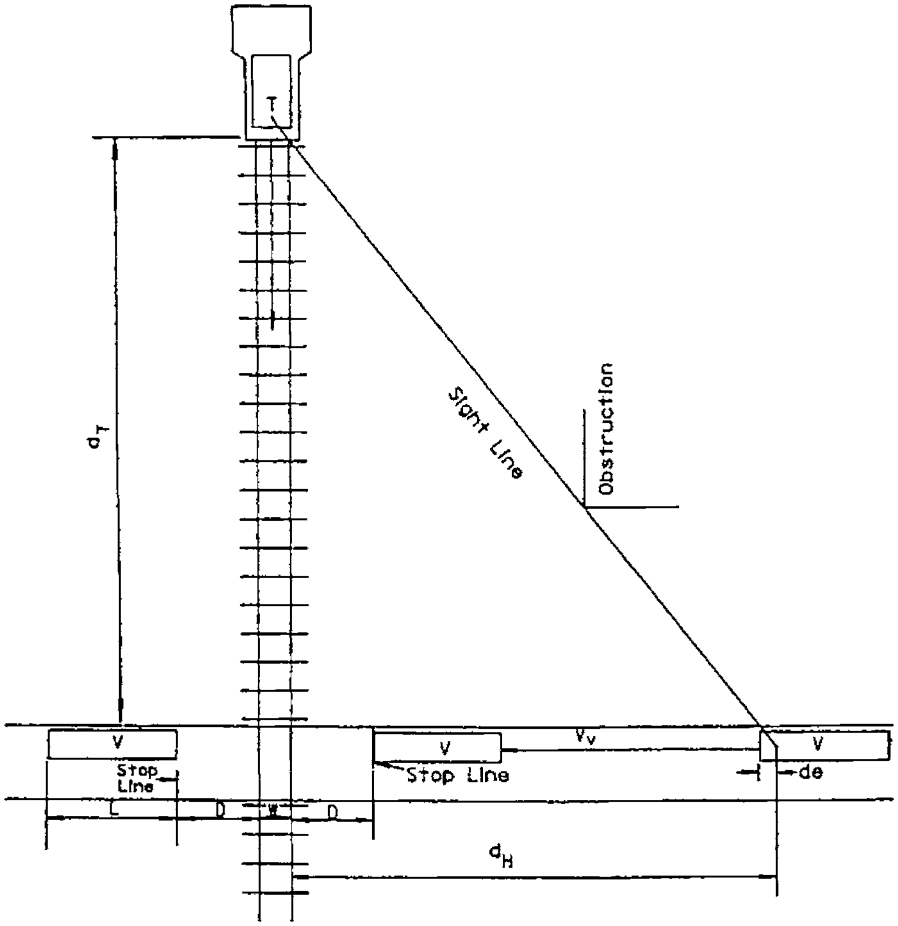


Figure 45. Case A: moving vehicle to safely cross or stop at railroad crossing (1).

- Turning roadways with corner islands (Chapter 9, p. 638–643)
- Control radii for minimum turning paths at median openings (Chapter 9, p. 694–704)
- Minimum designs for U-turns at median openings (Chapter 9, p 715)

The minimum turning radii for the current Green Book design vehicles are presented in Table 20, based on Green Book Exhibit 2-2. The Green Book establishes the minimum turning path for design trucks based on the boundaries of the outer trace of the front overhang and the sharpest turning radius of the right inner rear wheel. Minimum turning radius

TABLE 58 Required design sight distance for combination of highway and train vehicle speeds; 20-m [65-ft] truck crossing a single set of tracks at 90 percent (*1*)

Metric

Train speed (km/h)	Case B Departure from stop	Case A Moving vehicle Vehicle speed (km/h)												
	0	10	20	30	40	50	60	70	80	90	100	110	120	130
		Distance along railroad from crossing, d_T(m)												
10	45	39	24	21	19	19	19	19	20	21	21	22	23	24
20	91	77	49	41	38	38	38	39	40	41	43	45	47	48
30	136	116	73	62	57	56	57	58	60	62	64	67	70	73
40	181	154	98	82	77	75	76	77	80	83	86	89	93	97
50	227	193	122	103	96	94	95	97	100	103	107	112	116	121
60	272	232	147	123	115	113	113	116	120	124	129	134	140	145
70	317	270	171	144	134	131	132	135	140	145	150	156	163	169
80	362	309	196	164	153	150	151	155	160	165	172	179	186	194
90	408	347	220	185	172	169	170	174	179	186	193	201	209	218
100	453	386	245	206	192	188	189	193	199	207	215	223	233	242
110	498	425	269	226	211	207	208	213	219	227	236	246	256	266
120	544	463	294	247	230	225	227	232	239	248	258	268	279	290
130	589	502	318	267	249	244	246	251	259	269	279	290	302	315
140	634	540	343	288	268	263	265	271	279	289	301	313	326	339
		Distance along highway from crossing, d_H(m)												
		16	26	39	54	71	90	112	137	163	192	223	256	292

US Customary

Train speed (mph)	Case B Departure from stop	Case A Moving vehicle Vehicle speed (mph)							
	0	10	20	30	40	50	60	70	80
		Distance along railroad from crossing, d_T(ft)							
10	240	146	106	99	100	105	111	118	126
20	480	293	212	198	200	209	222	236	252
30	721	439	318	297	300	314	333	355	378
40	961	585	424	396	401	419	444	473	504
50	1201	732	530	494	501	524	555	591	630
60	1441	878	636	593	601	628	666	709	756
70	1681	1024	742	692	701	733	777	828	882
80	1921	1171	848	791	801	838	888	946	1008
90	2162	1317	954	890	901	943	999	1064	1134
		Distance along highway from crossing, d_H(ft)							
		71	137	222	326	449	591	753	933

is defined as the path of the outer front wheel, following a circular arc, at a speed of less than 16 km/h (10 mph), and is limited by the vehicle steering mechanism. Minimum inside radius is the path traced by the right rear wheel.

Because a truck has a long wheelbase, its rear wheels do not follow the same path as its front wheels during a turn. The differences in these paths are referred to as *offtracking*. Offtracking amounts vary directly with the wheelbase of a unit and inversely with the radius of turn. *Swept path width*, the difference in paths of the outside front tractor tire and the inside rear trailer tire, is a more appropriate parameter for design consideration. Swept path width determinations delineate the boundaries of the space occupied by the vehicle negotiating its turn. Offtracking and swept path widths are defined and discussed more fully in Chapter 4 of this report.

Critique of Geometric Design Criteria

Design Vehicle Changes

The recommendation to drop the WB-15 [WB-50] design vehicle from the Green Book will require changes to text and exhibits in Green Book Chapter 9. The recommended changes are presented in Appendix F.

Double and Triple Left-Turn Lanes

The use of double left-turn lanes, and even triple left-turn lanes, is becoming more common due to increasing demand levels. Under certain conditions, double left-turn lanes accompanied with a separate left-turn signalization phase can accommodate up to approximately 180 percent of the volume that can be served by a single left-turn lane with the same available green time. The Green Book states that where sufficient right-of-way, space for a long-radius turn, and a wide cross street are available, installation of double left-turn lanes may be a practical design to serve a heavy left-turn movement. The Green Book also indicates that the desirable turning radius for a double left-turn lane is 27 m [90 ft]. Exhibit 9-13A in the Green Book illustrates an intersection configuration with double left-turn lanes for one of the left-turning movements. In this illustration, the double left-turn lanes are located within the median of the divided highway and are separated from the through lanes by either an elongated island or by pavement markings. Given that left-turn maneuvers are accomplished simultaneously from both lanes, the median opening and crossroad pavement should be sufficiently wide to receive the two side-by-side traffic streams.

The Green Book provides guidance on ways to accommodate left-turn maneuvers of various design vehicles. Exhibit 9-76 shows the paths of several design vehicles positioned as they would govern median end design for vehicles making a left turn to both leave and enter a divided highway. Exhibits 9-77 through 9-83 provide guidance on control radii from minimum practical design of median openings and indicate how each control radius design affects larger vehicles and occasional movements other than those for which the design is developed. Exhibits 9-85 and 9-87 provide additional guidance on design of median openings, and other exhibits and sections of the Green Book provide general guidance to accommodate left-turn maneuvers at intersections. However, with the exception of indicating a desirable turning radius for a double left-turn lane and providing an illustration of an intersection with a double

METRIC

$$d_T = 0.278 V_T \left[\frac{V_G}{a_1} + \frac{L = 2D + W - d_a}{V_G} + J \right]$$

d_T = Sight distance along railroad tracks to allow a stopped vehicle to depart and safely cross the railroad tracks
V_T = Velocity of train
V_G = Maximum speed of vehicle in first gear (assumed 2.7 m/s)
a_1 = Acceleration of vehicle in first gear (assumed 0.45 m/s^2)

$d_a = \frac{V_G^2}{2a}$ = Or distance vehicle travels while accelerating to maximum speed in first gear

D = Distance from stop line to near rail (assumed 4.5 m)
W = Distance between outer rails (single track W = 1.5 m)
L = Length of vehicle (assumed 20 m)
J = Perception/reaction time (assumed 2.0 s)

Adjustments must be made for skewed crossings.
Assumed flat highway grades adjacent to and at crossings.

US CUSTOMARY

$$d_T = 1.47 V_T \left[\frac{V_G}{a_1} + \frac{L = 2D + W - d_a}{V_G} + J \right]$$

d_T = Sight distance along railroad tracks to allow a stopped vehicle to depart and safely cross the railroad tracks
V_T = Velocity of train
V_G = Maximum speed of vehicle in first gear (assumed 8.8 fps)
a_1 = Acceleration of vehicle in first gear (assumed 1.47 ft)

$d_a = \frac{V_G^2}{2a}$ = Or distance vehicle travels while accelerating to maximum speed in first gear

D = Distance from stop line to near rail (assumed 15 ft)
W = Distance between outer rails (single track W = 5 ft)
L = Length of vehicle (assumed 65 ft)
J = Perception/reaction time (assumed 2.0 s)

Adjustments must be made for skewed crossings.
Assumed flat highway grades adjacent to and at crossings.

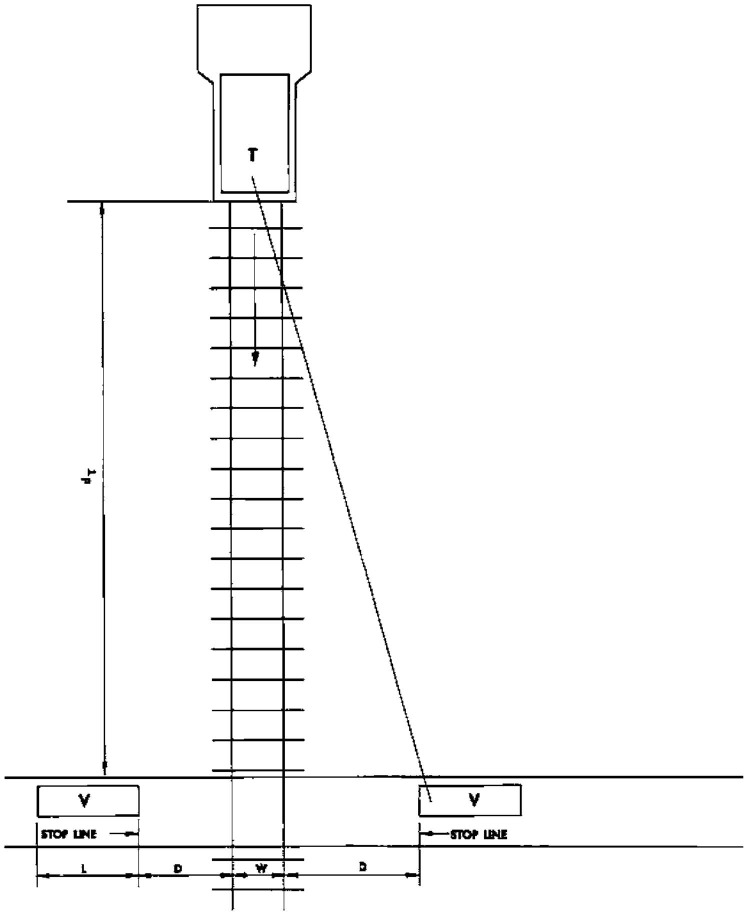


Figure 46. Case B: departure of vehicle from stopped position to cross single railroad track (1).

TABLE 59 Sensitivity analysis for sight distance along railroad from crossing (d_T) and along highway from crossing (d_H)

Train Speed (mph)	Case A (Moving Vehicle)																	
	Vehicle Length = 68.5 ft (WB-62)						Vehicle Length = 73.5 ft (WB-67)						Vehicle Length = 77.5 ft (WB-71)					
	Vehicle Speed (mph)																	
	20	30	40	50	60	70	20	30	40	50	60	70	20	30	40	50	60	70
Sight Distance Along Railroad From Crossing, d_T (ft)—Current AASHTO Policy (2001)																		
10	108	100	101	105	111	118	110	102	102	106	112	119	112	103	103	107	113	120
20	215	200	202	210	222	237	220	203	204	212	224	238	224	206	206	214	225	239
30	323	300	302	315	334	355	330	305	306	318	336	357	336	309	309	321	338	359
40	430	399	403	421	445	473	440	406	408	425	448	476	448	411	412	428	451	478
50	538	499	504	526	556	592	550	508	510	531	560	595	560	514	515	535	564	598
60	645	599	605	631	667	710	660	609	612	637	672	714	672	617	618	642	676	718
70	753	699	705	736	779	828	771	711	714	743	784	833	785	720	721	749	789	837
80	861	799	806	841	890	946	881	812	816	849	897	952	897	823	824	856	902	957
90	968	899	907	946	1,001	1,065	991	914	918	955	1,009	1,071	1,009	926	927	962	1,015	1,076
Sight Distance Along Highway From Crossing, d_H (ft)—Current AASHTO Policy (2001)																		
	137	221	325	447	589	750	137	221	325	447	589	750	137	221	325	447	589	750
Sight Distance Along Railroad From Crossing, d_T (ft)—Antilock Brake System																		
10	107	101	106	111	117	125	110	102	107	112	117	125	112	104	108	113	118	126
20	214	201	211	223	233	249	219	205	214	225	235	251	223	207	216	226	236	252
30	321	302	317	334	350	374	329	307	321	337	352	376	335	311	324	339	354	378
40	428	403	423	445	466	498	438	409	428	449	470	501	446	415	432	452	472	503
50	535	504	529	556	583	623	548	512	535	561	587	626	558	519	540	565	590	629
60	642	604	634	668	700	747	657	614	642	674	705	752	669	622	648	679	709	755
70	749	705	740	779	816	872	767	717	749	786	822	877	781	726	756	792	827	881
80	856	806	846	890	933	997	876	819	856	898	939	1,002	892	830	864	905	945	1,007
90	963	906	951	1,002	1,049	1,121	986	921	963	1,011	1,057	1,128	1,004	933	972	1,018	1,063	1,133
Sight Distance Along Highway From Crossing, d_H (ft)—Antilock Brake System																		
	136	224	344	478	621	793	136	224	344	478	621	793	136	224	344	478	621	793

left-turn lane, the Green Book does not go into further detail on the design of double left-turn lanes.

The primary factor to consider in designing double left-turn lanes is vehicle offtracking or swept path width. When vehicles negotiate the turn side by side, the vehicles should not encroach on the adjacent travel lane. Because many factors affect the control turning radius of double left-turn lanes, it is necessary to provide guidance on the range of offtracking or swept path width of design vehicles for various turning radii. The offtracking and resultant swept path widths of several design vehicles were determined for 90-deg turns with centerline turning radii of 15.2, 22.9, 30.5, and 45.7 m (50, 75, 100, and 150 ft) using AutoTURN software. It is recommended that an exhibit be added to the Green Book that indicates the swept path width of several design vehicles for centerline turning radii of 22.9, 30.5, and 45.7 m (75, 100, and 150 ft). This type of exhibit will provide flexibility in designing adequate turning paths for double left-turn lanes by allowing for interpolation of swept path widths for a range of turning radii.

Roundabouts

In Green Book Chapter 9, there is a brief introduction to roundabouts (p. 578–583); however, no quantitative discussion of truck performance at roundabouts is included. No sources were found in the literature that deal specifically with the issue of truck stability or rollover at roundabouts.

The FHWA Roundabout Guide *(84)* discusses in detail the geometric design of roundabouts considering large vehicles. The discussion includes design vehicles to be considered, and references the Green Book for obtaining dimensions and turning path requirements for a variety of common highway vehicles. The Roundabout Guide indicates that for single-lane roundabouts, the size of the inscribed circle is largely dependent on the turning requirements of the design vehicle. Table 60, from the Roundabout Guide, provides recommended maximum entry design speeds for specific categories of roundabouts. These were obtained from international studies as the optimum design speeds to minimize crashes. Furthermore, the Roundabout Guide provides recommended inscribed circle diameter ranges for various site categories and design vehicles (see Table 61).

With respect to superelevation, the Roundabout Guide recommends, for the circulatory roadway, a cross slope of 2 percent away from the central island. This is recommended, among other reasons, to increase the visibility of the central island and to promote low circulating speeds. Vehicles making through- and left-turning movements however must negotiate the roundabout at negative superelevation. High speeds

TABLE 60 Recommended maximum entry design speed (*84*)

Site category	Recommended maximum entry design speed
Mini-Roundabout	25 km/h [15 mph]
Urban Roundabout	25 km/h [15 mph]
Urban Single Lane	35 km/h [20 mph]
Urban Double Lane	40 km/h [25 mph]
Rural Single Lane	40 km/h [25 mph]
Rural Double Lane	50 km/h [30 mph]

through the roundabout can result in loss-of-load incidents for trucks; however, it is indicated in the Roundabout Guide that drivers generally expect to travel at slower speeds and will accept the higher side force caused by a reasonable superelevation rate. In summary, it is recommended that the Green Book section on roundabouts be expanded to incorporate the design guidelines developed in the Roundabout Guide, particularly those shown in Tables 60 and 61.

CRITICAL LENGTH OF GRADE

Current Geometric Design Criteria

The Green Book presents the current warrant for the addition of a truck climbing lane in terms of a *critical length of grade*. A climbing lane is not warranted if the grade does not exceed this critical length. If the critical length is exceeded, then a climbing lane is desirable and should be considered. The final decision to install a truck climbing lane may depend on several factors, but basically is determined by the reduction in level of service that would occur without the addition. This reduction, in turn, is a function of the traffic volume, the percentage of trucks, the performance capabilities of the trucks, the steepness of the grade, and the length of grade remaining beyond the critical length.

The critical length of grade, itself, is established by the "gradeability" of trucks. Subjectively, the critical length of grade is the "maximum length of a designated upgrade on which a loaded truck can operate without an unreasonable reduction in speed." The Green Book considers the critical length of grade to be dependent on three factors:

1. The weight and power of the representative truck used as the design vehicle, which determine its speed maintenance capabilities on grades;
2. The expected speed of the truck as it enters the critical length portion of the grade; and
3. The minimum speed on the grade below which interference to following vehicles is considered unreasonable.

Based on these factors, the Green Book defines the critical length of grade as the length of grade that would produce a speed reduction of 15 km/h (10 mph) for a 120 kg/kW (200 lb/hp) truck. The 120 kg/kW (200 lb/hp) truck is intended for use for average conditions in the United States. Figure 47 illustrates speed-distance curves for deceleration of a 120 kg/kW (200 lb/hp) truck on an upgrade, as presented in the Green Book. The use of a truck with a higher weight-to-power ratio is justified at sites with extremely low-powered or heavily loaded trucks in the traffic stream (e.g., in coal mining regions or near gravel quarries). Through the 1994 edition of the Green Book, critical length of grade was based on a 180-kg/kW (300-lb/hp) truck, rather than a 120-kg/kW (200-lb/hp) truck.

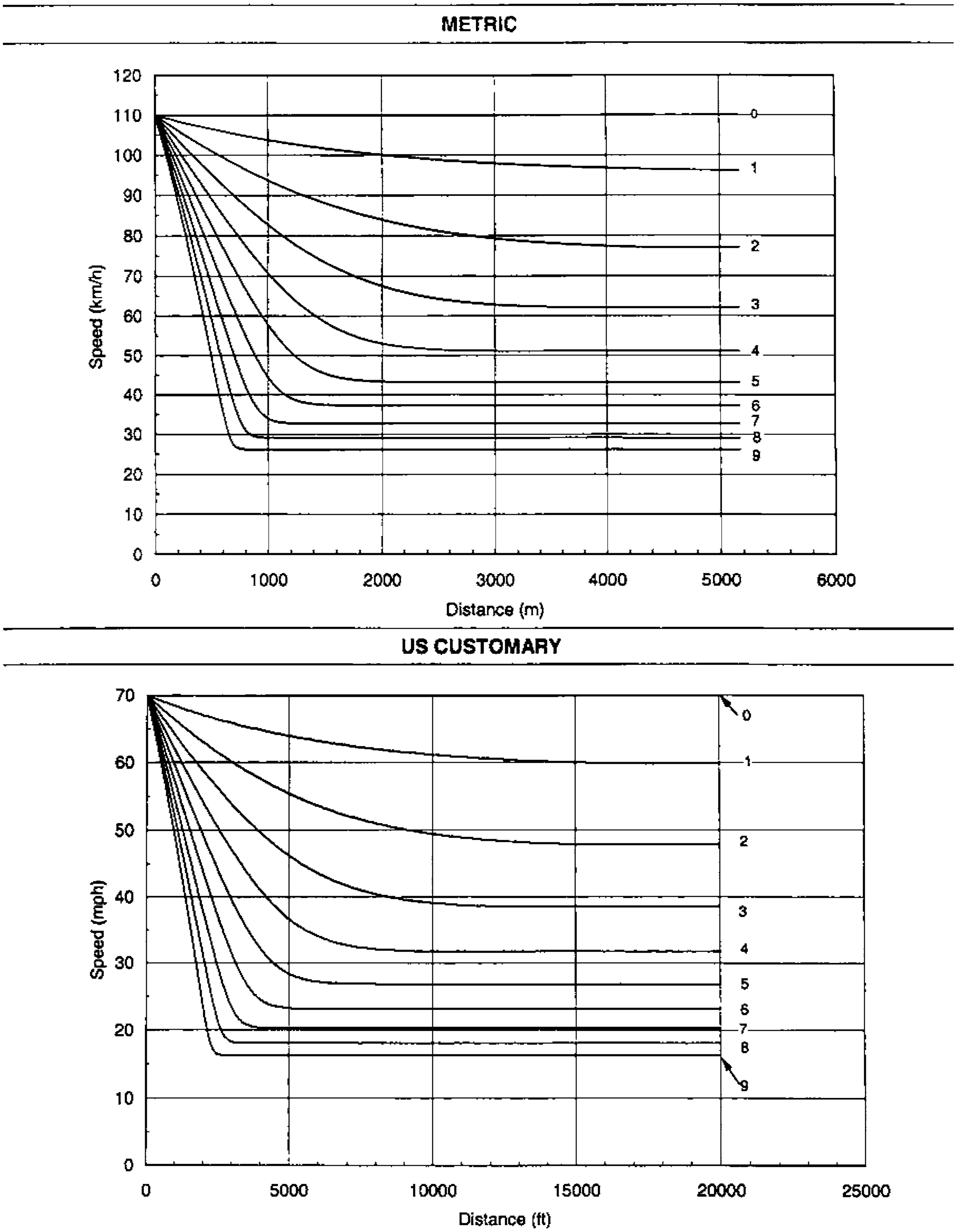
Critique of the Geometric Design Criteria

For the most part, the logical approach followed by the Green Book is well thought out. The procedures to be applied are straightforward and reasonable. Moreover, the AASHTO criteria for Factors 2 and 3 also seem reasonable. Factor 1, on the other hand, was, until recently, determined using truck performance data that were out of date. The revision from 180 to 120 kg/kW (300 to 200 lb/hp) was

TABLE 61 Diameter of inscribed circle for roundabouts of specific site categories and design vehicles (*84*)

Site Category	Typical Design Vehicle	Inscribed Circle Diameter Range*
Mini-Roundabout	Single-Unit Truck	13 – 25 m [45 – 80 ft]
Urban Compact	Single-Unit Truck/Bus	25 – 30 m [80 – 100 ft]
Urban Single Lane	WB-15 (WB-50)	30 – 40 m [100 – 130 ft]
Urban Double Lane	WB-15 (WB-50)	45 – 55 m [150 – 180 ft]
Rural Single Lane	WB-20 (WB-67)	35 – 40 m [115 – 130 ft]
Rural Double Lane	WB-20 (WB-67)	55 – 60 m [180 – 200 ft]

*Assumes 90° angles between entries and no more than four legs.



METRIC

US CUSTOMARY

Figure 47. Speed-distance curves for a typical heavy truck of 120 kg/kW [200 lb/hp] for deceleration of upgrades (1).

based on judgment, rather than actual field data and, therefore, merits closer review. Specific comments on the AASHTO criteria are presented below.

Unreasonable Interference with Following Vehicles

The amount of speed reduction used as the criterion for Factor 3 in determining the critical length of grade is based on its expected effect on the accident involvement rate of trucks. It is argued, based on known effects of speed differences between vehicles on accident rates, that any speed difference will increase accident rates to some extent. The amount of this increase that is "reasonable" has been determined through engineering judgment. The 1965 Blue Book used a 24-km/h (5-mph) speed reduction for critical length of grade; this was changed to the more conservative 16-km/h (10-mph) speed reduction in the 1984 Green Book and has been retained since.

Speed at Entrance to the Critical Length of Grade

The Green Book points out, properly, that the speed of trucks on a grade depends, in part, on their speed on entering the grade. It is reasonable to use the average running speed if the entrance is on level terrain. The chart for critical length of grade presented in Figure 48, based on Green Book Exhibit 3-63, is based on a truck speed entering the grade of 110 km/h (70 mph). However, if the upgrade in question is immediately preceded by a previous upgrade, the truck speed may already be depressed, which should be accounted for. Similarly, it is commonly known that truck drivers will accelerate somewhat on a downgrade immediately preceding an upgrade, to get a "running start" at it. In that case, the critical length of grade will be longer than with a level entrance. It would be desirable to provide designers with the capability to readily consider more than one value of entrance speed.

Design Vehicle

Field study results presented in Appendix D indicate that the 85th-percentile truck weight-to-power ratios range from 102 to 126 kg/kW (170 to 210 lb/hp) for the truck population on freeways and 108 to 168 kg/kW (180 to 280 lb/hp) for the truck population on two-lane highways. The available data suggest that truck performance is better for the freeway truck population than for the two-lane highway truck population and is better for the truck population in Western states than in Eastern states.

Final Climbing Speeds

The most common measure used to quantify truck performance on grades is the final climbing speed. This is the ultimate, slowest speed (the *crawl speed*) that the truck would be reduced to if the grade were sufficiently long. It is often reported in the literature or used in making comparisons between different vehicles. It is a useful measure for examining capacity, for example, on very long grades where trucks are actually reduced to their final climbing speeds. However, the important parameter in determining the critical length of grade is the distance required for the first 15 km/h (10 mph) of speed reduction on the grade. However, the final climbing speed or crawl speed of a truck can be used to estimate the truck's weight-to-power ratio and thereby determine the distance required for a 15-km/h (10-mph) speed reduction.

The relationship between truck speed profiles on specified grades and truck weight-to-power ratios can be made most readily with truck performance equations like those used in the TWOPAS computer simulation model *(85,86)*. The research has developed a Microsoft Excel spreadsheet, known as the Truck Speed Performance Model (TSPM), to apply the TWOPAS performance equations for trucks. This spreadsheet can be used to plot the speed-distance profile for a truck based on the following:

- Truck weight-to-power ratio,
- Vehicle profile of the roadway (percent grade and points of change), and
- Initial speed of the truck at the foot of the grade.

Aerodynamic drag forces on the truck are accounted for based on the elevation of the site above sea level.

Figure 49 presents an example of a truck speed profile on a grade developed with the TSPM spreadsheet. This spreadsheet is recommended for use as a design tool because, unlike Figures 47 and 48 used in the current Green Book, the TSPM spreadsheet is sensitive to the site-specific truck entrance speed, the estimated site-specific weight-to power ratios of trucks, and the actual vertical profile of the site, rather than an assumed constant grade. Figures 47 and 48 may be retained in the Green Book as examples, but the TSPM spreadsheet will provide a more useful tool for considering actual site conditions.

DOWNGRADES

Any vehicle, when traveling on a downgrade, loses potential energy because of its loss of elevation. This loss is equal to the product of its weight and its elevation descent. If there were no losses such as aerodynamic or rolling drag, and no braking, all of this energy would be converted to an increase in kinetic energy, expressed as $0.5\ MV^2$, where M is the vehicle mass and V is its speed. Fortunately, aerodynamic and rolling losses absorb some of this energy, but not all. (In passenger cars, these drag forces often can absorb most of the potential energy change, perhaps augmented by some modest braking on all but the most severe grades.)

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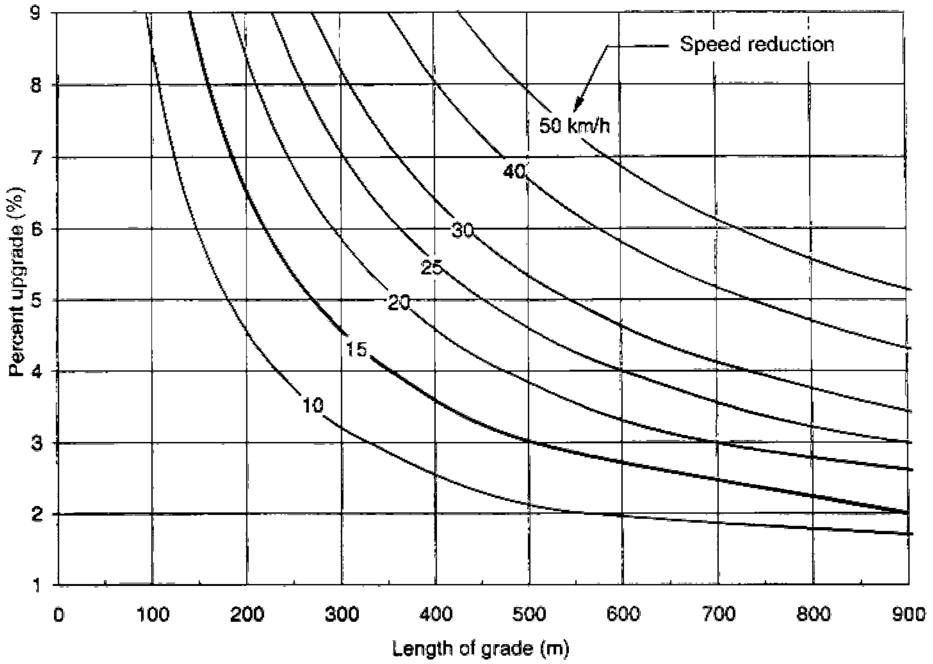

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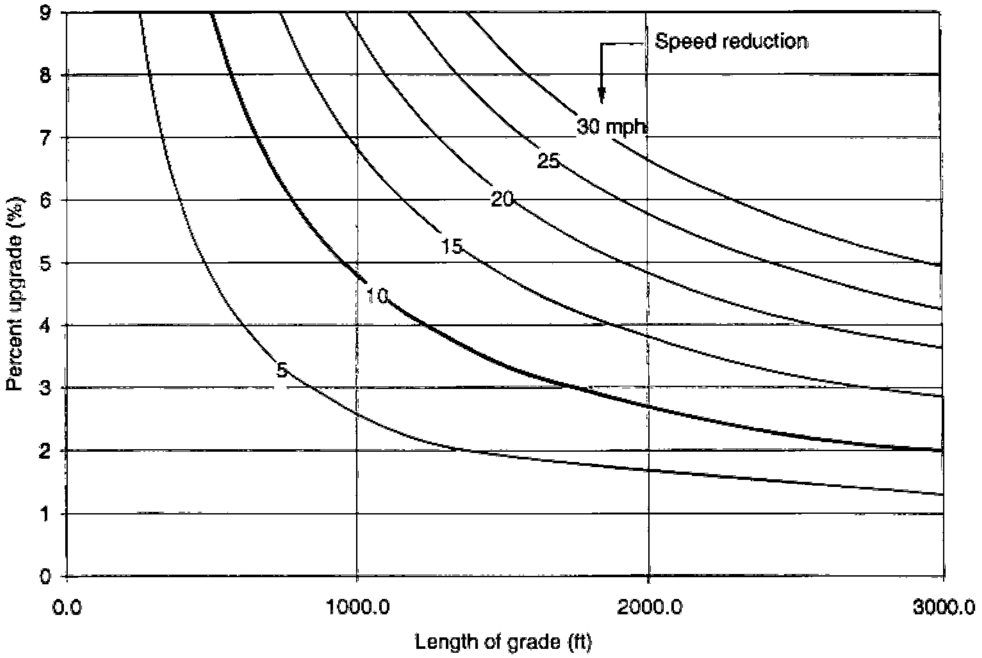


Figure 48. Critical lengths of grade for design, assumed typical heavy truck of 120 kg/kW [200 lb/hp], entering speed = 110 km/h [70 mph] (1).

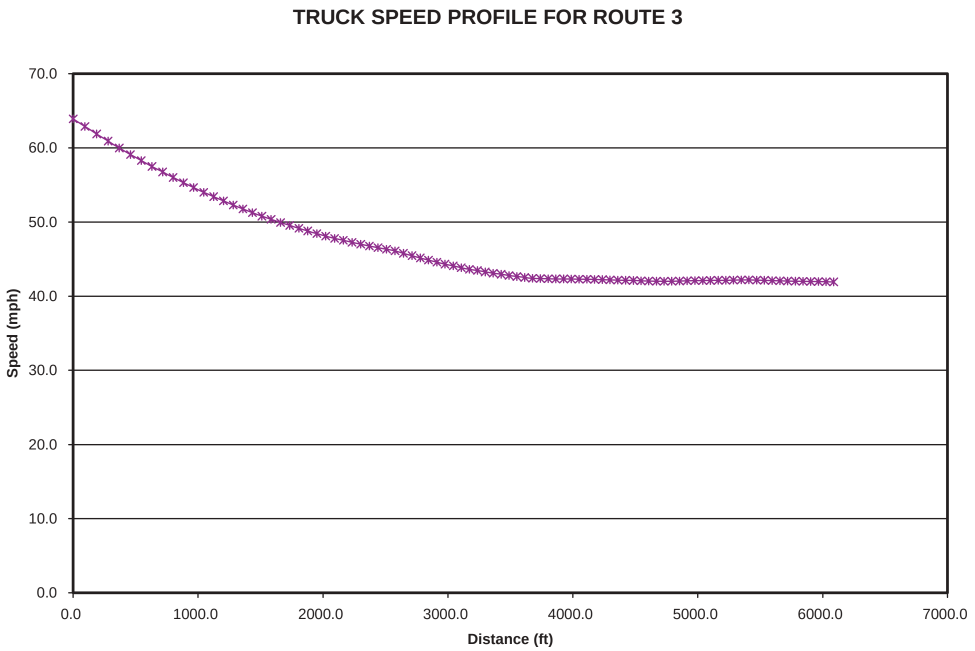


Figure 49. Example of truck speed profile plot from TSPM spreadsheet.

The major dissipater of excess energy in trucks is normally its brakes. The energy absorbed by the brakes is converted into heat, raising the temperature of the brake linings, brake drums/disks, and wheel assemblies. Their temperatures are commonly raised to 500 or 600°F or more. This heat, in turn, is dissipated to the surrounding air, primarily via convection, through fins and other means designed to be effective heat dissipaters. However, if the heat is not dissipated rapidly enough, and the brake temperature rises above some threshold, the brakes are said to become overheated, and they can no longer absorb energy at the same rate. Under these circumstances, the truck will begin to gain speed.

The truck driver must anticipate this situation, by selecting a lower gear ratio. This helps in two ways. In a lower gear ratio, the truck engine can absorb more energy per unit distance traveled. In addition, by selecting a lower gear ratio, the truck will be traveling at a lower speed, V, and thus reduce its needs to absorb energy as rapidly. FHWA has funded research regarding means of providing warning information to drivers *(87,88)*.

Trucks, when "in gear," can absorb large amounts of energy because of engine drag. Many truck operators who frequently travel in hilly or mountainous terrain use special engine brakes such as the Jacobs engine brake, known as a Jake Brake. These devices enable the engine's valve timing to be modified so these devices act as large air compressors, absorbing even more power. However, they can only operate through the drive wheels connected to the engine. They are quite effective on trucks such as tractor-semitrailer configurations, where two of the five axles are driven. However, they are much less effective on twin-trailer configurations (e.g., 2S-1-2 combinations) where only one of the five axles is driven.

There are two major impacts of truck downhill performance on highway design. First, where trucks should use lower gears, and thus lower "crawl" speeds, they may be traveling significantly slower than the rest of the traffic. If such regions are very long, or if there are not significant passing opportunities on two-lane roads for the other downgrade traffic, consideration might be given to adding a downgrade passing lane. The second potential impact is to provide for trucks whose drivers did not initially select a low enough gear ratio to enable them to maintain vehicle control on the downgrade. If a driver, early on the downgrade section, wishes to change to a lower gear ratio, he can brake to reduce speed, then downshift the transmission. However, if the brakes are already overheated from overusage, they may not be able to slow the truck further, so downshifting is no longer possible. In this situation, the driver can only hope that horizontal curvature and other traffic enable him to avoid an accident by steering the vehicle as it gains speed; another option is for the driver to intentionally leave the roadway to avoid becoming a "runaway." To provide assistance to drivers in this situation, emergency escape ramps are sometimes added by the highway agency. The Green Book provides information on the design of emergency escape ramps, but not on specific warrants for specific criteria for placement of such ramps.

Guidance on the issues of avoiding runaway trucks and providing emergency escape ramps is addressed by Allen et al. *(89)* and by Abdelwahab and Morrall *(90)*. In particular, Allen et al. (*89*) provide a recommended procedure for analysis of truck performance on downgrades that was recommended for incorporation in FHWA's Interactive Highway Safety Design Model (IHSDM). This procedure is based on four speed criteria:

1. The maximum speed at which the specified truck can descend the specified grade without losing braking ability;
2. The maximum speed at which the specified truck can descend the specified grade without rolling over on a horizontal curve;
3. The maximum speed at which the specified truck can descend the specified grade without losing the ability to brake safely to a stop using a deceleration rate of 3.4 m/s^2 (11.1 ft/s^2) or more; and
4. The maximum speed at which the specific truck can descend the specified grade without losing the ability to slow to the appropriate desired speed for any horizontal curve.

Criteria 1 and 2 are safety criteria that represent the thresholds at which accidents are expected. Speeds higher than the speed for Criterion 1 would be expected to result in loss of braking control (i.e., a runaway truck). Speeds higher than Criterion 2 would be expected to result in a truck rollover.

Criteria 3 and 4 are more conservative and represent thresholds for good design that do not approach impending loss of control. Criterion 3 ensures that a truck will be able to brake to a stop using a deceleration rate of not more than 3.4 m/s^2 (11.1 ft/s^2), the deceleration rate assumed in the current Green Book design criteria for stopping sight distance design (*1*). Criterion 4 ensures that the truck will not only not roll over on a horizontal curve, but also will be able to traverse each curve on the grade at the speed that drivers normally select for such curves when they are not on a downgrade.

The recommended truck operating speed for the grade is the lesser of the speeds determined for Criteria 3 and 4. The appropriateness of the recommended truck operating speed can also be judged by the magnitude of its margin of safety with respect to the loss-of-control speed (i.e., the lower of the speeds determined with Criteria 1 and 2). To judge the acceptability of the downgrade design, the designer must assess whether, with appropriate warning signs, it is reasonable to expect truckers to slow to the recommended truck operating speed before leaving the tope of the grade. Appropriate models can then be used to evaluate the location on the downgrade at which loss of safety margin, based on Criterion 3 or 4, would be expected and the location at which loss of control, based on Criterion 1 or 2, would be expected for various entering truck speeds. The recommended methodology for downgrade analysis to determine potential locations for emerging escape ramps is as follows (*89*):

- *Step 1*—Select a suitable truck for use as the design vehicle for downgrade analysis. If recreational vehicles are present in substantial numbers on the downgrade (e.g., 5 percent of the traffic stream or more), a suitable recreational vehicle should also be selected for analysis.
- *Step 2*—Determine the speeds designated by Criteria 1 through 4. Determine the recommended truck operating speed and the margin of safety to the loss-of-control speed.
- *Step 3*—Assess whether the recommended truck operating speed will be maintained by the vast majority of truck drivers. This assessment could be made with formal risk assessment logic based on further research, or it could be left to the judgment of the designer.
- *Step 4*—Modify the geometrics of the downgrade if necessary and feasible. This could involve using less steep slopes, flattening horizontal curves, or both.
- *Step 5*—If the recommended truck operating speed is deemed too low and it is physically or economically infeasible to modify the geometrics of the downgrade, the loss-of-control locations and the speed profiles following loss of control can be used to identify potential sites for emergency escape ramps. The speed profile data can also be used to anticipate potential truck entry speeds to the emergency escape ramp. The truck entry speed is an important design parameter in determining the required length of the ramp.

While the procedures recommended by Allen et al. (*89*) for locating emergency escape ramps would be a desirable addition to the Green Book, speed prediction models for implementing the procedure have not yet been developed. Allen et al. *(89)* present a plan for modifying the existing TWOPAS and VDANL models to provide suitable speed profiles for trucks on downgrades. However, these recommended model revisions have not yet been implemented. Therefore, the inclusion in the Green Book of the procedure presented above would be premature.

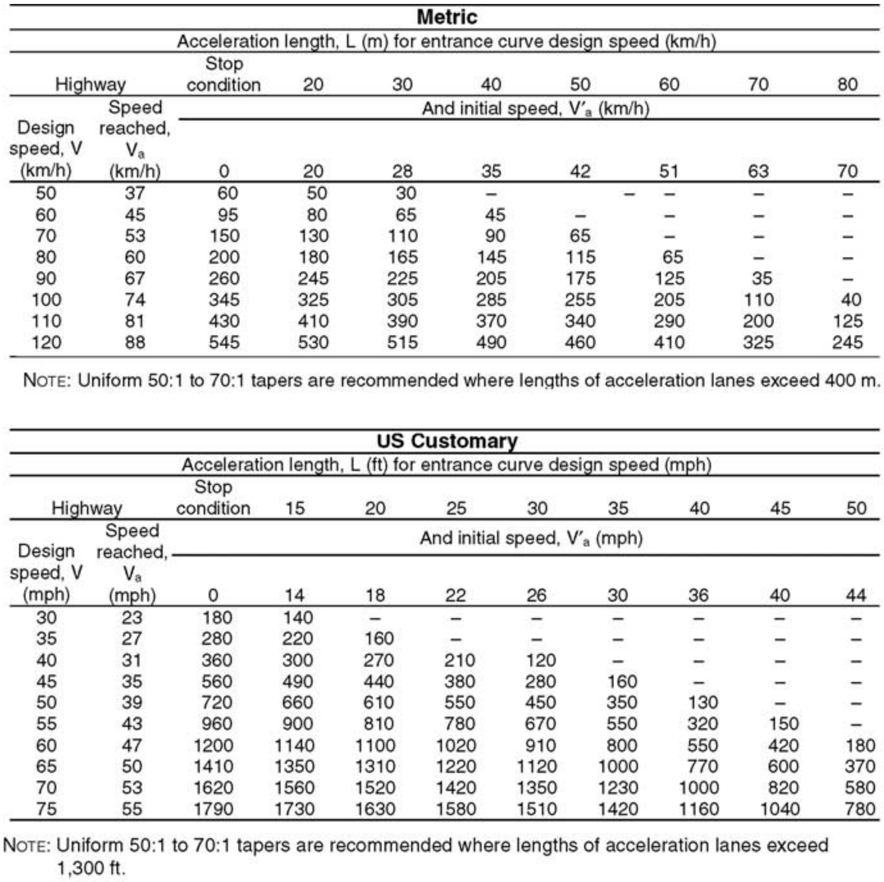
ACCELERATION LANES

Current Geometric Design Criteria

Acceleration lanes are speed-change lanes that provide sufficient distance for vehicles to accelerate to near highway speeds before entering the through lanes of a highway. Acceleration lane length is measured from the point where the left edge of the traveled way of the ramp joins the traveled way of the through roadway to the beginning of the downstream taper.

Table 62 presents the Green Book design values for acceleration lane length. Table 63 presents adjustment factors to those values that are applied to provide longer acceleration lanes on upgrades. The Green Book states that, to aid truck acceleration, high-speed entrance ramps should desirably be located on descending grades and that longer acceleration

TABLE 62 Minimum acceleration lengths for entrance terminals with flat grades of 2 percent or less (*1*)



Metric

Highway		Acceleration length, L (m) for entrance curve design speed (km/h)							
		Stop condition	20	30	40	50	60	70	80
Design speed, V (km/h)	Speed reached, V_a (km/h)	And initial speed, V'_a (km/h)							
		0	20	28	35	42	51	63	70
50	37	60	50	30	–	–	–	–	–
60	45	95	80	65	45	–	–	–	–
70	53	150	130	110	90	65	–	–	–
80	60	200	180	165	145	115	65	–	–
90	67	260	245	225	205	175	125	35	–
100	74	345	325	305	285	255	205	110	40
110	81	430	410	390	370	340	290	200	125
120	88	545	530	515	490	460	410	325	245

NOTE: Uniform 50:1 to 70:1 tapers are recommended where lengths of acceleration lanes exceed 400 m.

US Customary

Highway		Acceleration length, L (ft) for entrance curve design speed (mph)								
		Stop condition	15	20	25	30	35	40	45	50
Design speed, V (mph)	Speed reached, V_a (mph)	And initial speed, V'_a (mph)								
		0	14	18	22	26	30	36	40	44
30	23	180	140	–	–	–	–	–	–	–
35	27	280	220	160	–	–	–	–	–	–
40	31	360	300	270	210	120	–	–	–	–
45	35	560	490	440	380	280	160	–	–	–
50	39	720	660	610	550	450	350	130	–	–
55	43	960	900	810	780	670	550	320	150	–
60	47	1200	1140	1100	1020	910	800	550	420	180
65	50	1410	1350	1310	1220	1120	1000	770	600	370
70	53	1620	1560	1520	1420	1350	1230	1000	820	580
75	55	1790	1730	1630	1580	1510	1420	1160	1040	780

NOTE: Uniform 50:1 to 70:1 tapers are recommended where lengths of acceleration lanes exceed 1,300 ft.

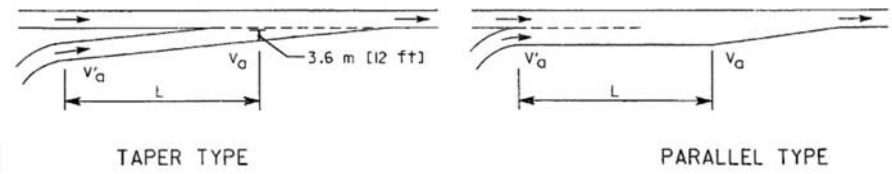


TABLE 63 Speed change lane adjustment factors as a function of grade (*1*)

Metric							US Customary					
Design speed of highway (km/h)	Acceleration lanes Ratio of length on grade to length of level for design speed of turning curve (km/h)[a]						Design speed of highway (mph)	Acceleration lanes Ratio of length on grade to length of level for design speed of turning curve (mph)[a]				
	40	50	60	70	80	All speeds		20	30	40	50	All speeds
			3 to 4% upgrade			3 to 4% downgrade			3 to 4% upgrade			3 to 4% downgrade
60	1.3	1.4	1.4	–	–	0.7	40	1.3	1.3	–	–	0.7
70	1.3	1.4	1.4	1.5	–	0.65	45	1.3	1.35	–	–	0.675
80	1.4	1.5	1.5	1.5	1.6	0.65	50	1.3	1.4	1.4	–	0.65
90	1.4	1.5	1.5	1.5	1.6	0.6	55	1.35	1.45	1.45	–	0.625
100	1.5	1.6	1.7	1.7	1.8	0.6	60	1.4	1.5	1.5	1.6	0.6
110	1.5	1.6	1.7	1.7	1.8	0.6	65	1.45	1.55	1.6	1.7	0.6
120	1.5	1.6	1.7	1.7	1.8	0.6	70	1.5	1.6	1.7	1.8	0.6
			5 to 6% upgrade			5 to 6% downgrade			5 to 6% upgrade			5 to 6% downgrade
60	1.5	1.5	–	–	–	0.6	40	1.5	1.5	–	–	0.6
70	1.5	1.6	1.7	–	–	0.6	45	1.5	1.6	–	–	0.575
80	1.5	1.7	1.9	1.8	–	0.55	50	1.5	1.7	1.9	–	0.55
90	1.6	1.8	2.0	2.1	2.2	0.55	55	1.6	1.8	2.05	–	0.525
100	1.7	1.9	2.2	2.4	2.5	0.5	60	1.7	1.9	2.2	2.5	0.5
110	2.0	2.2	2.6	2.8	3.0	0.5	65	1.85	2.05	2.4	2.75	0.5
120	2.3	2.5	3.0	3.2	3.5	0.5	70	2.0	2.2	2.6	3.0	0.5

[a] Ratio from this table multiplied by the length in Table 54 gives length of speed change lane on grade.

lanes should be provided on elevated freeways where entrance ramps must necessarily incorporate upgrades.

Critique of Geometric Design Criteria

An evaluation of Table 62 was conducted using the truck speed profile model (TSPM), described in Appendix E, to determine the weight-to-power ratios implied by the design values. To simplify the following discussion, all quantities are presented in U.S. customary units only. Since Table 62 pertains to grades of 2 percent or less, separate analyses were conducted for level (0 percent) grades and grades of 2 percent. Table 64 indicates the maximum weight-to-power ratio of a truck capable of achieving the given conditions as specified in Table 62, assuming a 0 percent grade. For example, Table 62 specifies that given the design speed of the highway is 30 mph and vehicles enter the acceleration lane from a stopped condition, the minimum acceleration lane length is 180 ft. Table 62 also specifies that vehicles are assumed to accelerate to a speed of 23 mph over this 180-ft distance. Table 64 indicates that a truck with a maximum weight-to-power ratio of 105 lb/hp is capable of accelerating from an initial speed of 0 mph to a final speed of 23 mph over a distance of 150 ft on a level (0 percent) grade. Similarly, given a highway design speed of 30 mph, an initial speed of 14 mph, a final speed of 23 mph, and an acceleration lane length of 140 ft (as specified in Table 62) on a 0 percent grade, Table 64 indicates that a truck with a maximum weight-to-power ratio of 140 lb/hp can achieve these given conditions. Table 65 indicates the maximum weight-to-power ratios of vehicles able to achieve the given conditions assuming minimum acceleration lane lengths (as specified in Table 62) and a constant grade of 2 percent.

Table 64 indicates that trucks with weight-to-power ratios in the range of 100 to 145 lb/hp have sufficient acceleration capabilities to achieve the given speeds within the minimum acceleration lengths, assuming a 0 percent grade. However, if the acceleration lanes have grades even as low as 2 percent, Table 65 indicates that trucks with weight-to-power ratios in

TABLE 64 Maximum weight-to-power ratios for minimum acceleration lengths (0 percent grades)

Maximum weight-to-power ratio (lb/hp) capable of reaching V_a given V'_a for 0 percent grades over acceleration lengths as specified in Table 62										
Highway		Stop condition	15	20	25	30	35	40	45	50
		And initial speed, V′a (mph)								
Design speed, V (mph)	Speed reached, V_a (mph)	0	14	18	22	26	30	36	40	44
30	23	105	140	–	–	–	–	–	–	–
35	27	110	120	130	–	–	–	–	–	–
40	31	105	115	120	125	120	–	–	–	–
45	35	120	120	125	135	135	135	–	–	–
50	39	120	120	120	120	120	125	145	–	–
55	43	120	120	115	120	120	120	120	130	–
60	47	110	115	115	115	110	115	110	120	130
65	50	110	110	110	110	110	115	110	110	110
70	53	105	105	105	105	105	105	105	105	105
75	55	105	105	100	100	105	105	105	105	100

TABLE 65 Maximum weight-to-power ratios for minimum acceleration lengths (2 percent grades)

Maximum weight-to-power ratio (lb/hp) capable of reaching V_a given V'_a for 2 percent grades over acceleration lengths as specified in Table 62										
Highway		Stop condition	15	20	25	30	35	40	45	50
		And initial speed, V′a (mph)								
Design speed, V (mph)	Speed reached, V_a (mph)	0	14	18	22	26	30	36	40	44
30	23	65	110	–	–	–	–	–	–	–
35	27	65	100	100	–	–	–	–	–	–
40	31	80	85	95	95	100	–	–	–	–
45	35	90	95	95	100	100	100	–	–	–
50	39	90	90	90	95	95	95	110	–	–
55	43	90	90	85	90	90	90	90	100	–
60	47	85	85	85	85	85	85	85	85	90
65	50	85	85	80	80	80	80	80	80	80
70	53	80	80	80	80	80	80	80	80	75
75	55	80	80	80	80	80	80	80	80	75

the range of 65 to 110 lb/hp have sufficient acceleration capabilities to achieve the given speeds within the minimum acceleration lengths. Considering that the 2001 Green Book indicates a 200-lb/hp truck is representative of the size and type of vehicle normally used for design control of major highways and that current field data indicate that on the freeways the 85th percentile weight-to-power ratios of trucks falls within a fairly narrow range around 170 to 210 lb/hp (see Appendix D), this analysis indicates that the underlying assumptions for estimating the minimum acceleration lengths in Table 62 do not necessarily account for the performance capabilities of heavily loaded vehicles. It appears that the current Green Book criteria can accommodate an average truck, but not a heavily loaded truck.

The TSPM once again was used to determine the minimum acceleration lengths required to enable a 180-lb/hp vehicle to reach the given conditions as specified in Table 62. Table 66 presents the minimum acceleration lengths assuming a 0 percent grade for the acceleration lane. Table 66 indicates that a 180 lb/hp truck can accelerate from an initial speed of 0 mph to a final speed of 23 mph over a distance of 275 ft on a level (0 percent) grade. The minimum acceleration lengths given in Table 66 are, on average, about 1.8 times greater than the minimum acceleration lengths given in Table 62.

Although the sensitivity analysis presented here indicates a potential need to increase acceleration lengths to accommodate heavily loaded trucks better, no accident data indicate that trucks have difficulties with acceleration lanes designed according to the current criteria. In addition, some of the lengths given in Table 66 are rather long, with the extreme case requiring a minimum acceleration length on the order of 0.6 mi. Therefore, no change to the current Green Book criteria is recommended at this time. However, future research should investigate truck-related accidents near acceleration lanes. If this future research should find that trucks have difficulties with acceleration lanes as currently designed, the design values in Table 62 should be increased to reflect the greater lengths as provided in Table 66, or a compromise should be reached for economic purposes. In addition, Table 63 would also require modification.

DECELERATION LANES

The Green Book design criteria for deceleration lanes are intended to provide sufficient distance for vehicles to slow from the speed of the major roadway to appropriate speed for any horizontal curve that may be located on the ramp. Such speed changes are normally made with controlled deceleration rates of which trucks are clearly capable. There is concern that trucks may skid or roll over on ramp curves if the truck is traveling substantially faster than the design speed of the curve (see subsequent discussion of horizontal curve design). However, there is no indication that driver choice of faster operating speeds is the result of short deceleration lanes or is correctable by using longer deceleration lanes. Therefore, no changes in the current Green Book design criteria for deceleration lane length are recommended.

LANE WIDTH

Current Geometric Design Criteria

The Green Book encourages the use of 3.6-m [12-ft] lanes for all but the lowest volume highways. In particular, on rural arterials, lane widths less than 3.6 m [12 ft] are normally used only for roads with design speeds less than 100 km/h [60 mph] and average daily traffic (ADT) less than 1,500 veh/day or design speeds less than 80 km/h [50 mph] and ADTs less than 2,000 veh/day (see Green Book Exhibit 7-3). For urban arterials, the AASHTO Green Book states that 3.0-m [10-ft] lanes should be used only in highly restricted areas having little or

TABLE 66 Minimum acceleration lengths for a 180 lb/hp truck

Acceleration length, L (ft), necessary for entrance curve to enable a 180 lb/hp truck to reach V_a given V'_a for a 0 percent grade										
Highway		Stop condition	15	20	25	30	35	40	45	50
		And initial speed, V′a (mph)								
Design speed, V (mph)	Speed reached, V_a (mph)	0	14	18	22	26	30	36	40	44
30	23	275	160	–	–	–	–	–	–	–
35	27	400	300	230	–	–	–	–	–	–
40	31	590	475	400	310	170	–	–	–	–
45	35	800	700	630	540	400	240	–	–	–
50	39	1100	1020	950	850	720	560	200	–	–
55	43	1510	1400	1330	1230	1100	920	580	240	–
60	47	2000	1900	1830	1740	1600	1430	1070	760	330
65	50	2490	2380	2280	2230	2090	1920	1560	1220	800
70	53	3060	2960	2900	2800	2670	2510	2140	1810	1260
75	55	3520	3430	3360	3260	3130	2960	2590	2290	1850

no truck traffic. However, both 3.3- and 3.6-m [11- and 12-ft] lane widths are used extensively on urban arterials.

The AASHTO Green Book does encourage wider lanes to accommodate trucks on some turning roadways at intersections and some horizontal curves. These issues are discussed later in this section.

Critique of Geometric Design Criteria

The lane width criteria in the AASHTO Green Book were established without reference to any explicit vehicle width specification. However, it is implicit in the criteria that the need for 3.3- and 3.6-m [11- and 12-ft] lanes is based on the consideration of truck width.

Two older studies have addressed the operational effects of wider vehicles and the implications of these effects for highway design. A joint NHTSA-FHWA assessment conducted in 1973 compared the operational effects of 2.4- and 2.6-m [8.0- and 8.5-ft] wide buses on two-lane, four-lane, six-lane, and eight-lane highways based on research reported in the literature *(91,92)*. This research found no effect of bus width on the lateral placement of adjacent cars, regardless of highway type and ambient wind conditions. There was a shift in the lateral position of cars by 300 to 460 mm [12 to 18 in.] when a bus was present, but the magnitude of this shift did not vary between 2.4- and 2.6-m [8.0- and 8.5-ft] wide buses.

A 1982 FHWA study of the effects of truck width on the positions of adjacent vehicles found no adverse effects of increased truck width either in passing maneuvers or at narrow bridges *(93)*. The passing maneuver studies were conducted on a two-lane highway with lane widths that varied from 3.2 to 3.6 m [10.5 to 12 ft]. Vehicle widths of 2.4, 2.6, 2.7, and 2.9 m [8.0, 8.5, 9.0, and 9.5 ft] were varied by changing the width of a fabricated wood and aluminum box on the trailer. The lateral position of the passing vehicle moved further to the left as the truck width increased, but there was no effect of truck widths on shoulder encroachments in passing maneuvers, which were observed consistently in about 6 percent of the passes. In studies at a narrow bridge on a two-lane highway with 3.5-m [11.5-ft] lanes, there was no effect of truck width on the speed or lateral placement of oncoming vehicles.

Research has shown a definite relationship between lane width and safety on two-lane roads *(94, 95)*. However, there is no indication in this research that the observed effect relates directly to truck widths. Rearward amplification, discussed in Chapter 5, refers to amplification of the magnitude of steering corrections in the rear trailers of multitrailer truck combinations. There is no indication that rearward amplification of sufficient magnitude to require lane widths greater than 3.3 to 3.6 m [11 to 12 ft] occurs with sufficient frequency that wider lanes are needed.

HORIZONTAL CURVE RADIUS AND SUPERELEVATION

This section of the report examines the role of truck considerations in the design of horizontal curves. Pavement widening on horizontal curves is addressed in the next section.

Current Geometric Design Criteria

The current design criteria for horizontal curves are established in the AASHTO Green Book. Under the AASHTO policy, a vehicle on a horizontal curve is represented as a point mass. From the basic laws of physics, the lateral acceleration of a point mass traveling at constant speed on a circular path can be represented by the relationship:

$$a = \frac{V^2}{15R} \tag{42}$$

where

a = lateral acceleration (g)
V = vehicle speed (mph)
R = radius of curve (ft)

The lateral acceleration experienced by the vehicle is expressed in units of the acceleration of gravity (g), which are equal to 9.8 m/s^2 [32.2 ft/s^2]. On a superelevated curve, the superelevation offsets a portion of the lateral acceleration, such that

$$a_{net} = \frac{V^2}{15R} - e \tag{43}$$

where

a_{net} = unbalanced portion of lateral acceleration (g)
e = superelevation (ft/ft)

The unbalanced portion of the lateral acceleration vehicle is a measure of the forces acting on the vehicle that tend to make it skid off the road or overturn. The side frictional demand of the vehicle is mathematically equivalent to the unbalanced lateral acceleration (a_{net}). For this reason, Equation 43 appears in the AASHTO Green Book in the following form:

$$f = \frac{V^2}{15R} - e \tag{44}$$

where f = side friction demand

The tendency of the vehicle to skid off the road must be resisted by tire/pavement friction. The vehicle will skid off the road, unless the tire/pavement friction coefficient exceeds the side friction demand. However, it is also critical for safe vehicle operations that vehicles not rollover on horizontal curves. The tendency of the vehicle to overturn must be resisted by the roll stability of the vehicle. The vehicle will roll over unless the rollover threshold of the vehicle exceeds the unbalanced lateral acceleration (a_{net}).

Selection of Radius and Superelevation

The objective of Green Book criteria for horizontal curve design is to select the radius and superelevation so that the unbalanced lateral acceleration is kept within tolerable limits. The Green Book criteria limit the unbalanced lateral acceleration for horizontal curves to a maximum of 0.175 g at 24 km/h [15 mph] decreasing to a maximum of 0.08 g at 129 km/h [80 mph]. This limitation is based on the results of research performed from 1936 through 1949 that established 0.17 g as the maximum unbalanced lateral acceleration at which drivers felt comfortable. Thus, these AASHTO criteria are based on maintaining comfort levels for passenger car drivers. The AASHTO criteria are not based explicitly on estimates of available tire/pavement friction levels or vehicle rollover thresholds, although it was assumed implicitly that available friction levels and rollover thresholds were higher than the specified driver comfort levels.

The Green Book provides design charts for maximum superelevation rates (e_{max}) from 4 to 12 percent. Highway agencies have established their own policies concerning the maximum superelevation rate that will be used on horizontal curves under their jurisdiction. Most highway agencies use maximum superelevation rates of either 6 or 8 percent. States that experience snow and ice conditions typically use lower superelevation rates. For any particular maximum superelevation rate and maximum side friction demand, the minimum radius of curvature can be determined as follows:

$$R_{min} = \frac{V_d^2}{15(e_{max} + f_{max})} \tag{45}$$

where

R_{min} = minimum radius of curvature (ft)
V_d = design speed of curve (mph)
e_{max} = specified maximum superelevation rate (ft/ft)
f_{max} = specified maximum side friction demand

Table 67, based on Green Book Exhibit 3-14, presents the minimum radius of curvature for specific combinations of maximum superelevation rate and maximum side friction demand considered in the Green Book.

In the design of a horizontal curve under the Green Book policy, the first major decision is to select its radius of curvature. Next, the selected radius is checked to ensure that it is not less than R_{min} for the design speed of the highway. Finally, if the selected radius is greater than R_{min}, a superelevation less than e_{max} is selected using Exhibits 3-21 through 3-25 of the Green Book.

TABLE 67 Minimum radius for design of rural highways, urban freeways, and high-speed urban streets using limiting values of e and f (*1*)

US Customary

Design Speed (mph)	Maximum e (%)	Limiting Values of f	Total (e/100 + f)	Calculated Radius (ft)	Rounded Radius (ft)
15	4.0	0.175	0.215	70.0	70
20	4.0	0.170	0.210	127.4	125
25	4.0	0.165	0.205	203.9	205
30	4.0	0.160	0.200	301.0	300
35	4.0	0.155	0.195	420.2	420
40	4.0	0.150	0.190	563.3	565
45	4.0	0.145	0.185	732.2	730
50	4.0	0.140	0.180	929.0	930
55	4.0	0.130	0.170	1190.2	1190
60	4.0	0.120	0.160	1505.0	1505
15	6.0	0.175	0.235	64.0	65
20	6.0	0.170	0.230	116.3	115
25	6.0	0.165	0.225	185.8	185
30	6.0	0.160	0.220	273.6	275
35	6.0	0.155	0.215	381.1	380
40	6.0	0.150	0.210	509.6	510
45	6.0	0.145	0.205	660.7	660
50	6.0	0.140	0.200	836.1	835
55	6.0	0.130	0.190	1065.0	1065
60	6.0	0.120	0.180	1337.8	1340
65	6.0	0.110	0.170	1662.4	1660
70	6.0	0.100	0.160	2048.5	2050
75	6.0	0.090	0.150	2508.4	2510
80	6.0	0.080	0.140	3057.8	3060
15	8.0	0.175	0.255	59.0	60
20	8.0	0.170	0.250	107.0	105
25	8.0	0.185	0.245	170.8	170
30	8.0	0.160	0.240	250.8	250
35	8.0	0.155	0.235	348.7	350
40	8.0	0.150	0.230	465.3	465
45	8.0	0.145	0.225	502.0	500
50	8.0	0.140	0.220	760.1	760
55	8.0	0.130	0.210	963.5	965
60	8.0	0.120	0.200	1204.0	1205
65	8.0	0.110	0.190	1487.4	1485
70	8.0	0.100	0.180	1820.9	1820
75	8.0	0.090	0.170	2213.3	2215
80	8.0	0.080	0.160	2675.6	2675
15	10.0	0.175	0.275	54.7	55
20	10.0	0.170	0.270	99.1	100
25	10.0	0.165	0.265	157.8	160
30	10.0	0.160	0.280	231.5	230
35	10.0	0.155	0.255	321.3	320
40	10.0	0.150	0.250	428.1	430
45	10.0	0.145	0.245	552.9	555
50	10.0	0.140	0.240	696.8	695
55	10.0	0.130	0.230	879.7	880
60	10.0	0.120	0.220	1094.6	1095
65	10.0	0.110	0.210	1345.8	1345
70	10.0	0.100	0.200	1838.8	1840
75	10.0	0.090	0.190	1980.3	1980
80	10.0	0.080	0.180	2378.3	2380
15	12.0	0.175	0.295	51.0	50
20	12.0	0.170	0.290	92.3	90
25	12.0	0.165	0.285	146.7	145
30	12.0	0.160	0.280	215.0	215
35	12.0	0.155	0.275	298.0	300
40	12.0	0.150	0.270	396.4	395
45	12.0	0.145	0.265	511.1	510
50	12.0	0.140	0.260	643.2	845
55	12.0	0.130	0.250	809.4	810
60	12.0	0.120	0.240	1003.4	1005
65	12.0	0.110	0.230	1228.7	1230
70	12.0	0.100	0.220	1489.8	1490
75	12.0	0.090	0.210	1791.7	1790
80	12.0	0.080	0.200	2140.5	2140

NOTE: In recognition of safety considerations, use of e_{max} = 4.0% should be limited to urban conditions.

Transition Design

Most horizontal curves are circular curves that directly adjoin tangent roadway sections at either end with no transition curve. Thus, a vehicle entering a curve theoretically encounters an instantaneous increase in lateral acceleration from a minimal level of the tangent section to the full lateral acceleration required to track the particular curve. The opposite occurs as a vehicle leaves a horizontal curve. In fact, there is a gradual rather than an instantaneous change in lateral acceleration, because drivers steer a spiral or transition path as they enter or leave a horizontal curve. The design of the superelevation transition section is used to partially offset the changes in lateral acceleration that do occur. First, a superelevation runout section is used on the tangent section to remove the adverse crown slope. Next, a superelevation runoff section is provided in which the pavement is rotated around its inside edge to attain the full required superelevation; typical design practice is to place two-thirds of the superelevation runoff on the tangent approach and one-third on the curve.

The Green Book encourages the use of spiral transition curves to provide a smooth transition between tangents and circular curves. In a spiral transition curve, the degree of curvature varies linearly from zero at the tangent end to the degree of the circular arc at the circular curve end. The length of the spiral transition curve can be made the same as the superelevation runoff, so that the degree of curvature and pavement cross slope change together.

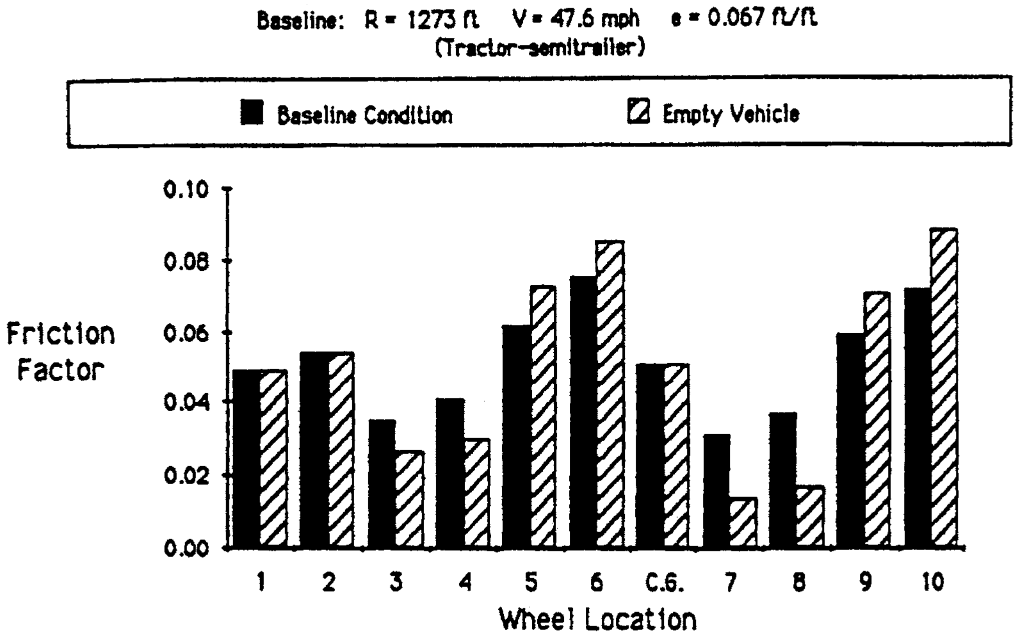
Critique of Geometric Design Criteria

Consideration of Friction Demand

The point mass representation of a vehicle that forms the basis for Equations 42, 43, and 44 is not based on any particular set of vehicle characteristics and is theoretically as applicable to trucks as to passenger cars. However, in light of the differences between passenger cars and trucks in size, number of tires, tire characteristics, and suspension characteristics, the suitability of the equations for trucks was recently reexamined.

A 1985 FHWA study by MacAdam et al. *(96)* found that, given that the basic laws of physics apply to both passenger cars and trucks, the point mass representation in Equation 44 can be used to determine the net side friction demand of both passenger cars and trucks. However, they found that while the friction demands at the four tires of a passenger car are approximately equal, the friction demands at the various tires of a tractor-trailer truck vary widely, as illustrated in Figure 50. The net result of this tire-to-tire variation in friction demand is that trucks typically demand approximately 10 percent higher side friction than passenger cars. The FHWA *Truck Characteristics* study termed this higher side friction demand the *effective side friction demand* of trucks.

The point mass representation of a vehicle has another weakness, however, that applies to both passenger cars and trucks. Equation 42 is based on the assumption that vehicles traverse curves following a path of constant radius equal to the radius of the curve. However, field studies have shown that all vehicles oversteer at some point on a horizontal curve. At the point of oversteering, the vehicle is following a path radius that is less than the radius of the curve *(97)*. Thus, at



Note: The wheel locations are for a 5-axle tractor-semitrailer and start at the front axle with wheel location number 1. Odd numbers represent the outside wheels on the turn.

Figure 50. Example of variation in side friction demand between wheels of a truck on a horizontal curve (96).

some point on each curve, the friction demand of each vehicle will be slightly higher than suggested by Equation 44. Oversteering by passenger cars is not considered in the AASHTO design policy for horizontal curves, but it is probably not critical because the AASHTO maximum lateral acceleration requirements are based on driver comfort levels rather than the available pavement friction. No data are available on the amount of oversteering by trucks relative to passenger cars.

Consideration of Rollover Threshold

As demonstrated above, AASHTO criteria for horizontal curve design do not explicitly consider vehicle rollover thresholds. The rollover threshold for passenger cars may be as high as 1.2 g, so a passenger car will normally skid off a road long before it would roll over. Thus, the consideration of rollover threshold is not critical for passenger cars. However, tractor-trailer trucks have relatively high centers-of-gravity and consequently tend to have low rollover thresholds. Furthermore, because of suspension characteristics, the rollover threshold of tractor-trailer trucks is substantially less than it would be if a truck were a rigid body.

Recent research, summarized in Chapter 5 of this report, has determined that the rollover thresholds of most trucks are greater than or equal to 0.35 g. Given that AASHTO design policy permits lateral acceleration as large as 0.17 g on horizontal curves, the margin of safety for trucks is typically at least 0.18 g. As discussed above, oversteer will generally result in a lateral acceleration greater than f_{max} at some point on the curve for vehicles traveling at the design speed.

As an example of truck operations on horizontal curves, Figure 51 presents the distribution of nominal side friction demand for trucks from combined data on four curves in the Chicago area as part of a NHTSA study *(98)*. The radii of the four curves range from 67 to 256 m [220 to 840 ft] and the superelevations range from 0.02 to 0.088. The distribution in Figure 51 was developed by measuring truck speeds on the curve and calculating the lateral acceleration for each truck from the known radius and superelevation using Equation 43.

The figure illustrates that trucks generating lateral accelerations above 0.30 g are observed, and the lateral accelerations for some trucks range as high as 0.40 g. No generalizations should be drawn from these data, because they represent only four particular horizontal curves, but they do illustrate that levels of side friction demand capable of producing rollovers for some trucks can occur.

Sensitivity Analyses

Sensitivity analyses have been conducted to determine whether the existing horizontal curve design criteria are adequate to accommodate trucks. The adequacy of the existing criteria was evaluated with respect to both their ability to keep vehicles from skidding off the road and their ability to keep vehicles from rolling over. These sensitivity analyses involved explicit comparisons between the margins of safety against skidding and rollover for passenger cars and trucks. There have been particular concerns about vehicles traveling faster than the design speed, particularly on freeway ramps. The sensitivity analysis presented here is an update of the analysis performed for the FHWA *Truck Characteristics* study *(2, 3)*, which resulted in the recent changes in Green Book design policy for horizontal curves.

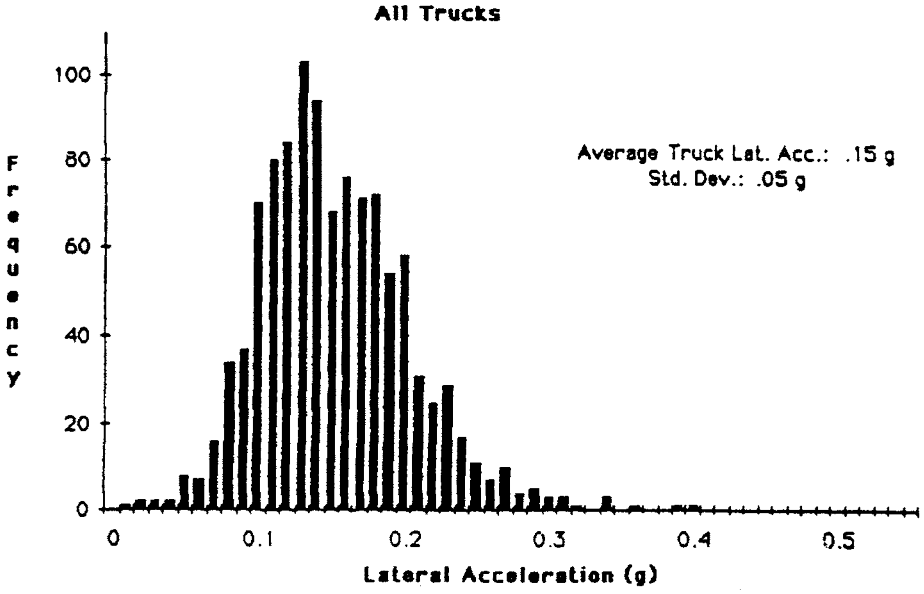


Figure 51. Nominal lateral accelerations of trucks based on their observed speeds on selected horizontal curves in the Chicago area (98).

Margin of Safety Against Skidding

Current design criteria for horizontal curves are intended to maintain the vehicle lateral acceleration within driver comfort levels that are below the lateral acceleration at which the vehicle would skid on a wet pavement. The vehicle's lateral acceleration is resisted by superelevation and tire-pavement friction. Table 68 shows that current design criteria provide a margin of safety of 0.30 to 0.41 g against a passenger car skidding off the road on a minimum radius curve on wet pavement when traveling at the design speed. The margin of safety is the magnitude of the additional lateral acceleration that the vehicle could undergo without skidding.

Tire-pavement friction on a given pavement is lower for truck tires than for passenger car tires. Olson et al. estimate that truck tires have coefficients of friction that are only about 70 percent of those of passenger car tires *(28).* In addition, the 1985 FHWA study discussed above has shown that trucks generate friction demands approximately 10 percent higher than passenger cars when traversing a curve *(96).* Thus, Table 68 shows that the margin of safety against a truck skidding off the road on a wet pavement is less than for a passenger car. The margin of safety against skidding for a truck traveling at the design speed on a minimum radius curve on a wet pavement ranges from 0.15 to 0.22 g.

On dry pavements, tire-pavement friction is much higher than on wet pavement. Locked-wheel pavement friction coefficients of 0.65 or more are typical for passenger cars on dry surfaces. Thus, peak friction levels would be even higher by a factor of 1.45. Peak friction levels for trucks were assumed to be 56 percent of the values for passenger cars. As shown in Table 68, the margin of safety for both passenger cars and trucks on dry surfaces is much higher than on wet surfaces.

A simple example will show how the margin of safety against skidding is calculated using the data in the first row of Table 68. This row represents a horizontal curve with a design speed of 20 mph and a maximum superelevation of 4.0 percent. Under the Green Book policy, a horizontal curve with a design speed of 32 km/h [20 mph] can be designed with a maximum tolerable lateral acceleration of 0.17 g. An equivalent statement is that the maximum side friction demand for a vehicle traveling at the design speed on a curve with maximum superelevation is 0.17 g. The minimum radius of curvature for this situation can be determined as follows:

$$R_{\min} = \frac{(20)^2}{15(0.04 + 0.17)} = 127 \text{ ft} \qquad (46)$$

The assumed pavement friction coefficient at 32 km/h [20 mph] for locked-wheel braking by a passenger car tire on a wet pavement is not specified in the current Green Book, but has been estimated in previous AASHTO policies for stopping sight distance as 0.40 (*48*). The peak friction coefficient available for cornering on a wet pavement is computed as follows:

$$0.40(1.45) = 0.58$$

A peak friction coefficient of 0.58 means that a vehicle can generate up to 0.58 g of unbalanced lateral acceleration without skidding. Therefore, the margin of safety against skidding for a passenger car on a wet pavement traveling at the design speed under assumed design conditions can be computed as the difference between the maximum lateral acceleration that can be developed without exceeding the available friction (0.58 g) and the friction demand (0.17 g):

$$0.58 - 0.17 = 0.41$$

The pavement friction coefficient under dry conditions was estimated as 0.65, as described above. Under dry conditions, the peak friction available for cornering is computed as follows:

$$0.65(1.45) = 0.94$$

Therefore, the margin of safety against skidding under dry conditions is as follows:

$$0.94 - 0.17 = 0.77$$

The calculations of the margin of safety against skidding for a truck are similar. As discussed above, the maximum demand friction for a truck is 10 percent higher than for a passenger car, based on the results of a 1985 FHWA study *(96).* Thus, when a truck is traversing a horizontal curve at the design speed under design conditions at the maximum tolerable lateral acceleration of 0.17 g, the effective maximum friction demand is as follows:

$$0.17(1.1) = 0.19$$

Since research has shown that truck tires can generate only about 70 percent of the friction of passenger car tires, the peak friction available under wet conditions for a truck is as follows:

$$0.58(0.70) = 0.41$$

and the margin of safety under wet conditions is as follows:

$$0.41 - 0.19 = 0.22$$

Similarly, under dry conditions, the available peak friction for a truck tire is as follows:

$$0.94(0.70) = 0.66$$

and the margin of safety under dry conditions is as follows:

$$0.66 - 0.19 = 0.47$$

TABLE 68 Margins of safety against skidding on horizontal curves

		Passenger car						Truck					
Design Speed (mph)	Maximum super-elevation e	Maximum tolerable lateral acceleration (g)	Maximum demand f	Minimum radius (ft)	Available f (wet)	Margin of safety (wet)	Margin of safety (dry)	Maximum tolerable lateral acceleration (g)	Minimum radius (ft)	Maximum demand f	Available f (wet)	Margin of safety (wet)	Margin of safety (dry)
20	4.0	0.17	0.17	127	0.58	0.41	0.77	0.17	127	0.19	0.41	0.22	0.47
30	4.0	0.16	0.16	300	0.51	0.35	0.78	0.16	300	0.18	0.36	0.18	0.48
40	4.0	0.15	0.15	561	0.46	0.31	0.79	0.15	561	0.17	0.32	0.16	0.50
50	4.0	0.14	0.14	926	0.44	0.30	0.80	0.14	926	0.15	0.30	0.15	0.51
60	4.0	0.12	0.12	1,500	0.42	0.30	0.82	0.12	1,500	0.13	0.29	0.16	0.53
20	6.0	0.17	0.17	116	0.58	0.41	0.77	0.17	116	0.19	0.41	0.22	0.47
30	6.0	0.16	0.16	273	0.51	0.35	0.78	0.16	273	0.18	0.36	0.18	0.48
40	6.0	0.15	0.15	508	0.46	0.31	0.79	0.15	508	0.17	0.32	0.16	0.50
50	6.0	0.14	0.14	833	0.44	0.30	0.80	0.14	833	0.15	0.30	0.15	0.51
60	6.0	0.12	0.12	1,333	0.42	0.30	0.82	0.12	1,333	0.13	0.29	0.16	0.53
70	6.0	0.10	0.10	2,042	0.41	0.31	0.84	0.10	2,042	0.11	0.29	0.18	0.55
80	6.0	0.08	0.08	3,048	0.40	0.32	0.86	0.08	3,048	0.09	0.28	0.19	0.57
20	8.0	0.17	0.17	107	0.58	0.41	0.77	0.17	107	0.19	0.41	0.22	0.47
30	8.0	0.16	0.16	250	0.51	0.35	0.78	0.16	250	0.18	0.36	0.18	0.48
40	8.0	0.15	0.15	464	0.46	0.31	0.79	0.15	464	0.17	0.32	0.16	0.50
50	8.0	0.14	0.14	758	0.44	0.30	0.80	0.14	758	0.15	0.30	0.15	0.51
60	8.0	0.12	0.12	1,200	0.42	0.30	0.82	0.12	1,200	0.13	0.29	0.16	0.53
70	8.0	0.10	0.10	1,815	0.41	0.31	0.84	0.10	1,815	0.11	0.29	0.18	0.55
80	8.0	0.08	0.08	2,667	0.40	0.32	0.86	0.08	2,667	0.09	0.28	0.19	0.57
20	10.0	0.17	0.17	99	0.58	0.41	0.77	0.17	99	0.19	0.41	0.22	0.47
30	10.0	0.16	0.16	231	0.51	0.35	0.78	0.16	231	0.18	0.36	0.18	0.48
40	10.0	0.15	0.15	427	0.46	0.31	0.79	0.15	427	0.17	0.32	0.16	0.50
50	10.0	0.14	0.14	694	0.44	0.30	0.80	0.14	694	0.15	0.30	0.15	0.51
60	10.0	0.12	0.12	1,091	0.42	0.30	0.82	0.12	1,091	0.13	0.29	0.16	0.53
70	10.0	0.10	0.10	1,633	0.41	0.31	0.84	0.10	1,633	0.11	0.29	0.18	0.55
80	10.0	0.08	0.08	2,370	0.40	0.32	0.86	0.08	2,330	0.09	0.28	0.19	0.57
20	12.0	0.17	0.17	92	0.58	0.41	0.77	0.17	92	0.19	0.41	0.22	0.47
30	12.0	0.16	0.16	214	0.51	0.35	0.78	0.16	214	0.18	0.36	0.18	0.48
40	12.0	0.15	0.15	395	0.46	0.31	0.79	0.15	395	0.17	0.32	0.16	0.50
50	12.0	0.14	0.14	641	0.44	0.30	0.80	0.14	641	0.15	0.30	0.15	0.51
60	12.0	0.12	0.12	1,000	0.42	0.30	0.82	0.12	1,000	0.13	0.29	0.16	0.53
70	12.0	0.10	0.10	1,485	0.41	0.31	0.84	0.10	1,485	0.11	0.29	0.18	0.55
80	12.0	0.08	0.08	2,133	0.40	0.32	0.86	0.08	2,133	0.09	0.28	0.19	0.57

NOTE: Adapted from Reference 2 to incorporate 2001 Green Book criteria for horizontal curve design.

The margins of safety for trucks in Table 67 are large enough to provide safe truck operations if there are no major deviations from the basic assumptions used in horizontal curve design. The effects of deviations from the basic assumptions are considered below.

Margin of Safety Against Rollover

Table 69 presents an analysis of the margin of safety against rollover provided by current horizontal curve design criteria. The margin of safety is the magnitude of the additional lateral acceleration that the vehicle could undergo without rolling over. The table shows the rollover margin of safety for passenger cars with roll over thresholds of 1.20 g and for trucks with rollover thresholds from 0.35 to 0.40 g.

The margin of safety against rollover for passenger cars traveling at the design speed ranges from 1.03 to 1.10 g. At all design speeds, the margin of safety against rollover for a passenger car is much higher than the margin of safety against skidding on either a wet or dry pavement. Thus, rollover is not a major concern for passenger cars because, unless they collide with another vehicle or object, passenger cars will skid rather than roll over. In contrast to the related issue of skidding off the road, the margin of safety against rollover is not dependent on whether the pavement is wet or dry.

Chapter 5 of this report establishes that a conservative value of truck rollover threshold appropriate for use in design is 0.35 g. The margin of safety for a truck with a rollover threshold of 0.35 g ranges from 0.18 to 0.27 g. This margin of safety is adequate to prevent rollover for trucks traveling at or below the design speed. The margin of safety against rollover increases with increasing design speed, while the margin of safety against skidding decreases.

Comparison of Tables 68 and 69 indicates that rollover is a particular concern for trucks. Under the assumed design conditions for horizontal curves, a truck will roll over before it will skid on a dry pavement. Under the assumed design conditions on a wet pavement, a truck will roll over before it skids at design speeds of 64 to 80 km/h [40 to 50 mph] and below; above that speed, a truck will skid before it rolls over. The effects of deviations from the basic assumptions are considered below.

Deviations from Assumed Design Conditions

The margins of safety against skidding and rollover are a measure of the extent to which real-world drivers, vehicles, and highways can deviate from the assumed conditions without resulting in a skid or a rollover. Deviations from assumed conditions that can increase the likelihood of skidding include the following:

- Vehicles traveling faster than the design speed,
- Vehicles turning more sharply than the curve radius,
- Lower pavement friction than assumed by the *Green Book*, and
- Poorer tires than assumed by the *Green Book.*

Traveling faster than the design speed and turning more sharply than the curve radius would also increase the likelihood of rollovers. In addition, the likelihood of a rollover would also be increased for a truck with a rollover threshold less than the assumed value of 0.35 g.

It would seem logical that the practice of providing less than full superelevation at the point of curvature (PC) would also increase the likelihood of rollovers, but this is not always the case. Horizontal curves without spiral transitions are typically designed with $^2/_3$ of the superelevation runoff on the tangent in advance of the PC and $^1/_3$ of the superelevation runoff on the curve itself. Thus, only $^2/_3$ of the design superelevation is available at the PC, and this lack of full superelevation at the PC would appear to have the potential to offset up to approximately 0.03 g of the available margin of safety. However, the *Green Book* assumes, and field and simulation studies confirm, that even on horizontal curves without spiral transitions, drivers tend to steer a spiral path. Thus, where maximum superelevation is not available, the driver is usually not steering a minimum-radius path.

Computer simulation studies of trucks traversing horizontal curves reported in the FHWA *Truck Characteristics* study *(2, 3)* found that developing full superelevation on the tangent approach to a conventional circular curve actually developed slightly more lateral acceleration than development of superelevation with the $^2/_3$ to $^1/_3$ rule. While the difference in lateral acceleration is small—at most 0.03 g—it is in the wrong direction, so development of full superelevation on the tangent is not a desirable approach to reducing truck rollovers. The same study found a small decrease in lateral acceleration—typically less than 0.01 g—when spiral transitions were used to develop the superelevation. Thus, the use of spiral transitions is desirable but, because of the small reduction in lateral acceleration, the use of spirals is unlikely to provide a major reduction in rollover accidents.

Field data show that vehicles traversing a curve do not precisely follow the curve. Thus, while the path may have a larger radius than the curve at the PC, it will also have a smaller radius than the curve at some point in the curve. Simulation results show that the maximum lateral acceleration occurs several hundred feet after entering a curve. However, simulation results also show that the maximum excursion of lateral acceleration above the value obtained from the standard curve formula is approximately 0.02 g, which would offset a small portion of the margins of safety against rolling and skidding. Field studies for passenger cars suggest that this is a reasonable average value, but more extreme values can occur. Truck drivers may have lower excursions of lateral acceleration than passenger car drivers, but there are no data on this issue.

TABLE 69 **Margins of safety against rollover on horizontal curves**

		Passenger car			Truck			
Design Speed (mph)	Maximum e	Maximum tolerable lateral acceleration	Minimum radius (ft)	Rollover margin of safety RT = 1.20 g	Maximum tolerable lateral acceleration	Minimum radius (ft)	Rollover margin of safety	
							RT = 0.35 g	RT = 0.40 g
20	4.0	0.17	127	1.03	0.17	127	0.18	0.23
30	4.0	0.16	300	1.04	0.16	300	0.19	0.24
40	4.0	0.15	561	1.05	0.15	561	0.20	0.25
50	4.0	0.14	926	1.06	0.14	926	0.21	0.26
60	4.0	0.12	1,500	1.08	0.12	1,500	0.23	0.28
20	6.0	0.17	116	1.03	0.17	116	0.18	0.23
30	6.0	0.16	273	1.04	0.16	273	0.19	0.24
40	6.0	0.15	508	1.05	0.15	508	0.20	0.25
50	6.0	0.14	833	1.06	0.14	833	0.21	0.26
60	6.0	0.12	1,333	1.08	0.12	1,333	0.23	0.28
70	6.0	0.10	2,042	1.10	0.10	2,042	0.25	0.30
80	6.0	0.08	3,048	1.12	0.08	3,048	0.27	0.32
20	8.0	0.17	107	1.03	0.17	107	0.18	0.23
30	8.0	0.16	250	1.04	0.16	250	0.19	0.24
40	8.0	0.15	464	1.05	0.15	464	0.20	0.25
50	8.0	0.14	758	1.06	0.14	758	0.21	0.26
60	8.0	0.12	1,200	1.08	0.12	1,200	0.23	0.28
70	8.0	0.10	1,815	1.10	0.10	1,815	0.25	0.30
80	8.0	0.08	2,667	1.12	0.08	2,667	0.27	0.32
20	10.0	0.17	99	1.03	0.17	99	0.18	0.23
30	10.0	0.16	231	1.04	0.16	231	0.19	0.24
40	10.0	0.15	427	1.05	0.15	427	0.20	0.25
50	10.0	0.14	694	1.06	0.14	694	0.21	0.26
60	10.0	0.12	1,091	1.08	0.12	1,091	0.23	0.28
70	10.0	0.10	1,633	1.10	0.10	1,633	0.25	0.30
80	10.0	0.08	2,370	1.12	0.08	2,330	0.27	0.32
20	12.0	0.17	92	1.03	0.17	92	0.18	0.23
30	12.0	0.16	214	1.04	0.16	214	0.19	0.24
40	12.0	0.15	395	1.05	0.15	395	0.20	0.25
50	12.0	0.14	641	1.06	0.14	641	0.21	0.26
60	12.0	0.12	1,000	1.08	0.12	1,000	0.23	0.28
70	12.0	0.10	1,485	1.10	0.10	1,485	0.25	0.30
80	12.0	0.08	2,133	1.12	0.08	2,133	0.27	0.32

NOTE: Adapted from Reference 2 to incorporate 2001 Green Book criteria for horizontal curve design.

The Green Book criteria for tire-pavement friction are based on a poor, wet pavement and (apparently) on worn tires. Table 68 has provided an adjustment to these values for the differences between passenger cars and trucks. The assumptions appear to be conservative for design purposes. In fact, an interesting aspect of this factor discussed below is what happens when the likelihood of skidding is reduced because tire pavement-friction is higher than the design value.

The review of the potential for safety problems created by deviations from the design assumptions indicates that traveling faster than the design speed of the curve is the single greatest concern. This is a particular concern on freeway ramps for two reasons. First, freeway ramps generally have lower design speeds than major roadways, which means that they have lower margins of safety against rollover (but higher margins of safety against skidding). Second, traveling faster than the design speed is especially likely on off-ramps, where vehicles traveling at higher speeds enter the ramp from the major roadway.

Table 70 compares the speeds at which skidding or rollover would occur for passenger cars and trucks traversing minimum radius curves designed in accordance with current Green Book criteria. The table shows that, on a dry pavement, a passenger car will skid at a lower speed than it will roll over, and a truck with rollover threshold of 0.35 g will roll over at a lower speed than it will skid. On a wet pavement, a passenger car will still skid at a lower speed than it will roll over. A truck, on the other hand, will roll over before it skids at design speeds of 32 km/h [20 mph] or less under the assumed values for pavement friction on wet pavements. At higher speeds, a truck generally will skid before it will roll over. However, if a wet pavement has above-minimum friction, the truck may still roll over at a lower speed than it will skid.

PAVEMENT WIDENING ON HORIZONTAL CURVES

Current Geometric Design Criteria

The Green Book presents the current criteria for pavement widening on horizontal curves to accommodate offtracking of trucks. Offtracking is the phenomenon, common to all vehicles although much more pronounced with large trucks, in which the rear wheels do not track precisely behind the front wheels when the vehicle negotiates a horizontal curve.

The Green Book criteria call for widening of curves according to tabulated criteria that depend on the pavement width on the tangent, the design speed, and the degree of curve. The pavement-widening criteria are presented in Green Book Exhibits 3-51 and 35-2. These exhibits note that pavement-widening is not needed when the widening value is less than 0.6 m [2 ft]. The tabulated values apply to the WB-15 [WB-50] design vehicle; adjustments for other design vehicles are provided. The Green Book tables apply only to two-lane roads (one- or two-way); the values given are to be adjusted upward for three- or four-lane roads.

The Green Book also details how the widening should be accomplished. In other words, it notes whether the added width should be on the inside or outside of the curve, how it should be transitioned, and how the center line should be adjusted.

Critique of Geometric Design Criteria

The current design criteria for pavement widening on horizontal curves was updated to reflect recommended changes to the Green Book design vehicles. Green Book Exhibits 3-51 and 3-52 are affected primarily because of the recommendation to eliminate the WB-15 [WB-50] as a design vehicle, and the values shown for traveled way widening are based on the WB-15 [WB-50] design vehicle. The values in Green Book Exhibits 3-51 and 3-52 were adjusted accordingly to reflect the WB-19 [WB-62] as the base vehicle, and the previous column for the WB-19 [WB-62] design vehicle was removed (see Appendix F).

CROSS-SLOPE BREAKS

Current Geometric Design Criteria

The following represents a brief summary of the Green Book criteria for cross-slope rates:

- On tangent or long-radius curved alignment with normal crown and turf shoulders, the maximum shoulder slope rates result in algebraic differences of 6 to 7 percent between the pavement and the shoulder.
- For desirable operation, all or part of the shoulder on the outside of a horizontal curve should be sloped upward at about the same rate or at a lesser rate than the superelevated pavement.
- The cross-slope break at the edge of the paved surface is limited to a maximum of approximately 8 percent.
- To alleviate severe cross-slope breaks, the use of a continuously rounded shoulder cross section may be used on the outside of superelevated pavements.

Critique of Geometric Design Criteria

Cross-Slope Breaks

A 1982 FHWA study investigated the operational effects of cross-slope breaks on highway curves *(99)*. Using the Highway-Vehicle-Object Simulation Model (HVOSM), vehicle traversals were simulated for various combinations of pavement and shoulder slopes for a range of horizontal curvature. The objective criterion was to limit lateral acceleration to a level that was stable at the tire-pavement interface

TABLE 70 Vehicle speed at impending skidding or rollover on horizontal curves

					Passenger car speed (mph)			Truck speed (mph)			
										@ rollover	
Design speed (mph)	Maximum e	Maximum tolerable lateral acceleration	Minimum radius (ft)	Passenger car available cornering f	@ impending skid (wet)	@ impending skid (dry)	@ rollover RT = 1.20 g	@ impending skid (wet)	@ impending skid (dry)	RT = 0.35 g	RT = 0.40 g
20	4.0	0.17	127	0.58	34.4	43.2	48.6	27.9	34.9	27.3	29.0
30	4.0	0.16	300	0.51	49.7	66.4	74.7	40.5	53.7	41.9	44.5
40	4.0	0.15	561	0.46	64.9	90.8	102.1	52.9	73.4	57.3	60.8
50	4.0	0.14	926	0.44	81.7	116.7	131.2	66.7	94.3	73.6	78.2
60	4.0	0.12	1,500	0.42	101.7	148.5	167.0	83.1	120.0	93.7	99.5
20	6.0	0.17	116	0.58	33.4	41.7	46.8	27.3	33.9	26.7	28.3
30	6.0	0.16	273	0.51	48.3	64.0	71.8	39.7	52.0	41.0	43.4
40	6.0	0.15	508	0.46	62.9	87.3	98.0	51.8	70.9	55.9	59.2
50	6.0	0.14	833	0.44	79.0	111.8	125.5	65.2	90.8	71.6	75.8
60	6.0	0.12	1,333	0.42	98.0	141.4	158.7	80.9	114.9	90.5	95.9
70	6.0	0.10	2,042	0.41	120.0	175.0	196.5	99.1	142.2	112.1	118.7
80	6.0	0.08	3,048	0.40	145.0	213.8	240.0	119.1	173.7	136.9	145.0
20	8.0	0.17	107	0.58	32.5	40.5	45.3	26.8	33.0	26.3	27.8
30	8.0	0.16	250	0.51	47.0	61.8	69.3	38.9	50.5	40.2	42.4
40	8.0	0.15	464	0.46	61.3	84.3	94.4	50.9	68.8	54.7	57.8
50	8.0	0.14	758	0.44	76.9	107.7	120.6	64.0	87.9	69.9	73.9
60	8.0	0.12	1,200	0.42	94.9	135.5	151.8	79.1	110.6	88.0	93.0
70	8.0	0.10	1,815	0.41	115.5	166.6	186.7	96.3	136.1	108.2	114.3
80	8.0	0.08	2,667	0.40	138.6	202.0	226.3	115.7	164.9	131.2	138.6
20	10.0	0.17	99	0.58	31.8	39.3	43.9	26.4	32.2	25.9	27.2
30	10.0	0.16	231	0.51	46.0	60.0	67.1	38.4	49.2	39.5	41.6
40	10.0	0.15	427	0.46	59.9	81.6	91.2	50.2	67.0	53.7	56.6
50	10.0	0.14	694	0.44	75.0	104.0	116.3	62.9	85.4	68.4	72.1
60	10.0	0.12	1,091	0.42	92.2	130.5	145.9	77.5	107.0	85.8	90.5
70	10.0	0.10	1,633	0.41	111.8	159.6	178.7	94.0	130.9	105.0	110.7
80	10.0	0.08	2,370	0.40	133.3	192.3	215.0	112.3	157.7	126.5	133.3
20	12.0	0.17	92	0.58	31.1	38.2	42.7	26.0	31.5	25.5	26.8
30	12.0	0.16	214	0.51	45.0	58.3	65.1	37.8	48.1	38.8	40.9
40	12.0	0.15	395	0.46	58.6	79.2	88.4	49.5	65.3	52.8	55.5
50	12.0	0.14	641	0.44	73.4	101.0	112.7	62.0	83.2	67.2	70.7
60	12.0	0.12	1,000	0.42	90.0	126.1	140.7	76.2	103.9	84.0	88.3
70	12.0	0.10	1,485	0.41	108.7	153.7	171.5	92.1	126.6	102.3	107.6
80	12.0	0.08	2,133	0.40	129.0	184.2	205.5	109.5	151.8	122.6	129.0

NOTE: Adapted from Reference 6 to incorporate 2001 Green Book criteria for horizontal curve design.

and tolerable to the driver. A 1971 Dodge Coronet was the passenger car used in the simulations.

The study results indicated that a four-wheel traversal and entry to a cross-slope break produce a more extreme response than a two-wheel traversal. The dynamic effects were found to be most sensitive to shoulder cross slope and to exceed reasonable driver discomfort levels for the design conditions that reduce the conditions associated with higher cross-slope breaks. It was determined that relatively large negative slopes are tolerable on very narrow shoulders. As shoulder width increases, permissible shoulder slopes should decrease to maintain the established maximum driver discomfort level. Specifically, the study found that maximum driver discomfort occurred when all four wheels were on the shoulder, not when the vehicle crosses the break.

The FHWA study identified two unanswered questions regarding the sensitivity of trucks to cross-slope break traversals *(99)*:

1. Do professional (truck) drivers exhibit higher tolerable levels of driver discomfort?
2. Do shoulder traversals by trucks occur often enough to justify the truck as the "design" vehicle for cross-slope break recommendations?

No further data were found in the literature to shed any additional light on these issues.

Centerline Crowns

In another portion of the same FHWA study discussed above, the dynamic effects of centerline crowns on expected vehicle maneuvers were evaluated for the purpose of recommending maximum centerline crown designs as a function of vehicle type and design speed *(100)*. The controlling operational maneuver was the passing situation. Research was limited to tangent roadway sections. Vehicle types considered included compact and midsize passenger cars, loaded and empty tractor-trailer truck combinations, and single-unit trucks.

The pertinent truck-related findings include the following:

- A loaded or empty tractor-trailer truck generates lower tire friction demand than automobiles on 2-percent cross slopes.
- Driver discomfort levels and vehicle roll angle are also less for trucks than automobiles on 2-percent cross slopes at high speed (approximately 121 km/h [75 mph].
- An empty tractor-trailer produces similar tire friction demands (approximately 0.30 g), but has significantly lower driver discomfort and roll angle values.

The implication of the findings is that cross slopes should be kept to a minimum on high-speed highways. The primary reason is that the simulation of nominally critical passing behavior produced vehicle dynamic responses on the order of 0.28 to 0.34 g for cross slopes of 2 percent for all vehicle types.

VERTICAL CLEARANCES

The Green Book criteria for vertical clearance are generally 4.3 m [14 ft] on local roads and collectors and 4.9 m [16 ft] on arterials and freeways. The design vehicles specified in the Green Book have a maximum height of 4.1 m [13.5 ft]. Most trucks have heights less than 4.1 m [13.5 ft], so vertical clearance is generally not an issue for overhead structures designed in accordance with the Green Book.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The conclusions of the research are as follows:

1. NAFTA may lead to increased truck volumes using U.S. highways, but it is unlikely that new truck types not currently considered in highway geometric design will be entering the United States. Although trucks larger and heavier than currently permitted in the United States do operate in both Canada and Mexico, any trucks entering the United States are required to comply with current federal and state laws governing truck size and weight. The creation of a NAFTA international access network of roads is being considered, but the proposed criteria for the truck sizes that would operate on that network do not differ substantively from current U.S. limits applicable in many states.
2. A substantial number of three- and four-axle single-unit trucks in the current truck fleet are larger than the two-axle single-unit design vehicle presented in the Green Book.
3. The WB-15 [WB-50] design vehicle is no longer common in the U.S. truck fleet.
4. The WB-19 [WB-62] design vehicle shown in the Green Book has a KCRT distance of 12.3 m [40.5 ft]. The laws of many states allow KCRT distances up to 12.5 m [41 ft].
5. The WB-20 [WB-65] design vehicle shown in the Green Book involves neither the best nor worst case of the rear tandem axles of the truck.
6. Where trucks larger than the WB-19 [WB-62] design vehicle operate with the rear axles pulled forward to a KCRT distance of 12.5 m [41 ft], their offtracking and swept path width are the same as that of the WB-19 [WB-62] design vehicle. Pulling the axles forward to a KCRT distance of 12.5 m [41 ft] is required by many states and, even when not required, is preferred by truckers to increase the maneuverability of such a vehicle.
7. In states where combination trucks with semitrailers longer than 16.2 m [53 ft] are permitted to operate, they constitute only 0.5 to 4 percent of all trucks.
8. Combination trucks, known as Rocky Mountain Doubles, with one 14.6-m [48-ft] semitrailer and one 8.7-m [28.5-ft] full trailer, operate in 20 states (mostly in the western United States), including 3 states where Turnpike Doubles are not permitted and 6 states where triple-trailer trucks are not permitted. In such states, Rocky Mountain Doubles may be the largest combination trucks that can legally operate.
9. *TRB Special Report 267* (*13*) has recommended that single-semitrailer trucks with six axles, including a rear tridem axle, be permitted to operate with gross vehicle weight up to 40,900 kg [90,000 lb]. Implementation of this recommendation would not have any effect on geometric design because single-semitrailer trucks with six axles have offtracking and swept path width that are slightly less than a comparable five-axle truck.
10. Design vehicles that might be needed in the Green Book at some future time include the following:
    - A combination truck with a single 17.4-m [53-ft] semitrailer, designated the WB-22 [WB-71] design vehicle;
    - A combination truck with two 10.1-m [33-ft] trailers, designated the WB-23D [WB-77D] design vehicle;
    - A Turnpike Double combination truck, with two 16.1-m [53-ft] trailers, designated the WB-37D [WB-120D] design vehicle; and
    - A B-Train double combination with one 8.5-m [28-ft] trailer and one 9.6-m [31.5-ft] trailer.

    None of these vehicles currently operate with sufficient frequency to warrant adoption as a design vehicle, although in *TRB Special Report 267* (*13*), the WB-23D [WB-77D] has been proposed for wider operation. Therefore, the dimensions and turning performance of these vehicles have been documented in the research, but no recommendation has been made to include these design vehicles in the Green Book. Their incorporation in the Green Book should be considered if truck size and weight laws are changed to permit such vehicles to operate more widely and if they are actually present in sufficient numbers to warrant their consideration as design vehicles.
11. Rear swingout is the phenomenon by which the rear outside corner of a truck follows a path outside the rear outside axle of the truck during a turn. Rear swingout increases as the distance from the rear axle to the rear of the truck, known as rear overhang, increases. However, turning plots show that, while the outside rear corner of the trailer follows a path outside the rear

trailer wheels, it is inside the swept path of the truck. For this reason, rear swingout is rarely a concern to other vehicles, unless they are making a parallel turn. None of the current Green Book design vehicles or the new design vehicles recommended in this report for inclusion in the Green Book have rear swingout that exceeds 0.21 m [0.69 ft] for a turn with a radius of 15 m [50 ft], even with the rear axles pulled forward to maintain a KCRT distance of 12.5 m [41 ft].

12. Trucks the size of the WB-19 [WB-62] or larger have swept path widths so great that the truck cannot make a 90-deg right turn from one two-lane road to another while remaining within a 3.6-m [12-ft] lane for turning radii of 23 m [75 ft] or less. Trucks making such turns at locations with curb return radii of 23 m [75 ft] or less must either encroach on the roadway shoulder (or curb line) or on an opposing lane.
13. The minimum rollover threshold for trucks is generally in the range from 0.35 to 0.40 g. This minimum rollover threshold generally applies to trucks fully loaded with uniform density cargo.
14. Antilock brake systems improve the braking distances of trucks by reducing the variability in driver control efficiency observed with conventional braking systems. An antilock brake system applies the vehicle brakes and then releases them, as needed, to prevent wheel lock-up, which may lead to loss of control. Trucks with antilock brakes require longer braking distances than passenger cars, but the braking distances of passenger cars and trucks on wet pavement are nearly the same.
15. Antilock brake systems are now available on nearly all truck tractors. Field observations during 2002 found that antilock brake systems are available on approximately 43 percent of trailers. Based on the expected service life of trailers, it can be expected that within 10 years nearly all trailers will be equipped with antilock brake systems.
16. The current Green Book design criteria for passing sight distance are such that a truck can safely pass a passenger car on any crest vertical curve where a passenger car can safely pass a truck.
17. The current Green Book criteria for intersection sight distance were recently updated and include explicit adjustment factors for trucks. There is no indication of a need for further changes in these design criteria.
18. Current Green Book design criteria for sight distance at railroad-highway grade crossings appear to be appropriate for the current truck fleet.
19. The 85th-percentile weight/power ratios of trucks in the current truck fleet range from 102 to 126 kg/kW [170 to 210 lb/hp] for the truck population using freeways and from 108 to 168 kg/kW [180 to 280 lb/hp] for the truck population using two-lane highways.
20. Analysis indicates that the minimum lengths of acceleration lanes presented in the Green Book may be sufficient to accommodate average trucks but not to accommodate heavily loaded trucks. No change is recommended at this time because there is no indication that trucks are encountering specific problems on acceleration lanes designed in accordance with the Green Book criteria.
21. The current Green Book criteria for lane width and pavement widening on horizontal curves appear to be appropriate for the current truck fleet.
22. The current Green Book criteria for horizontal curve design provide an adequate margin of safety against skidding and rollover by trucks traveling at the design speed. The lowest margins of safety are for horizontal curves with design speeds of 30 km/h [20 mph] or less. It is important that the design speed for such curves be selected based on consideration of likely operating speeds because exceeding the design speed of a 30-km/h [20-mph] curve by as little as 13 km/h [8 mph] could lead to skidding on a wet pavement or rollover.
23. The current Green Book criteria for cross-slope breaks and vertical clearances appear to be appropriate for the current truck fleet.

The recommendations of the research are as follows:

1. A design vehicle representing a three-axle single-unit truck should be added to the Green Book.
2. The WB-15 [WB-50] design vehicle should be dropped from the Green Book.
3. The KCRT distance for the WB-19 [WB-62] design vehicle should be increased from 12.3 to 12.5 m [40.5 to 41 ft].
4. The WB-20 [WB-65] design vehicle should be dropped from the Green Book, and the WB-20 [WB-67] design vehicle, which represents the worst-case placement of the rear axles for a truck with a single 16.2-m [53-ft] semitrailer, should be retained.
5. Where trucks larger than the WB-19 [WB-62] design vehicle operate with the rear axles pulled forward to a KCRT distance of 12.5 m [41 ft], design elements such as intersection geometrics should be based on the WB-19 [WB-62] design vehicle. However, where the overall length of the vehicle is the basis for design, such as for sight distance at railroad-highway grade crossings, the length of the actual design vehicle should be used.
6. A design vehicle representing a Rocky Mountain Double combination should be added to the Green Book.
7. Based on the comparable braking distances for passenger cars and trucks on wet pavement, there does not appear to be any need for a change in the Green Book design criteria for stopping sight distance. The Green Book expresses a concern that stopping sight distance

for trucks may be particularly critical at the end of a long downgrade. Computer simulation research to assess truck braking capability for a superelevated horizontal curve at the end of a downgrade would be desirable.

8. There is no indication that a change in passing sight distance criteria is needed to better accommodate trucks. Although passing maneuvers involving trucks require longer distances than passing maneuvers involving only passenger cars, there is no indication that trucks encounter any particular safety problems in passing zones marked with current criteria.
9. Where trucks the size of the WB-19 [WB-62] or larger are present and make right turns in substantial numbers, curb return radii larger than 23 m [75 ft] are recommended. In many cases, such radii can best be provided in conjunction with a channelized right-turn roadway. The offtracking and swept path width of the specific selected design vehicle should be considered in developing the channelization geometrics.
10. The design of double- and triple-left-turn lanes requires consideration of the swept path width of left-turning trucks. Although this issue can be addressed in the design process with computer modeling of truck paths, it is recommended that a table showing the swept path widths of various design vehicles making left turns with radii of 22.9 to 47.7 m [75 to 150 ft] be added to the Green Book for use by designers.
11. Additional guidance should be provided in the Green Book on the maximum entry speeds and diameter of the inscribed circle for roundabouts of specific site categories for specific design vehicles.
12. A truck speed profile model (TSPM) has been developed in the form of a spreadsheet that can be used to estimate the truck speed profile on an upgrade for any specified truck weight/power ratio, initial speed, and vertical alignment. This spreadsheet is recommended for design application as an alternative to the charts for critical length of grade currently presented in the Green Book, which are based on a single value of truck weight/power ratio, a single value of initial speed, and a uniform (constant percent) grade.
13. Additional research is recommended to determine whether trucks encounter any specific safety problems on acceleration lanes designed in accordance with Green Book criteria.

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APPENDIX A

SUMMARY OF TRUCK CHARACTERISTICS

This appendix presents tables from the VIUS database *(9)* of the number of trucks, truck miles of travel, and average annual mileage per truck overall and broken down by a broad variety of variables including the following:

- Major use,
- Body type,
- Annual miles,
- Primary range of operation,
- Weeks operated per year,
- Base of operation,
- Vehicle size,
- Average weight,
- Total length,
- Year model,
- Vehicle acquisition,
- Lease characteristics,
- Primary operator classification,
- Primary products carried,
- Hazardous materials carried,
- Truck fleet size,
- Miles per gallon,
- Equipment type,
- Full conservation equipment,
- Maintenance responsibility,
- Engine type and size,
- Refueling location,
- Truck type and axle arrangement, and
- Cab type.

The VIUS database can be used to look at selected combinations of the variables that are not available in tables published by the Bureau of the Census.

TABLE 3a. Trucks, truck miles, and average annual miles for trucks, excluding pickups, panels, minivans, sport utilities, and station wagons: 1997 and 1992

[Detail may not add to total because of rounding. For meaning of abbreviations and symbols, see introductory text]

Vehicular and operational characteristics	1997 trucks[1] (thousands)	1992 trucks (thousands)	Percent change	1997 truck miles[2] (millions)	1992 truck miles[2] (millions)	Percent change	1997 average miles per truck[2] (thousands)	1992 average miles per truck[2] (thousands)	Percent change
	A	B	C	D	E	F	G	H	I
Total trucks	5 664.7	5 112.4	10.8	157 363.7	116 579.5	35.0	27.8	22.8	21.9
MAJOR USE									
Agriculture	854.7	898.7	-4.9	7 927.3	7 454.9	6.3	9.3	8.3	12.0
Forestry and lumbering	112.1	100.6	11.4	3 186.4	2 611.5	22.0	28.4	26.0	9.2
Mining and quarrying	82.1	79.2	3.7	1 921.8	1 480.6	29.8	23.4	18.7	25.1
Construction	1 161.8	1 015.4	14.4	17 558.4	13 453.5	30.5	15.1	13.2	14.4
Manufacturing	258.6	257.6	.4	8 921.9	8 446.7	5.6	34.5	32.8	5.2
Wholesale trade	440.4	438.3	.5	14 753.6	12 397.4	19.0	33.5	28.3	18.4
Retail trade	469.3	434.9	7.9	11 528.8	8 552.3	34.8	24.6	19.7	24.9
For-hire transportation	938.2	769.6	21.9	69 019.0	49 164.5	40.4	73.6	63.9	15.2
Utilities	204.9	183.4	11.7	2 570.9	2 015.8	27.5	12.5	11.0	13.6
Services	591.4	421.2	40.4	12 438.3	6 782.1	83.4	21.0	16.1	30.4
Daily rental	171.2	90.6	89.0	5 907.8	2 865.4	106.2	34.5	31.6	9.2
One-way rental	28.3	14.1	100.7	645.5	305.4	111.4	22.8	21.6	5.6
Personal transportation	183.0	231.0	-20.8	952.5	996.3	-4.4	5.2	4.3	20.9
Other	V	S	S	V	S	S	V	S	S
Not in use	168.6	177.8	-5.2	31.8	53.0	-40.0	.2	.3	-33.3
Not reported	V	V	N	V	V	N	V	V	N
BODY TYPE									
Multistop or stepvan	560.4	408.4	37.2	9 428.6	6 088.5	54.9	16.8	14.9	12.8
Platform with added devices	308.2	295.7	4.2	3 670.1	3 034.7	20.9	11.9	10.3	15.5
Low boy or depressed center	111.1	89.8	23.7	2 708.6	1 944.8	39.3	24.4	21.6	13.0
Basic platform	1 176.1	1 183.3	-.6	22 383.8	18 223.0	22.8	19.0	15.4	23.4
Livestock truck	39.1	48.3	-19.0	1 037.3	1 105.3	-6.2	26.5	22.9	15.7
Insulated nonrefrigerated van	34.5	23.3	48.1	2 575.8	1 297.9	98.5	74.6	55.6	34.2
Insulated refrigerated van	234.0	204.8	14.3	16 363.0	12 194.0	34.2	69.9	59.5	17.5
Drop-frame van	54.9	60.1	-8.7	2 357.5	2 373.2	-.7	43.0	39.5	8.9
Open-top van	20.8	20.1	3.5	1 032.9	809.8	27.6	49.7	40.3	23.3
Basic enclosed van	1 009.0	785.4	28.5	55 849.4	35 706.3	56.4	55.4	45.5	21.8
Beverage	70.2	73.0	-3.8	1 244.7	1 136.0	9.6	17.7	15.6	13.5
Public utility	152.0	157.0	-3.2	1 669.0	1 572.5	6.1	11.0	10.0	10.0
Winch or crane	55.0	58.8	-6.5	808.1	665.2	21.5	14.7	11.3	30.1
Wrecker	111.9	104.1	7.5	1 737.3	1 482.0	17.2	15.5	14.2	9.2
Pole or logging	55.7	53.9	3.3	2 158.8	1 857.6	16.2	38.8	34.5	12.5
Auto transport	20.1	22.3	-9.9	915.3	1 032.3	-11.3	45.5	46.3	-1.7
Service truck	168.6	144.1	17.0	2 263.8	1 978.6	14.4	13.4	13.7	-2.2
Yard tractor	10.8	8.1	33.3	113.8	52.1	118.4	10.5	6.4	64.1
Oilfield truck	26.1	26.5	-1.5	440.7	353.6	24.6	16.9	13.3	27.1
Grain body	299.1	310.8	-3.8	2 772.5	2 482.2	11.7	9.3	8.0	16.3
Garbage hauler	91.6	72.4	26.5	2 307.0	1 514.7	52.3	25.2	20.9	20.6
Dump truck	670.8	611.9	9.6	11 369.6	9 381.8	21.2	16.9	15.3	10.5
Tank truck (liquids or gases)	249.4	231.9	7.5	8 604.6	7 284.3	18.1	34.5	31.4	9.9
Tank truck (dry bulk)	39.7	33.8	17.5	1 855.3	1 558.5	19.0	46.7	46.1	1.3
Concrete mixer	73.1	61.0	19.8	1 126.4	830.1	35.7	15.4	13.6	13.2
Other	22.6	23.7	-4.6	570.0	620.4	-8.1	25.2	26.2	-3.8
Not reported	V	V	N	V	V	N	V	V	N
ANNUAL MILES									
Less than 5,000	1 554.2	1 663.1	-6.5	2 553.0	2 752.9	-7.3	1.6	1.7	-5.9
5,000 to 9,999	753.4	751.9	.2	5 102.5	5 045.1	1.1	6.8	6.7	1.5
10,000 to 19,999	1 128.8	978.6	15.3	15 315.6	13 079.4	17.1	13.6	13.4	1.5
20,000 to 29,999	585.4	512.6	14.2	13 535.1	11 826.9	14.4	23.1	23.1	V
30,000 to 49,999	571.1	458.8	24.5	20 903.8	16 839.0	24.1	36.6	36.7	-.3
50,000 to 74,999	374.5	284.9	31.4	22 269.9	16 844.9	32.2	59.5	59.1	.7
75,000 or more	697.3	462.3	50.8	77 663.8	50 191.3	54.8	111.4	108.6	2.6
PRIMARY RANGE OF OPERATION									
Local	2 971.2	2 968.2	.1	38 225.3	35 737.6	7.0	12.9	12.0	7.5
Short-range	927.1	740.9	25.1	26 155.8	19 731.0	32.6	28.2	26.6	6.0
Short-range medium	426.6	297.1	43.6	19 733.2	13 618.7	44.9	46.3	45.8	1.1
Long-range medium	421.7	259.1	62.8	28 273.8	18 136.6	55.9	67.1	70.0	-4.1
Long-range	434.4	301.4	44.1	42 881.3	27 463.8	56.1	98.7	91.1	8.3
Off-the-road	350.6	431.1	-18.7	2 094.2	1 891.8	10.7	6.0	4.4	36.4
Not reported	133.1	114.6	16.1	V	V	N	V	V	N
WEEKS OPERATED									
Less than 1	227.5	264.4	-14.0	43.8	95.0	-53.9	.2	.4	-50.0
1 to 4	326.7	348.2	-6.2	526.9	575.8	-8.5	1.6	1.7	-5.9
5 to 8	303.3	304.0	-.2	1 278.9	1 187.5	7.7	4.2	3.9	7.7
9 to 12	237.5	231.6	2.5	1 620.9	1 363.5	18.9	6.8	5.9	15.3
13 to 16	159.7	177.4	-10.0	1 676.2	1 515.5	10.7	10.5	8.5	23.5
17 to 20	138.9	143.6	-3.3	1 757.6	1 679.7	4.6	12.6	11.7	7.7
21 to 24	199.8	209.5	-4.6	2 857.1	2 541.5	12.4	14.3	12.1	18.2
25 to 28	251.4	240.1	4.7	4 181.7	3 812.7	9.7	16.6	15.9	4.4
29 to 32	165.9	135.5	22.4	4 196.1	2 628.9	59.6	25.3	19.4	30.4
33 to 36	190.6	164.4	15.9	4 260.3	3 489.6	22.1	22.4	21.2	5.7
37 to 40	257.0	227.1	13.2	6 978.3	5 281.2	32.1	27.2	23.3	16.7
41 to 44	287.2	224.2	28.1	9 827.2	6 897.2	42.5	34.2	30.8	11.0
45 to 48	509.8	390.2	30.7	22 128.4	14 241.3	55.4	43.4	36.5	18.9
49 to 52	2 217.7	2 008.4	10.4	89 939.2	70 622.1	27.4	40.6	35.2	15.3
Not reported	191.6	43.9	336.4	6 069.0	648.0	839.7	31.8	14.8	114.9

See footnotes at end of table.

TABLE 3a. (Continued)

[Detail may not add to total because of rounding. For meaning of abbreviations and symbols, see introductory text]

Vehicular and operational characteristics	1997 trucks[1] (thousands)	1992 trucks (thousands)	Percent change	1997 truck miles[2] (millions)	1992 truck miles[2] (millions)	Percent change	1997 average miles per truck[2] (thousands)	1992 average miles per truck[2] (thousands)	Percent change
	A	B	C	D	E	F	G	H	I
BASE OF OPERATION									
Percentage of miles traveled outside base-of-operation state:									
Less than 25 percent	3 846.7	3 759.7	2.3	67 173.7	56 531.7	18.8	17.5	15.0	16.7
25 to 49 percent	223.4	163.3	36.8	11 223.0	7 546.8	48.7	50.2	46.2	8.7
50 to 74 percent	236.2	194.6	21.4	15 751.5	11 883.8	32.5	66.7	61.1	9.2
75 to 100 percent	357.3	268.7	33.0	30 013.3	21 561.7	39.2	84.0	80.2	4.7
No home base	132.3	N	N	10 999.2	N	N	83.1	N	N
Not reported	810.7	557.8	45.3	22 202.9	10 369.4	114.1	27.4	18.6	47.3
VEHICLE SIZE									
Light	1 208.7	1 326.2	-8.9	13 664.8	14 156.0	-3.5	11.3	10.7	5.6
Medium	1 191.2	1 037.5	14.8	15 640.2	11 447.8	36.6	13.1	11.0	19.1
Light-heavy	729.3	732.2	-.4	10 128.8	8 143.2	24.4	13.9	11.1	25.2
Heavy-heavy	2 535.5	2 018.4	25.7	117 929.9	82 831.9	42.4	46.5	41.1	13.1
AVERAGE WEIGHT (POUNDS)									
Less than 6,001	279.7	360.6	-22.4	2 497.7	3 074.8	-18.8	8.9	8.5	4.7
6,001 to 10,000	929.0	965.5	-3.8	11 167.1	11 072.0	.9	12.0	11.5	4.3
10,001 to 14,000	625.0	514.9	21.4	8 525.1	5 922.0	44.0	13.6	11.5	18.3
14,001 to 16,000	289.2	255.7	13.1	3 561.2	2 596.9	37.1	12.3	10.2	20.6
16,001 to 19,500	277.0	267.3	3.6	3 553.9	2 939.7	20.9	12.8	11.0	16.4
19,501 to 26,000	729.3	732.0	-.4	10 128.8	8 142.3	24.4	13.9	11.1	25.2
26,001 to 33,000	427.7	387.2	10.5	7 092.0	5 693.7	24.6	16.6	14.7	12.9
33,001 to 40,000	256.7	232.6	10.4	6 594.0	5 285.0	24.8	25.7	22.7	13.2
40,001 to 50,000	399.9	338.6	18.1	13 078.1	9 621.8	35.9	32.7	28.4	15.1
50,001 to 60,000	311.4	226.7	37.4	12 652.5	8 698.5	45.5	40.6	38.4	5.7
60,001 to 80,000	1 069.8	781.1	37.0	74 723.5	51 043.6	46.4	69.9	65.4	6.9
80,001 to 100,000	46.3	33.3	39.0	2 427.0	1 528.8	58.8	52.5	45.9	14.4
100,001 to 130,000	17.9	12.3	45.5	1 050.7	733.8	43.2	58.6	59.5	-1.5
130,001 or more	5.9	4.6	28.3	311.8	226.7	37.5	52.5	49.1	6.9
Not reported	V	V	N	V	V	N	V	V	N
TOTAL LENGTH (FEET)									
Less than 20.0	1 381.5	1 524.8	-9.4	16 356.8	15 731.7	4.0	11.8	10.3	14.6
20.0 to 27.9	1 885.1	1 682.9	12.0	23 564.3	18 770.4	25.5	12.5	11.2	11.6
28.0 to 35.9	625.8	529.2	18.3	11 430.9	8 475.9	34.9	18.3	16.0	14.4
36.0 to 40.9	156.1	141.3	10.5	3 023.1	2 617.6	15.5	19.4	18.5	4.9
41.0 to 44.9	80.1	69.8	14.8	1 820.4	1 555.2	17.1	22.7	22.3	1.8
45.0 or more	1 536.0	1 164.5	31.9	101 166.4	69 428.6	45.7	65.9	59.6	10.6
Not reported	V	S	S	V	S	S	V	S	S
YEAR MODEL									
1998	50.7	N	N	2 324.9	N	N	45.8	N	N
1997	275.1	N	N	14 996.5	N	N	54.5	N	N
1996	312.9	N	N	19 223.4	N	N	61.4	N	N
1995	420.7	N	N	22 116.1	N	N	52.6	N	N
1994	310.3	N	N	15 470.1	N	N	49.9	N	N
1993	251.0	S	S	12 084.2	S	S	48.1	S	S
1992	190.4	159.3	19.5	8 285.5	8 288.5	V	43.5	52.0	-16.3
1991	205.6	212.2	-3.1	7 211.1	9 769.4	-26.2	35.1	46.0	-23.7
1990	269.1	274.4	-1.9	8 491.0	12 102.3	-29.8	31.6	44.1	-28.3
1989	286.0	304.9	-6.2	8 046.1	13 186.6	-39.0	28.1	43.3	-35.1
1988	297.7	302.9	-1.7	7 317.8	11 439.9	-36.0	24.6	37.8	-34.9
Pre-1988	2 795.1	3 818.0	-26.8	31 797.1	60 700.7	-47.6	11.4	15.9	-28.3
Not reported	V	V	N	V	V	N	V	V	N
VEHICLE ACQUISITION									
Purchased new	2 323.6	2 091.2	11.1	83 418.9	61 078.6	36.6	35.9	29.2	22.9
Purchased used	2 762.6	2 601.1	6.2	44 648.1	37 362.8	19.5	16.2	14.4	12.5
Leased from someone else	522.2	373.6	39.8	27 900.7	17 045.0	63.7	53.4	45.6	17.1
Other	N	6.2	N	N	189.0	N	N	30.3	N
Not reported	56.3	40.3	39.7	1 396.0	904.3	54.4	24.8	22.4	10.7
LEASE CHARACTERISTICS[3] [4]									
Leased without driver	775.0	501.7	54.5	36 281.9	20 427.3	77.6	46.8	40.7	15.0
Leased with driver other than owner-operator	77.8	76.1	2.2	3 999.0	4 014.7	-.4	51.4	52.7	-2.5
Leased with owner-operator	194.1	154.9	25.3	9 856.0	7 241.6	36.1	50.8	46.7	8.8
Provisions of lease:									
Financing	270.0	184.8	46.1	14 874.8	8 339.4	78.4	55.1	45.1	22.2
Full maintenance	251.8	161.8	55.6	14 007.0	8 538.5	64.0	55.6	52.8	5.3
Maintenance on specific parts	25.1	13.3	88.7	1 271.8	702.6	81.0	50.7	52.7	-3.8
Payment of taxes	245.4	134.7	82.2	13 895.5	7 351.6	89.0	56.6	54.6	3.7
Obtaining licenses and permits	284.6	179.7	58.4	17 221.9	10 357.2	66.3	60.5	57.6	5.0
Record keeping for leased trucks	222.7	123.5	80.3	13 584.8	7 433.0	82.8	61.0	60.2	1.3
Other	40.4	26.2	54.2	2 210.2	1 525.2	44.9	54.7	58.3	-6.2

See footnotes at end of table.

(*continued on next page*)

TABLE 3a. (Continued)

[Detail may not add to total because of rounding. For meaning of abbreviations and symbols, see introductory text]

Vehicular and operational characteristics	1997 trucks[1] (thousands)	1992 trucks (thousands)	Percent change	1997 truck miles[2] (millions)	1992 truck miles[2] (millions)	Percent change	1997 average miles per truck[2] (thousands)	1992 average miles per truck[2] (thousands)	Percent change
	A	B	C	D	E	F	G	H	I
PRIMARY OPERATOR CLASSIFICATION									
Not for hire	4 554.9	4 250.3	7.2	82 436.9	64 553.3	27.7	18.1	15.2	19.1
Business use	4 327.1	3 966.9	9.1	81 343.2	63 422.8	28.3	18.8	16.0	17.5
Personal transportation	211.6	267.9	–21.0	982.7	1 015.9	–5.2	4.5	3.8	18.4
Mixed—business use/personal transportation	16.2	15.5	4.5	130.9	114.6	14.2	8.1	7.4	9.5
For hire	938.6	771.4	21.7	69 019.0	49 160.0	40.4	73.5	63.7	15.4
Motor carrier	696.3	567.3	22.7	52 512.9	37 233.0	41.0	75.4	65.6	14.9
Owner/operator	187.2	153.8	21.7	13 142.3	9 905.7	32.7	70.2	64.4	9.0
Independent	100.7	81.9	23.0	5 832.9	4 331.8	34.7	57.9	52.9	9.5
Leased to a company	86.5	71.9	20.3	7 309.3	5 573.9	31.1	84.5	77.6	8.9
Not reported	21.5	27.3	–21.2	1 589.0	964.2	64.8	73.8	35.4	108.5
Daily rental	171.2	90.7	88.8	5 907.8	2 865.4	106.2	34.5	31.6	9.2
Mixed—not for hire/for hire	29.1	S	S	1 400.3	S	S	48.2	S	S
For-hire jurisdiction:									
Interstate	577.0	412.4	39.9	51 788.4	34 698.7	49.3	89.7	84.1	6.7
Intrastate	184.9	183.4	.8	9 172.2	8 139.2	12.7	49.6	44.4	11.7
Local	115.6	96.1	20.3	3 283.0	2 528.8	29.8	28.4	26.3	8.0
Not reported	58.3	56.4	3.4	4 692.4	2 736.3	71.5	80.5	48.5	66.0
Type of carrier (interstate only):									
Contract	251.9	167.5	50.4	24 455.5	14 956.2	63.5	97.1	89.3	8.7
Common	302.2	226.7	33.3	25 314.8	18 189.3	39.2	83.8	80.2	4.5
Exempt	15.9	14.6	8.9	1 397.8	1 260.3	10.9	87.8	86.1	2.0
Not reported	7.7	3.5	120.0	685.8	292.9	134.1	89.0	83.0	7.2
Kind of service:									
Truckload	579.8	453.1	28.0	46 815.6	33 847.2	38.3	80.7	74.7	8.0
Less than truckload	283.2	231.2	22.5	16 471.9	11 065.7	48.9	58.2	47.9	21.5
Not reported	72.6	64.1	13.3	5 646.6	3 190.0	77.0	77.8	49.8	56.2
PRIMARY PRODUCTS CARRIED									
Farm products	617.6	614.8	.5	10 020.4	8 638.2	16.0	16.2	14.1	14.9
Live animals	115.2	149.7	–23.0	2 766.5	2 543.0	8.8	24.0	17.0	41.2
Animal feed	98.5	101.1	–2.6	2 171.6	2 022.3	7.4	22.0	20.0	10.0
Mining products	38.7	35.9	7.8	1 552.5	1 382.9	12.3	40.1	38.5	4.2
Logs and other forest products	119.1	112.2	6.1	3 704.8	3 096.5	19.6	31.1	27.6	12.7
Lumber and fabricated wood products	159.6	137.2	16.3	5 087.3	3 800.9	33.8	31.9	27.7	15.2
Processed foods	492.8	447.6	10.1	23 741.8	17 547.3	35.3	48.2	39.2	23.0
Textile mill products	107.7	73.7	46.1	4 944.3	2 523.1	96.0	45.9	34.2	34.2
Building materials	795.6	649.2	22.6	15 571.4	12 041.3	29.3	19.6	18.5	5.9
Household goods	147.6	65.0	127.1	4 014.9	2 071.8	93.8	27.2	31.8	–14.5
Furniture or hardware	88.2	91.8	–3.9	3 278.3	2 894.2	13.3	37.2	31.5	18.1
Paper products	103.8	94.7	9.6	6 404.4	5 255.0	21.9	61.7	55.5	11.2
Chemicals	147.2	138.3	6.4	4 998.5	3 936.4	27.0	33.9	28.5	18.9
Petroleum	170.4	171.0	–.4	4 942.1	4 580.8	7.9	29.0	26.8	8.2
Plastics and/or rubber	64.4	46.2	39.4	2 710.1	1 887.4	43.6	42.1	40.9	2.9
Primary metal products	100.4	96.2	4.4	4 746.9	3 777.5	25.7	47.3	39.3	20.4
Fabricated metal products	106.8	111.4	–4.1	3 359.4	2 894.2	16.1	31.5	26.0	21.2
Machinery	285.4	201.4	41.7	7 400.2	3 678.0	101.2	25.9	18.3	41.5
Transportation equipment	213.5	205.6	3.8	6 297.8	5 196.6	21.2	29.5	25.3	16.6
Glass products	11.5	11.5	V	625.8	587.3	6.6	54.4	51.1	6.5
Miscellaneous products of manufacturing	108.8	84.8	28.3	5 195.9	2 920.3	77.9	47.8	34.5	38.6
Industrial "waste" water	6.2	8.4	–26.2	210.1	201.4	4.3	33.7	23.8	41.6
Scrap, refuse, or garbage	166.8	152.5	9.4	3 326.4	2 527.8	31.6	19.9	16.6	19.9
Mixed cargoes	359.8	257.1	39.9	18 411.6	10 786.7	70.7	51.2	42.0	21.9
Craftsman's equipment	369.4	322.5	14.5	5 046.7	3 924.4	28.6	13.7	12.2	12.3
Recyclable products	49.3	39.1	26.1	1 286.4	878.1	46.5	26.1	22.4	16.5
Hazardous waste (EPA manifest)	7.5	7.3	2.7	465.8	424.2	9.8	62.2	58.0	7.2
Hazardous waste (non-EPA manifest)	2.2	3.1	–29.0	82.7	114.7	–27.9	37.8	37.2	1.6
Personal transportation	183.0	230.8	–20.7	952.5	995.8	–4.3	5.2	4.3	20.9
Passengers	19.0	5.5	245.5	277.3	117.4	136.2	14.6	21.2	–31.1
No load carried	179.3	208.8	–14.1	1 793.6	1 904.5	–5.8	10.0	9.1	9.9
Not in use	168.6	180.0	–6.3	31.8	61.3	–48.1	.2	.3	–33.3
Other	60.7	58.0	4.7	1 944.0	1 369.6	41.9	32.0	23.6	35.6
Not reported	V	V	N	V	V	N	V	V	N
HAZARDOUS MATERIALS CARRIED									
Carrying hazardous materials[4] [5]	403.3	N	N	24 787.3	N	N	61.5	N	N
Hazmat placard names:									
Explosives 1.1 (formerly explosive A)	7.2	14.9	–51.7	57.9	44.6	29.8	8.1	3.0	170.0
Explosives 1.2 (formerly explosive A)	3.8	4.5	–15.6	S	16.9	S	S	3.8	S
Explosives 1.3 (formerly explosive B)	4.5	8.2	–45.1	29.9	50.4	–40.7	6.7	6.2	8.1
Explosives 1.4 (formerly dangerous)	37.3	27.8	34.2	120.1	138.2	–13.1	3.2	5.0	–36.0
Explosives 1.5 (formerly blasting agents)	22.7	16.1	41.0	86.6	117.4	–26.2	3.8	7.3	–47.9
Explosives 1.6 (formerly dangerous)	25.3	20.7	22.2	86.1	114.7	–24.9	3.4	5.5	–38.2
Flammable gas	115.3	103.9	11.0	1 453.5	1 560.7	–6.9	12.6	15.0	–16.0
Nonflammable gas	83.0	74.7	11.1	730.5	692.3	5.5	8.8	9.3	–5.4
Poisonous gas	34.1	28.9	18.0	101.0	161.3	–37.4	3.0	5.6	–46.4
Flammable	218.0	182.0	19.8	3 860.7	2 582.2	49.5	17.7	14.2	24.6
Combustible	127.5	110.3	15.6	1 791.9	1 136.1	57.7	14.1	10.3	36.9
Flammable solid	65.4	66.6	–1.8	237.4	314.0	–24.4	3.6	4.7	–23.4
Spontaneously combustible (formerly flammable solid)	41.4	29.4	40.8	168.7	118.4	42.5	4.1	4.0	2.5
Dangerous when wet (formerly flammable solid W)	47.4	36.2	30.9	160.6	142.4	12.8	3.4	3.9	–12.8
Oxidizer	90.8	81.6	11.0	478.8	542.4	–11.7	5.3	6.6	–19.7

See footnotes at end of table.

TABLE 3a. (Continued)

[Detail may not add to total because of rounding. For meaning of abbreviations and symbols, see introductory text]

Vehicular and operational characteristics	1997 trucks[1] (thousands)	1992 trucks (thousands)	Percent change	1997 truck miles[2] (millions)	1992 truck miles[2] (millions)	Percent change	1997 average miles per truck[2] (thousands)	1992 average miles per truck[2] (thousands)	Percent change
	A	B	C	D	E	F	G	H	I
HAZARDOUS MATERIALS CARRIED—Con.									
Hazmat placard names—Con.									
Oxygen	39.0	32.4	20.4	199.8	234.9	–14.9	5.1	7.3	–30.1
Organic peroxide	46.5	30.6	52.0	123.5	154.5	–20.1	2.7	5.0	–46.0
Poison (formerly poisons A and B, solids, and liquids)	70.9	51.8	36.9	287.9	226.1	27.3	4.1	4.4	–6.8
Keep away from food	49.6	30.8	61.0	177.4	131.2	35.2	3.6	4.3	–16.3
Radioactive	19.2	22.6	–15.0	78.7	106.4	–26.0	4.1	4.7	–12.8
Corrosive	159.2	129.3	23.1	2 105.3	1 475.6	42.7	13.2	11.4	15.8
Class 9	53.5	38.4	39.3	596.0	375.7	58.6	11.1	9.8	13.3
Hazardous materials not specified[5]	40.6	26.6	52.6	2 734.5	1 296.3	110.9	67.4	48.8	38.1
No hazardous materials carried	4 482.5	4 149.8	8.0	113 704.9	89 001.9	27.8	25.4	21.4	18.7
Not reported	778.6	546.7	42.5	18 671.4	8 442.7	123.5	24.2	15.4	57.1
TRUCK FLEET SIZE									
1	751.4	724.3	3.7	16 243.6	12 043.0	34.9	21.6	16.6	30.1
2 to 5	1 406.6	1 394.8	.8	21 416.7	18 420.4	16.3	15.2	13.2	15.2
6 to 9	459.3	447.7	2.6	9 266.8	8 559.5	8.3	20.2	19.1	5.8
10 to 24	584.7	581.9	.5	14 879.9	14 373.0	3.5	25.4	24.7	2.8
25 to 99	635.9	557.5	14.1	21 968.0	18 273.9	20.2	34.5	32.8	5.2
100 or more	1 093.0	859.7	27.1	56 871.5	36 652.7	55.2	52.0	42.6	22.1
Not reported	733.8	546.6	34.2	16 717.2	8 257.0	102.5	22.8	15.1	51.0
MILES PER GALLON									
Less than 5	522.9	580.7	–10.0	14 682.4	15 779.4	–7.0	28.1	27.2	3.3
5 to 6.9	1 841.9	1 653.9	11.4	84 527.2	63 353.9	33.4	45.9	38.3	19.8
7 to 8.9	1 040.6	951.8	9.3	22 219.0	14 890.2	49.2	21.4	15.6	37.2
9 to 10.9	841.5	778.1	8.1	12 006.7	9 926.5	21.0	14.3	12.8	11.7
11 to 12.9	411.3	377.3	9.0	5 773.0	4 814.2	19.9	14.0	12.8	9.4
13 to 14.9	163.0	132.8	22.7	2 590.7	1 917.5	35.1	15.9	14.4	10.4
15 or more	290.5	240.6	20.7	4 309.4	3 050.5	41.3	14.8	12.7	16.5
15 to 20.9	275.0	222.1	23.8	4 007.6	2 757.3	45.3	14.6	12.4	17.7
21 to 24.9	8.9	9.3	–4.3	118.1	119.2	–.9	13.3	12.9	3.1
25 or more	6.6	9.2	–28.3	S	174.0	S	S	19.0	S
Not reported	553.0	397.3	39.2	11 255.3	2 847.4	295.3	20.4	7.2	183.3
EQUIPMENT TYPE[4]									
Braking system	5 664.7	5 093.9	11.2	157 363.7	116 460.8	35.1	27.8	22.9	21.4
Hydraulic	1 252.5	1 294.8	–3.3	13 993.0	12 922.6	8.3	11.2	10.0	12.0
Hydraulic (power)	1 453.6	1 504.9	–3.4	19 229.7	18 537.4	3.7	13.2	12.3	7.3
Air	2 457.4	1 973.3	24.5	112 645.0	80 318.5	40.2	45.8	40.7	12.5
Other	78.7	71.0	10.8	1 018.0	927.4	9.8	12.9	13.1	–1.5
Not reported	422.5	249.7	69.2	10 478.0	3 754.9	179.0	24.8	15.0	65.3
Antilock brakes	748.9	363.2	106.2	37 195.5	12 420.7	199.5	49.7	34.2	45.3
Power steering	4 398.3	3 749.0	17.3	134 968.2	98 855.4	36.5	30.7	26.4	16.3
Vehicle control aids for handicapped drivers	V	V	N	V	V	N	V	V	N
Air-conditioning	2 242.3	1 513.6	48.1	110 506.1	73 760.5	49.8	49.3	48.7	1.2
Wheelchair lift	V	V	N	V	V	N	V	V	N
Engine retarder	831.5	540.0	54.0	55 246.5	30 386.0	81.8	66.4	56.3	17.9
Reflective materials	1 182.8	846.6	39.7	50 555.8	28 296.2	78.7	42.7	33.4	27.8
Electronic vehicle management system	468.9	175.6	167.0	36 157.9	11 471.7	215.2	77.1	65.3	18.1
Electronic vehicle identification device (transponder, etc.)	147.9	46.6	217.4	13 134.2	3 685.8	256.4	88.8	79.1	12.3
Trip recorders/on board computer system	409.1	199.9	104.7	28 440.0	11 950.7	138.0	69.5	59.8	16.2
Navigational systems	64.9	31.0	109.4	5 769.0	2 051.5	181.2	88.8	66.2	34.1
Airbag(s)[5]	427.4	N	N	28 107.6	N	N	65.8	N	N
FUEL CONSERVATION EQUIPMENT[4]									
Aerodynamic features	853.0	575.9	48.1	62 997.6	38 664.8	62.9	73.9	67.1	10.1
Axle or drive ratio	1 287.4	1 020.6	26.1	71 247.1	46 809.9	52.2	55.3	45.9	20.5
Fuel economy engine	1 508.3	1 117.7	34.9	82 709.3	55 447.5	49.2	54.8	49.6	10.5
Radial tires	3 732.2	2 984.8	25.0	127 736.3	95 947.3	33.1	34.2	32.1	6.5
Road speed governors	1 451.4	1 137.6	27.6	71 638.3	41 709.8	71.8	49.4	36.7	34.8
Variable fan drives	1 303.2	999.3	30.4	72 215.0	50 988.1	41.6	55.4	51.0	8.6
Other fuel conservation devices	326.7	258.3	26.5	24 915.7	15 632.8	59.4	76.3	60.5	26.1
MAINTENANCE[4]									
General maintenance performed by—									
Owner	1 875.4	1 931.9	–2.9	32 857.4	28 952.2	13.5	17.5	15.0	16.7
Company's maintenance facilities	2 132.3	1 958.7	8.9	79 856.7	62 638.7	27.5	37.5	32.0	17.2
Dealership's service department	525.1	410.0	28.1	20 456.9	13 352.5	53.2	39.0	32.6	19.6
Leasing company	102.6	81.9	25.5	5 689.8	4 323.2	31.6	55.4	52.8	4.9
Independent garage	1 346.1	1 153.9	16.7	36 206.5	25 951.7	39.5	26.9	22.5	19.6
Component distributorship	73.7	59.9	23.0	4 246.4	3 401.4	24.8	57.6	56.8	1.4
No one	32.8	28.3	15.9	252.4	143.4	76.0	7.7	5.1	51.0
Other	30.1	23.2	29.7	1 175.6	1 033.8	13.7	39.0	44.6	–12.6
Not reported	551.3	305.5	80.5	16 679.9	5 064.0	229.4	30.3	16.6	82.5

See footnotes at end of table.

(*continued on next page*)

TABLE 3a. (Continued)

[Detail may not add to total because of rounding. For meaning of abbreviations and symbols, see introductory text]

Vehicular and operational characteristics	1997 trucks[1] (thousands)	1992 trucks (thousands)	Percent change	1997 truck miles[2] (millions)	1992 truck miles[2] (millions)	Percent change	1997 average miles per truck[2] (thousands)	1992 average miles per truck[2] (thousands)	Percent change
	A	B	C	D	E	F	G	H	I
MAINTENANCE[4]—Con.									
Major overhauls performed by—									
Owner	441.5	515.9	−14.4	6 534.4	7 580.0	−13.8	14.8	14.7	.7
Company's maintenance facilities	1 137.7	1 100.9	3.3	40 042.7	36 523.2	9.6	35.2	33.2	6.0
Dealership's service department	824.1	683.6	20.6	38 015.2	25 584.7	48.6	46.1	37.4	23.3
Leasing company	68.1	62.0	9.8	3 581.2	3 045.1	17.6	52.6	49.1	7.1
Independent garage	1 212.5	1 141.2	6.2	27 038.4	24 398.1	10.8	22.3	21.4	4.2
Component distributorship	266.0	237.4	12.0	14 691.1	10 577.0	38.9	55.2	44.5	24.0
No one	144.8	140.5	3.1	2 701.3	1 952.0	38.4	18.7	13.9	34.5
Other	19.0	19.4	−2.1	632.9	937.5	−32.5	33.3	48.3	−31.1
Not reported	1 993.4	1 661.4	20.0	43 030.5	23 746.8	81.2	21.6	14.3	51.0
ENGINE TYPE AND SIZE									
Engine	5 664.7	5 112.4	10.8	157 363.7	116 579.5	35.0	27.8	22.8	21.9
Gasoline	2 155.3	2 473.5	−12.9	18 676.1	20 361.4	−8.3	8.7	8.2	6.1
Diesel	3 323.4	2 464.1	34.9	136 516.5	94 719.3	44.1	41.1	38.4	7.0
Liquefied gas or other	54.0	65.5	−17.6	702.6	782.2	−10.2	13.0	11.9	9.2
Not reported	132.0	109.4	20.7	1 468.5	716.7	104.9	11.1	6.6	68.2
Cylinders[6]	5 664.7	5 112.4	10.8	157 363.7	116 579.5	35.0	27.8	22.8	21.9
4	118.1	78.4	50.6	2 495.8	1 685.1	48.1	21.1	21.5	−1.9
6	2 407.7	1 529.2	57.4	119 110.0	72 862.2	63.5	49.5	47.6	4.0
8	2 064.0	1 897.2	8.8	25 368.7	22 994.6	10.3	12.3	12.1	1.7
Other	6.4	1.9	236.8	93.3	28.8	224.0	14.6	15.1	−3.3
Not reported	1 068.5	1 605.7	−33.5	10 295.9	19 008.8	−45.8	9.6	11.8	−18.6
Cubic inch displacement[7]	5 664.7	5 003.1	13.2	157 363.7	115 862.6	35.8	27.8	23.2	19.8
Gasoline engines	2 155.3	2 473.5	−12.9	18 676.1	20 361.4	−8.3	8.7	8.2	6.1
Less than 200	24.8	23.4	6.0	340.3	460.3	−26.1	13.7	19.7	−30.5
200 to 299	88.0	73.3	20.1	1 360.8	1 025.6	32.7	15.5	14.0	10.7
300 to 349	67.2	71.3	−5.8	692.1	527.3	31.3	10.3	7.4	39.2
350 to 399	847.1	852.4	−.6	9 075.8	9 516.9	−4.6	10.7	11.2	−4.5
400 or more	382.7	321.6	19.0	4 687.8	3 975.2	17.9	12.2	12.4	−1.6
Not reported	745.6	1 131.6	−34.1	2 519.3	4 856.0	−48.1	3.4	4.3	−20.9
Diesel engines	3 323.4	2 464.1	34.9	136 516.5	94 719.3	44.1	41.1	38.4	7.0
Less than 400	425.6	278.9	52.6	8 716.3	5 900.3	47.7	20.5	21.2	−3.3
400 to 599	842.5	548.9	53.5	18 104.4	11 716.9	54.5	21.5	21.3	.9
600 to 799	759.6	361.1	110.4	44 581.0	16 409.4	171.7	58.7	45.4	29.3
800 or more	742.6	584.3	27.1	48 059.0	42 987.5	11.8	64.7	73.6	−12.1
Not reported	552.9	690.9	−20.0	17 055.9	17 705.2	−3.7	30.8	25.6	20.3
Other engines	54.0	65.5	−17.6	702.6	782.2	−10.2	13.0	11.9	9.2
Less than 400	23.3	26.9	−13.4	333.6	417.4	−20.1	14.3	15.5	−7.7
400 or more	17.3	14.2	21.8	308.7	227.4	35.8	17.9	16.0	11.9
Not reported	13.4	24.4	−45.1	60.3	137.4	−56.1	4.5	5.6	−19.6
Not reported	132.0	109.4	20.7	1 468.5	716.7	104.9	11.1	6.6	68.2
REFUELING LOCATION									
Central company-owned fueling facility	1 515.4	1 540.6	−1.6	49 156.6	41 184.7	19.4	32.4	26.7	21.3
Single contract fueling facility located off-site	315.7	271.6	16.2	9 895.6	7 193.8	37.6	31.3	26.5	18.1
Public fueling stations	3 142.0	2 757.0	14.0	84 014.3	60 717.7	38.4	26.7	22.0	21.4
Other	215.7	236.7	−8.9	3 637.7	3 817.7	−4.7	16.9	16.1	5.0
Not reported	429.5	287.9	49.2	10 093.2	3 547.0	184.6	23.5	12.3	91.1
TRUCK TYPE AND AXLE ARRANGEMENT									
Single-unit trucks	3 853.1	3 684.2	4.6	51 467.4	42 413.9	21.3	13.4	11.5	16.5
2 axles	3 266.9	3 177.1	2.8	41 320.8	34 794.6	18.8	12.6	11.0	14.5
3 axles	475.0	430.1	10.4	7 186.8	5 763.5	24.7	15.1	13.4	12.7
4 axles or more	111.2	77.0	44.4	2 959.7	1 855.8	59.5	26.6	24.1	10.4
Combinations	1 811.5	1 428.2	26.8	105 896.3	74 165.6	42.8	58.5	51.9	12.7
Single-unit truck with trailer	105.8	113.7	−6.9	2 673.8	2 349.1	13.8	25.3	20.7	22.2
4 axles	48.7	65.5	−25.6	782.6	814.4	−3.9	16.1	12.4	29.8
5 axles or more	57.1	48.2	18.5	1 891.1	1 534.6	23.2	33.1	31.9	3.8
Single-unit truck with utility trailer	162.0	148.5	9.1	2 098.0	1 835.9	14.3	13.0	12.4	4.8
3 axles	44.1	46.3	−4.8	488.7	522.0	−6.4	11.1	11.3	−1.8
4 axles	96.8	76.5	26.5	1 285.4	917.0	40.2	13.3	12.0	10.8
5 axles or more	21.1	25.7	−17.9	323.8	396.9	−18.4	15.3	15.5	−1.3
Truck-tractor with single trailer	1 438.2	1 107.1	29.9	92 221.3	65 318.4	41.2	64.1	59.0	8.6
3 axles	78.0	76.7	1.7	2 183.2	1 980.1	10.3	28.0	25.8	8.5
4 axles	211.7	172.3	22.9	8 808.7	6 803.2	29.5	41.6	39.5	5.3
5 axles or more	1 148.5	858.2	33.8	81 229.4	56 535.0	43.7	70.7	65.9	7.3
Truck-tractor with double trailers	101.0	58.0	74.1	8 466.7	4 584.3	84.7	83.8	79.1	5.9
5 axles	56.3	39.2	43.6	4 730.3	3 256.8	45.2	84.1	83.1	1.2
6 axles	24.0	5.8	313.8	2 239.3	454.2	393.0	93.3	78.8	18.4
7 axles or more	20.8	13.0	60.0	1 497.1	873.3	71.4	72.1	67.0	7.6
Truck-tractor with triple trailers	4.5	.9	400.0	436.6	77.9	460.5	97.1	85.4	13.7
7 axles	S	.4	S	S	40.2	S	S	91.2	S
8 axles or more	4.3	.5	760.0	414.8	37.7	1 000.3	97.3	79.9	21.8
Trailer not specified	V	V	N	V	V	N	V	V	N
Powered axles	5 664.7	5 112.4	10.8	157 363.7	116 579.5	35.0	27.8	22.8	21.9
1	3 802.7	3 718.7	2.3	62 755.3	52 741.2	19.0	16.5	14.2	16.2
2	1 800.0	1 366.7	31.7	91 028.6	63 098.8	44.3	50.6	46.2	9.5
3 or more	62.0	29.0	113.8	3 579.8	739.5	384.1	57.8	25.5	126.7
Not reported	V	V	N	V	V	N	V	V	N

See footnotes at end of table.

TABLE 3a. (Continued)

[Detail may not add to total because of rounding. For meaning of abbreviations and symbols, see introductory text]

Vehicular and operational characteristics	1997 trucks[1] (thousands)	1992 trucks (thousands)	Percent change	1997 truck miles[2] (millions)	1992 truck miles[2] (millions)	Percent change	1997 average miles per truck[2] (thousands)	1992 average miles per truck[2] (thousands)	Percent change
	A	B	C	D	E	F	G	H	I
CAB TYPE									
Cab forward of engine	181.5	110.0	65.0	3 335.8	1 724.2	93.5	18.4	15.7	17.2
Cab over engine	705.8	804.0	−12.2	19 006.4	26 549.4	−28.4	26.9	33.0	−18.5
Conventional cab	4 240.4	3 851.4	10.1	124 166.7	83 490.6	48.7	29.3	21.7	35.0
Cab beside engine	37.6	43.0	−12.6	531.4	559.9	−5.1	14.2	13.0	9.2
Other	88.0	101.3	−13.1	1 190.0	1 405.1	−15.3	13.5	13.9	−2.9
Not reported	365.0	184.1	98.3	8 567.0	2 731.6	213.6	23.5	14.8	58.8

Note: Some estimates may have high relative standard errors of estimate (RSEs). The U.S. estimates may differ from the sum of the state estimates because of rounding.

[1] Includes trucks registered in one state with a mailing address of another state. These trucks were excluded from the 1992 survey.
[2] Truck miles distribution shown for hazardous materials carried.
[3] Lease characteristics include both "leased from" and "leased to" vehicles. Lease provisions apply to a period of 1 year or more.
[4] Detail does not add to total because items were not applicable or multiple responses were possible.
[5] New or modified data line from 1992.
[6] Data were derived from administrative records. "Not reported" indicates those trucks for which the cylinders are unknown.
[7] Data were derived from administrative records. "Not reported" indicates those trucks for which the cubic inch displacement is unknown.

APPENDIX B

WEIGH STATION DATA COLLECTION

This appendix discusses the data collection activities conducted at weigh stations to gather data on trailer length, rear overhang, and the usage of antilock brake systems (ABS) in the existing truck population. Data collection activities were performed during spring 2002 at three weigh stations in the states of Kansas, Texas, and Missouri. Data were collected over a period of two days at each weigh station. This appendix discusses the primary objectives for the weigh station data collection activities, the locations of the weigh stations, the data collection procedures, and the analysis of the field data.

The goal of the weigh station data collection activities was to obtain a better understanding of the characteristics and composition of the current U.S. truck fleet, focusing on data elements that were not readily available in existing sources. In particular, information on trailer length, rear overhang, and ABS usage was sought. The primary objectives were to document the following:

- The proportion of single-semitrailer trucks with trailers over 16.2 m [53 ft] in length;
- The distribution of rear overhang lengths; and
- The percentage of trailers with ABS.

This information was needed for use in decisions concerning potential changes to design vehicle dimensions and for evaluating sight distance/deceleration issues.

WEIGH STATION LOCATIONS

Information on the locations of the weigh stations where the data collection activities were conducted is summarized in Table B-1. The three weigh stations where data were collected are located in the states of Kansas, Texas, and Missouri. Weigh stations in these respective states were selected for specific reasons. Missouri was included because the state does not generally allow trucks with trailers longer than 16.2 m [53 ft]; such vehicles can only operate legally with a permit. Kansas and Texas were selected because they do allow trailers over 16.2 m [53 ft] in length to operate on all state highways without a permit; the maximum trailer length in Kansas is 18.1 m [59.5 ft], and the maximum trailer length in Texas is 18.0 m [59 ft]. The specific weigh stations in Kansas and Texas were selected, in consultation with these states, at locations that were considered most likely to have truck trailers over 16.2 m [53 ft] in length. The Kansas site was located between Wichita and the Oklahoma state line; Oklahoma also permits trucks up to 18.2 m [59.6 ft] in length. The Texas site was located on a major intrastate trucking route between Houston and Dallas.

DATA COLLECTION PROCEDURES

Three types of data were collected at each weigh station for the trailers of combination trucks:

- Trailer length,
- Rear overhang, and
- Antilock brakes.

Trailer length and rear overhang were measured while each truck stopped on the scales to be weighed. As a truck approached the scale, one data collector was positioned near the rear of the trailer with a measuring wheel, and one data collector was positioned near the front of the trailer. When the truck came to a complete stop, the data collector positioned near the front of the trailer marked, with his foot, the location of the front of the trailer, and the data collector at the rear of the trailer began measuring from the rear bumper of the trailer to the center of the rear axle group, to obtain the rear overhang, and continued measuring to the front of the trailer to obtain the full length of the trailer (Figure B-1). The data collector positioned near the front of the trailer recorded both lengths. The only exception to this procedure relates to measurement of the trailer length and rear overhang for automobile transport trucks (auto carriers). Since this type of trailer often carries vehicles that extend beyond the rear bumper, the trailer length and rear overhang were measured from the rearmost portion of the vehicles being transported to the front of the trailer.

To obtain an accurate measurement of the trailer length and rear overhang, a truck needed to be stopped for approximately 5 seconds. At the weigh scales in Missouri and Texas, it is common procedure to have trucks come to a complete stop on the scales to be weighed, so the data collection procedures did not disrupt the normal scale operations. However, at the weigh station in Kansas, trucks typically roll through the scale at speeds of approximately 8 km/h [5 mph], but the scale operators were very cooperative and had trucks come to a complete stop so measurements could be made for this research.

In Missouri and Texas, not all trucks that enter the weigh station proceed through the scales. As trucks approach the facilities, they pass over weigh-in-motion scales. Based on their readings, trucks are instructed via traffic signals to either bypass the static scales or proceed to the static scales. This process can be manually overridden by the scale operators to either bypass all vehicles or to weigh all vehicles. Trailer lengths and rear overhangs were measured only for those

TABLE B-1 Locations of truck weigh stations where field studies were conducted

State	Location	Interstate	Direction of travel
KS	South of Wichita	I-35	NB
TX	North of Houston	I-45	NB
MO	East of Kansas City	I-70	EB

trucks that were instructed by the scale operator to proceed to the static scales. A large percentage of the trucks that passed over the static scales during the data collection period were measured for this research.

In Kansas, the weigh station had a bypass lane, but it was closed during the two-day data collection period so all trucks that entered the weigh station proceeded over the scale. A large percentage of the trucks that passed over the static scales during the data collection period were measured for this research.

To collect information on whether a trailer was equipped with ABS, data collectors looked for the presence of an amber light located on the driver's side of the trailer near the rear. Figure B-2 provides several illustrations of the amber ABS indicators observed on several types of trailers. In Missouri, data collectors positioned themselves such that ABS data were collected for all trucks passing through the weigh station, including those in the bypass lane. In Texas and Kansas, ABS data were collected only for vehicles that passed over the scales.

In Missouri and Texas, the layout of the weigh stations made it easier and safer for data collectors to measure trailer lengths and rear overhangs on the passenger side of the vehicles. This prohibited simultaneous collection of lengths (trailer lengths and rear overhang) and ABS data because the amber light is located on the driver's side of the trailer. Therefore, trailer length and rear overhang data were collected during certain periods of each day, while ABS data were collected during different periods. Over the two-day data collection period in Missouri, length data were collected for approximately 8.5 hours, while ABS data were collected for approximately 3.5 hours. Over the two-day data collection period in Texas, length data were collected for a period of approximately 11 hours, while ABS data were collected for approximately 2 hours.

Figure B-1. Measuring trailer length and rear overhang.

In Kansas all three types of trailer data were collected at the same time. Trailer lengths and rear overhangs were measured from the driver's side of the vehicle, which permitted observation of ABS lights. Approximately 12 hours of data were collected over the two-day period.

When recording all three types of trailer data, each vehicle was classified according to the truck configuration. Trailer length and rear overhang data were collected for single-semitrailer trucks, but not for double- or triple-semitrailers nor for single unit vehicles. ABS data were collected for single-, double-, and triple-semitrailer trucks, but not for single unit vehicles. When collecting ABS data for double- and triple-semitrailer trucks, the data were recorded separately for each trailer.

SUMMARY OF FIELD DATA

Table B-2 shows the number of trailers measured that were 16.2 m [53 ft] in length or less and the number of trailers greater than 16.2 m [53 ft] in length. The frequency is broken down by truck configuration and state. The last two columns give the total number of trailers measured and the percentage (by row) of trailers greater than 16.2 m [53 ft] in length. In Kansas, a total of 543 trailers were measured, and only 4 trailers (0.7 percent) were greater than 16.2 m [53 ft] in length. In Texas, a total of 524 trailers were measured, and 23 trailers (or 4.4 percent) were greater than 53 ft in length. In Missouri, 1 of 432 trailers (0.2 percent) measured was greater than 53 ft in length.

The last two rows of Table B-2 combine the trailer length data for Kansas, Texas, and Missouri and for Kansas and Texas. Combining the trailer length data for Kansas, Texas, and Missouri, a total of 1,499 trailers were measured with 1.9 percent of the trailers being greater than 16.2 m [53 ft] in length. Combining the data for the two states that permit trailers over 16.2 m [53 ft] in length (Kansas and Texas) data, 2.5 percent of the 1,067 trailers were greater than 16.2 m [53 ft] in length.

Table B-3 summarizes the trailer length data by configuration for all three states. Several points are of interest. First

Figure B-2. Amber ABS indicators.

the table shows that van type configurations are the most prevalent on highways. Of the 1,499 trailers measured, 1,026 were vans. Vans had the greatest frequency of trailers greater than 16.2 m [53 ft] in length, but this only accounted for 1.7 percent of van trailers. On the other hand, 21.6 percent of the automobile transporters were greater than 16.2 m [53 ft] in length. Recall that since automobile transporters often have vehicles that extend beyond the rear bumper, trailer length was measured from the rearmost portion of the vehicles being transported to the front of the trailer. The other types of configurations that had trailers greater than 16.2 m [53 ft] in length were flat beds (2 trucks) and low boy (1 truck).

Table B-4 presents the rear overhang data by configuration and by state. The rear overhang data are categorized into groups of 1.2-m [4-ft] intervals. In all three states, most of the trailers had a rear overhang of between 1.2 to 3.6 m [4 to 12 ft].

Table B-5 presents the ABS data by truck configuration and by state. The table shows the total number of trailers with ABS, the total number without ABS, the total number of trailers observed, and the percentage of trailers with ABS. In Kansas, approximately 39 percent of the trailers were equipped with ABS. In Texas, approximately 37 percent of the trailers were equipped with ABS. In Missouri, approximately 46 percent of the trailers were equipped with ABS. In all three states combined, approximately 43 percent of the trailers were equipped with ABS; if equal weight is given to the data from each state, the average ABS penetration for truck trailers is 41 percent.

Table B-6 summarizes the ABS data by configuration for all three states combined. Van trailers had the highest percentage (49 percent) of trailers equipped with ABS, while triple trailers had the lowest percentage (16.7) of trailers equipped with ABS. However, it should be noted

TABLE B-2 Frequency of trailer greater than 53 ft in length by truck configuration and by state

State	Configuration	Number of trailers 53 ft in length or less	Number of trailers greater than 53 ft in length	Number of trailers measured	Percentage of trailers greater than 53 ft in length
KS	Van	348	2	350	0.6
	Flat Bed	104	0	104	0.0
	Grain	17	0	17	0.0
	Tanker	35	0	35	0.0
	Low Boy	7	0	7	0.0
	Auto	10	2	12	16.7
	Other	18	0	18	0.0
	Totals	539	4	543	0.7
TX	Van	317	15	332	4.5
	Flat Bed	99	2	101	2.0
	Grain	4	0	4	0.0
	Tanker	44	0	44	0.0
	Low Boy	9	1	10	10.0
	Auto	7	5	12	41.7
	Other	21	0	21	0.0
	Totals	501	23	524	4.4
MO[1]	Van	344	0	344	0.0
	Flat Bed	34	0	34	0.0
	Grain	12	0	12	0.0
	Tanker	19	0	19	0.0
	Low Boy	8	0	8	0.0
	Auto	12	1	13	7.7
	Other	2	0	2	0.0
	Totals	431	1	432	0.2
Total for All 3 States		1471	28	1499	1.9
Totals for KS & TX		1040	27	1067	2.5

[1] Trailers over 53 ft in length are not permitted to operate on Missouri highways without a permit.

TABLE B-3 Frequency of trailers greater than 53 ft in length by truck configuration

Configuration	Number of trailers 53 ft in length or less	Number of trailers greater than 53 ft in length	Number of trailers measured	Percentage of trailers greater than 53 ft in length
Van	1009	17	1026	1.7
Flat Bed	237	2	239	0.8
Grain	33	0	33	0.0
Tanker	98	0	98	0.0
Low Boy	24	1	25	4.0
Auto	29	8	37	21.6
Other	41	0	41	0.0
Totals	1471	28	1499	1.9

NOTE: Data for all three states combined.

TABLE B-4 Frequency of rear overhang length by truck configuration and by state

State	Configuration	Length of rear overhang						Total
		0 - 4 ft	4 - 8 ft	8 - 12 ft	12 - 16 ft	16 - 20 ft	20 - 24 ft.	
KS	Van	2	79	217	54	0	0	352
	Flat Bed	1	76	24	3	0	0	104
	Grain	5	11	1	0	0	0	17
	Tanker	8	27	0	0	0	0	35
	Low Boy	3	3	0	1	0	0	7
	Auto	1	3	1	3	4	0	12
	Other	5	12	1	0	0	0	18
	Totals	25	211	244	61	4	0	545
TX	Van	7	68	150	79	1	0	335
	Flat Bed	1	67	28	5	0	0	101
	Grain	1	3	0	0	0	0	4
	Tanker	1	41	0	2	0	0	44
	Low Boy	0	8	0	2	0	0	10
	Auto	0	0	0	4	7	1	12
	Other	4	14	1	1	1	0	21
	Totals	14	201	209	93	9	1	527
MO	Van	1	77	204	61	0	0	343
	Flat Bed	0	21	12	1	0	0	34
	Grain	8	4	0	0	0	0	12
	Tanker	5	14	0	0	0	0	19
	Low Boy	2	2	2	2	0	0	8
	Auto	0	1	1	4	7	0	13
	Other	1	0	0	1	0	0	2
	Totals	17	119	219	69	7	0	431
Total for All 3 States		56	531	672	223	20	1	1503
Percentage of Totals		3.73	35.33	44.71	14.84	1.33	0.07	

TABLE B-5 Frequency of trailers with ABS by configuration and by state

State	Trailer configuration	Number of trailers with ABS	Number of trailers without ABS	Number of trailers observed	Percent of trailers with ABS
KS	Van	161	190	351	45.9
	Flat Bed	36	67	103	35.0
	Grain	7	11	18	38.9
	Tanker	11	27	38	29.0
	Low Boy	2	5	7	28.6
	Auto	1	8	9	11.1
	Double	4	20	24	16.7
	Triple	2	10	12	16.7
	Other	5	13	18	27.8
	Total	229	351	580	39.5
TX	Van	35	50	85	41.2
	Flat Bed	9	14	23	39.1
	Grain	1	0	1	100.0
	Tanker	4	11	15	26.7
	Low Boy	0	3	3	0.0
	Auto	3	2	5	60.0
	Double	4	10	14	28.6
	Triple	0	0	0	0.0
	Other	2	9	11	18.2
	Total	58	99	157	36.9
MO	Van	261	239	500	52.2
	Flat Bed	27	47	74	36.5
	Grain	6	14	20	30.0
	Tanker	4	19	23	17.4
	Low Boy	2	4	6	33.3
	Auto	7	6	13	53.9
	Double	21	39	60	35.0
	Triple	0	0	0	0.0
	Other	2	14	16	12.5
	Total	330	382	712	46.4
Total for All 3 States		617	832	1449	42.6

TABLE B-6 Frequency of trailers with ABS by truck configuration

Trailer configuration	Number of trailers with ABS	Number of trailers without ABS	Number of trailers observed	Percent of trailers with ABS
Van	457	479	936	48.8
Flat Bed	72	128	200	36.0
Grain	14	25	39	35.9
Tanker	19	57	76	25.0
Low Boy	4	12	16	25.0
Auto	11	16	27	40.7
Double	29	69	98	29.6
Triple	2	10	12	16.7
Other	9	36	45	20.0
Total	617	832	1449	42.6

NOTE: Data for all three states combined.

that the sample size of triple trailers was small (12 trailers observed).

The field data presented in Tables B-2 through B-6 provide useful data to characterize the current truck population. In the two states that permitted longer trailers, only approximately 2.5 percent of the trailers measured were, in fact, over 16.2 m [53 ft] in length. This does not suggest a current need to include a design vehicle with a trailer length greater than 16.2 m [53 ft] in the Green Book. The field data on trailer lengths and rear overhangs was considered in the offtracking investigation (see Appendix C). Finally, the field data suggest that the ABS penetration in the trailer population is approximately 42 percent.

APPENDIX C

TURNING PERFORMANCE ANALYSIS OF SPECIFIC DESIGN VEHICLES

One of the overall objectives of the research is to recommend appropriate changes to the design vehicles in the 2001 *Green Book (1)* and recommend vehicles for consideration as future design vehicles. This appendix presents an evaluation of the turning performance characteristics for several of the design vehicles included in the 2001 *Green Book* and additional vehicles being considered for inclusion as design vehicles in future versions of the *Green Book*. This comparison was conducted using AutoTURN, a commercially available vehicle turn simulation software program.

The evaluation was conducted in three phases. Phase I was defining the parameters of each vehicle to be investigated. Phase II consisted of modeling 180° turns with minimum turning radii and determining the minimum distance between the center of the turning radius and the path of the rear axle set and the maximum distance between the center of the turning radius and the path of the front overhang. Phase III consisted of defining four 90° turns with turning radii of 15.2, 22.9, 30.5, and 45.7 m (50, 75, 100, and 150 ft), guiding each vehicle through each predefined turning path, and measuring the maximum offtracking, swept path width, and rear swingout. The remainder of this appendix presents each phase of the analysis.

PHASE ONE—DEFINING VEHICLE PARAMETERS

A total of 13 vehicles were modeled within AutoTURN, including 4 of the design vehicles defined in the 2001 *Green Book* and 9 vehicles considered for inclusion as design vehicles in future versions of the *Green Book.* The first step in evaluating the turning performance of each vehicle was to define the parameters of each vehicle. Within AutoTURN, the basic parameters to be defined include the longitudinal dimensions of the vehicle, the widths of the tractors and trailers, the tracks of the tractors and trailers, the minimum turning radii, the maximum steering angles, and the maximum articulating angles.

The user has several means to define the parameters of a vehicle in AutoTURN. The user can (1) create a customized vehicle by providing the input for all the vehicle parameters, (2) select a predefined design vehicle from within the software program in which case the vehicle parameters are provided, or (3) select a predefined design vehicle from within the software program and modify the parameters as necessary. When selecting a predefined vehicle from within the program, the user can select design vehicles from sources such as the 2001 *Green Book* and the Canadian design guide.

One of the limitations of AutoTURN concerns axle settings. The program does not account for the difference in turning performance between a single axle, double (tandem) axle, or tridem axle group. Because the type of axle has only a minor impact on the turning performance of a vehicle, this limitation of the program is not a concern. The program simulates the turning performance of vehicles using calculations based upon the center of the axle groups for both the tractor and the trailer. Thus, when defining a vehicle, it is important to accurately specify the location of the center of the axle set or group.

Selected Design Vehicles from the 2001 *Green Book*

Four design vehicles in the 2001 *Green Book* were simulated within AutoTURN for comparison purposes. The simulated vehicles included:

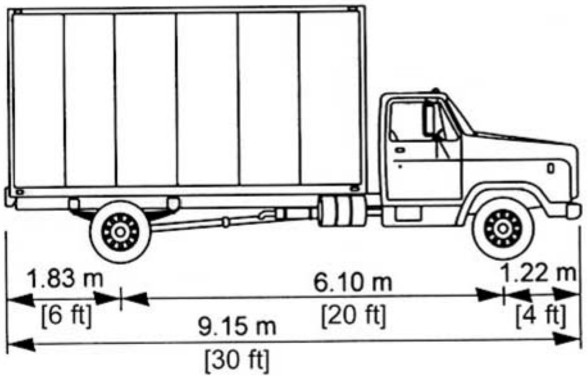
- Single unit truck (SU)
- WB-19 (WB-62) tractor-semitrailer
- WB-20D (WB-67D) double trailer
- WB-33B (WB-109D) double trailer

The parameters of each design vehicle as defined in the 2001 *Green Book* are illustrated in Figures C-1 to C-4.

Vehicles Considered for Inclusion as Future Design Vehicles

Chapter 4 of this report presents the vehicles being considered for inclusion as future design vehicles in the *Green Book*. This includes one single unit truck, four tractor-semitrailer combinations, and four double trailer combinations. This section presents figures that show the detailed parameters of each vehicle. More details are presented in the figures than are required for input into AutoTURN.

When inputting the design parameters into AutoTURN, in most cases the design vehicle from the 2001 *Green Book* most similar to the proposed vehicle was selected from the AutoTURN program and then modified as appropriate. In doing so, default values for vehicle parameters such as maximum steering angles and the maximum articulating angles were applied. For example, the WB-20 [WB-65 and WB-67] design vehicle in the 2001 *Green Book* is very similar to several of the proposed new design vehicles. Thus, the assumed steering angle for the WB-20 [WB-65 and WB-67] as specified in the 2001 *Green Book*, or a value very similar to it, was



Width: 8.00 ft Track: 8.00 ft Steering Angle: 31.70°

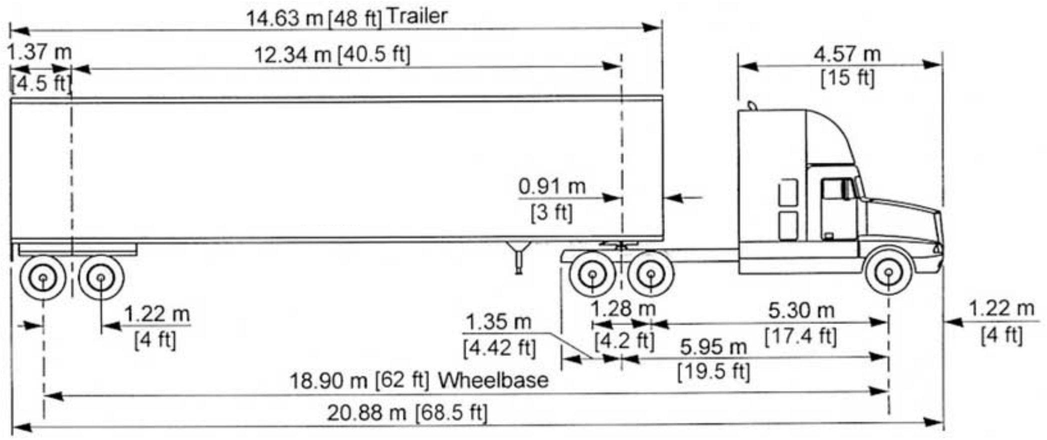
Figure C-1. 2001 Green Book design vehicle: single unit (SU).

input as the steering angle for the respective proposed new design vehicles.

The basis for selecting a value for an input parameter such as the maximum steering angle is significant because, in particular, this parameter impacts the minimum turning radius of a vehicle. The minimum turning radius of a vehicle is a function of the maximum steering angle and the wheelbase of the tractor. The minimum turning radius of each vehicle was calculated as shown in Figure C-5.

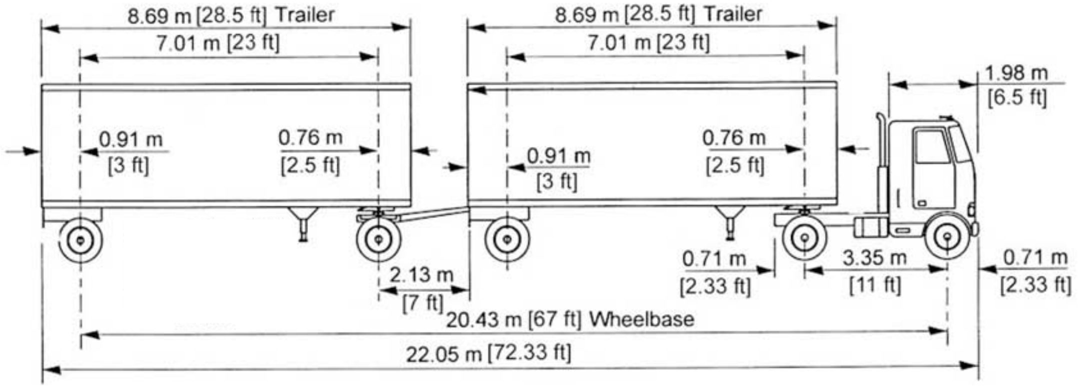
These calculations were verified with AutoTURN. In several cases, there were slight differences between the calculated minimum turning radii and the minimum turning radii permitted within AutoTURN, in which case the minimum turning radii permitted within AutoTURN were recorded as the minimum turning radii for the vehicles.

When defining the vehicle parameters for double-trailer combinations, there is a difference in the way the 2001 *Green Book* specifies articulation capabilities of double trailer combinations and the way AutoTURN defines the articulation capabilities of double trailer combinations. The 2001 *Green Book* specifies an assumed steering angle, an assumed tractor/trailer angle, and an assumed trailer/trailer angle. By contrast, AutoTURN requires the input of two angles, the steering angle and the articulating angle. When defining the parameters of the proposed new double-trailer combinations, the design vehicles from the 2001 *Green Book* most similar to the proposed tractor double trailer combinations were selected as predefined design vehicles from within the software program, and the parameters were modified as appropriate. The default articulating angles were applied. For example, one



Tractor Width: 8.00 ft Trailer Width: 8.50 ft Steering Angle: 28.40°
Tractor Track: 8.00 ft Trailer Track: 8.50 ft Articulating Angle: 65.00°

Figure C-2. 2001 Green Book design vehicle: WB-19 [WB-62] tractor semi-trailer.



Tractor Width: 8.00 ft Tractor Track: 8.00 ft

Trailer Width: 8.50 ft Trailer Track: 8.50 ft

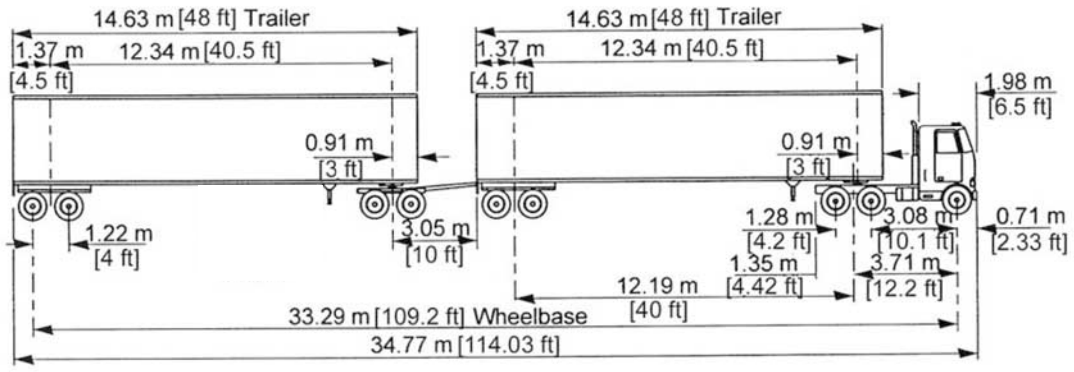
Steering Angle: 15.70° Tractor/Trailer Angle: 35.10° Trailer/Trailer Angle: 56.00°

Figure C-3. 2001 Green Book design vehicle: WB-20D [WB-67D] double trailer.

of the proposed design vehicles is a double trailer combination with two 16.15 m [53 ft] trailers. In the 2001 *Green Book*, the most similar vehicle to this double trailer combination is the WB-33D [WB-109D], with two 14.63 m [48 ft] trailers. The WB-33D [WB-109D] was selected as predefined in the software program and modified to include 16.15 m [53 ft] trailers rather than 14.63 m [48 ft] trailers. The articulating angle of the WB-33D [WB-109D], as predefined within AutoTURN, was used as the articulating angle for the proposed double trailer combination with 16.15 m [53 ft] trailers.

Single-Unit Truck

The new single-unit truck design vehicle recommended for inclusion in the *Green Book* is a three-axle truck with an overall length of 12.0 m [39.5 ft] (Figure C-6), designated as



Tractor Width: 8.00 ft Tractor Track: 8.00 ft

Trailer Width: 8.50 ft Trailer Track: 8.50 ft

Steering Angle: 12.70° Tractor/Trailer Angle: 45.00° Trailer/Trailer Angle: 70.00°

Figure C-4. 2001 Green Book design vehicle: WB-33B [WB-109D] double trailer.

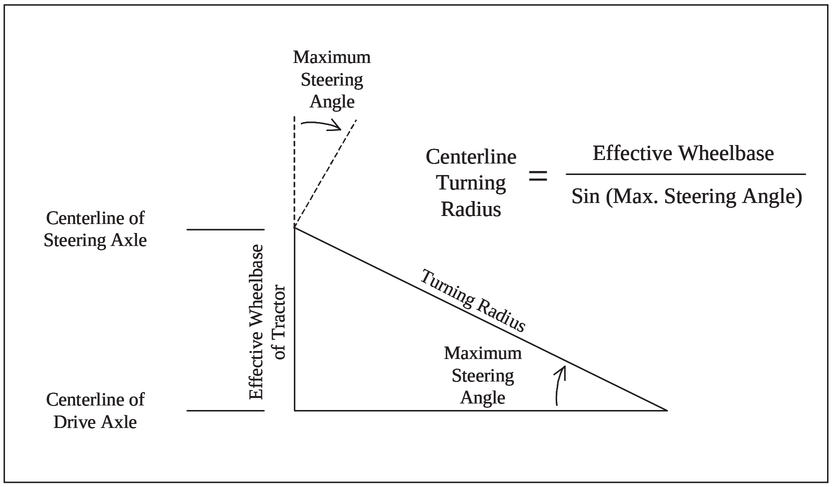


Figure C-5. Minimum centerline turning radius calculations.

the SU-8 [SU-25] design vehicle. The minimum centerline turning radius of this single unit truck is 14.5 m [47.5 ft]. In comparison, the single-unit design vehicle in the 2001 *Green Book* is a two-axle truck with an overall length of 9.15 m [30 ft]. The primary differences between the two vehicles are the number of axles, the overall length of the vehicles, and the wheelbases.

WB-20 [WB-67] Tractor-Semitrailer

The WB-20 [WB-67] tractor-semitrailer design vehicle is a variation of the WB-20 [WB-65] design vehicle already illustrated in the 2001 *Green Book*. This configuration has a 16.2 m [53 ft] trailer; the rear axles are located at the extreme rear of the trailer, with a KCRT of 13.9 m [45.5 ft] (see Figure C-7). The minimum centerline turning radius of this WB-20 [WB-67] tractor-semitrailer configuration is 12.50 m [41.0 ft]. The only difference between the WB-20 [WB-67] design vehicle and the WB-20 [WB-65] design vehicle shown in the *Green Book* is the KCRT distance, which is 13.9 m [45.5 ft], rather than 13.3 m [43.5 ft].

WB-20 [WB-67] Tractor-Semitrailer: 12.5 m [41 ft] KCRT

Another vehicle investigated is a variation of the WB-20 [WB-67] design vehicle discussed above. This variation, shown in Figure C-8, has the rear trailer axles pulled for-

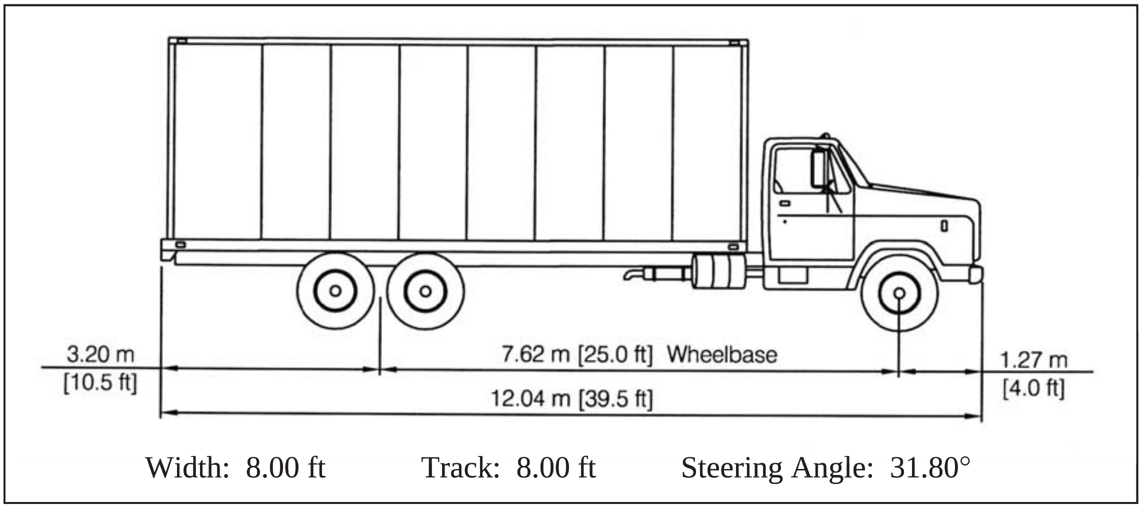
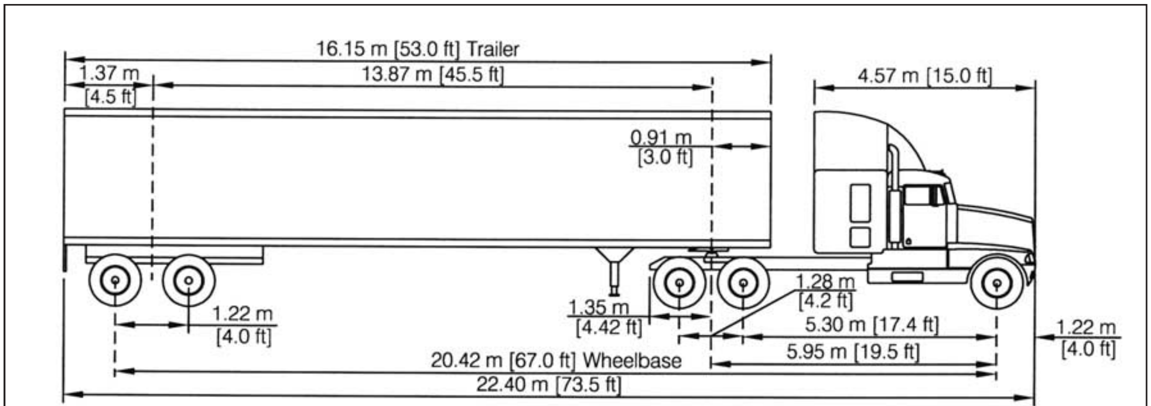


Figure C-6. Single unit truck.



Tractor Width: 8.00 ft
Tractor Track: 8.00 ft

Trailer Width: 8.50 ft
Trailer Track: 8.50 ft

Steering Angle: 28.40°
Articulating Angle: 75.00°

Figure C-7. WB-20 [WB-67] tractor-semitrailer.

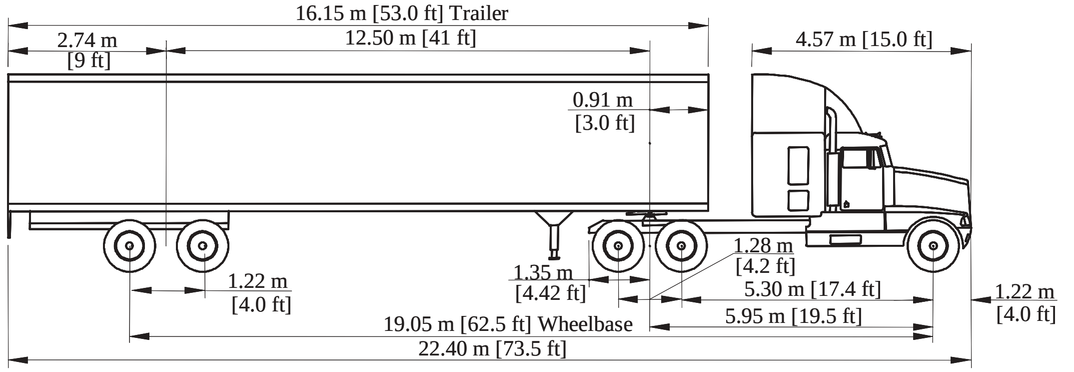
ward to a KCRT distance of 12.5 m [41 ft], which is the maximum permitted KCRT distance permitted in many states. Pulling the rear axles forward creates a rear overhang of 2.7 m [9 ft].

WB-22 [WB-71] Tractor-Semitrailer

Another vehicle considered for possible future inclusion in the *Green Book* is the WB-22 [WB-71] design vehicle. This vehicle is a tractor-semitrailer configuration with a 17.34 m [57 ft] trailer (see Figure C-9). The rear axles are located at the extreme rear of the trailer, with a KCRT distance of 15.1 m [49.5 ft]. The minimum centerline turning radius of this WB-22 [WB-71] tractor-semitrailer configuration is 12.7 m [41.5 ft].

WB-22 [WB-71]: Tractor-Semitrailer—12.5 m [41 ft] KCRT Distance

A variation of the WB-22 [WB-71] design vehicle was also investigated. This variation, shown in Figure C-10, has the rear axles pulled forward to a KCRT distance of 12.5 m [41 ft], which is the maximum permitted KCRT distance in many states. Pulling the rear axles forward creates a rear overhang of 4.0 m [13 ft].

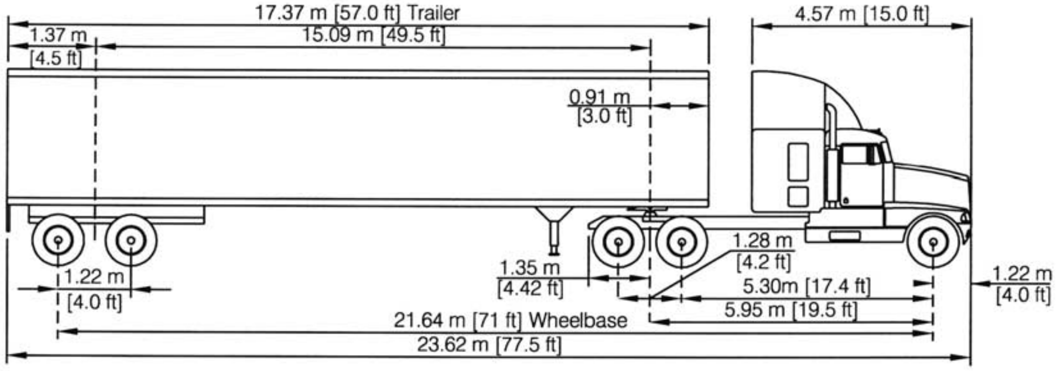


Tractor Width: 8.00 ft
Tractor Track: 8.00 ft

Trailer Width: 8.50 ft
Trailer Track: 8.50 ft

Steering Angle: 28.40°
Articulating Angle: 75.00°

Figure C-8. WB-20 [WB-67] tractor-semitrailer—12.5 m [41 ft] KCRT distance.



Tractor Width: 8.00 ft	Trailer Width: 8.50 ft	Steering Angle: 28.40°
Tractor Track: 8.00 ft	Trailer Track: 8.50 ft	Articulating Angle: 75.00°

Figure C-9. WB-22 [WB-71] tractor-semitrailer.

WB-23D [WB-77D]: Double-Trailer Combination with Twin 10.1-m [33-ft] Trailers

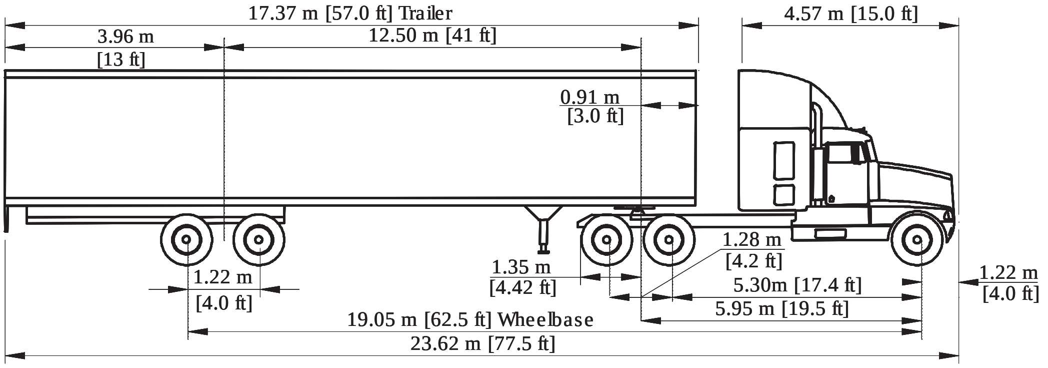
This double-trailer combination for possible future inclusion in the *Green Book* has an overall length of 24.8 m [81.5 ft] with two 10.1-m [33-ft] trailers (see Figure C-11). It has tandem axles at both the front and rear of each trailer. The KCRT distance is 8.0 m [26.5 ft]. It has a minimum centerline turning radius of 13.7 m [45.0 ft].

WB-37D [WB-120D]: Turnpike Double Combination with Two 16.2 m [53 ft] Trailers

This Turnpike Double combination for possible future inclusion in the *Green Book* has an overall length of 39.3 m [129.3 ft] with two 16.2 m [53 ft] trailers (see Figure C-12). It has tandem axles at both the front and rear of each trailer. The KCRT distance is 12.5 m [41 ft]. It has a minimum centerline turning radius of 23.8 m [78.0 ft].

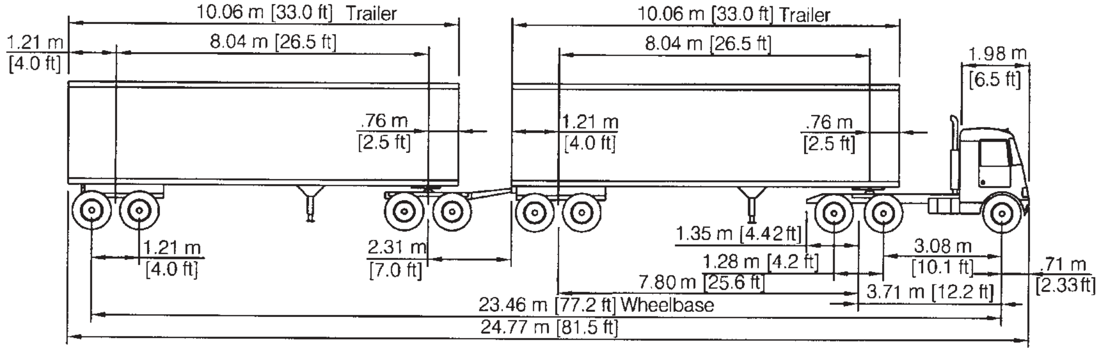
WB-28D (WB-92D): Rocky Mountain Double Trailer Combination

This double-trailer combination recommended for inclusion in the *Green Book* has an overall length of 30.0 m [98.3 ft] (see Figure C-13). The first trailer has a length of 14.6 m [48.0 ft], while the second trailer has a length of 8.7 m [28.5 ft]. The first trailer has tandem axles at both the front and rear of the trailer, while the second trailer has single axles at both the front and



Tractor Width: 8.00 ft	Trailer Width: 8.50 ft	Steering Angle: 28.40°
Tractor Track: 8.00 ft	Trailer Track: 8.50 ft	Articulating Angle: 75.00°

Figure C-10. WB-22 [WB-71]: Tractor-semitrailer: 12.5 m [41 ft] KCRT distance.

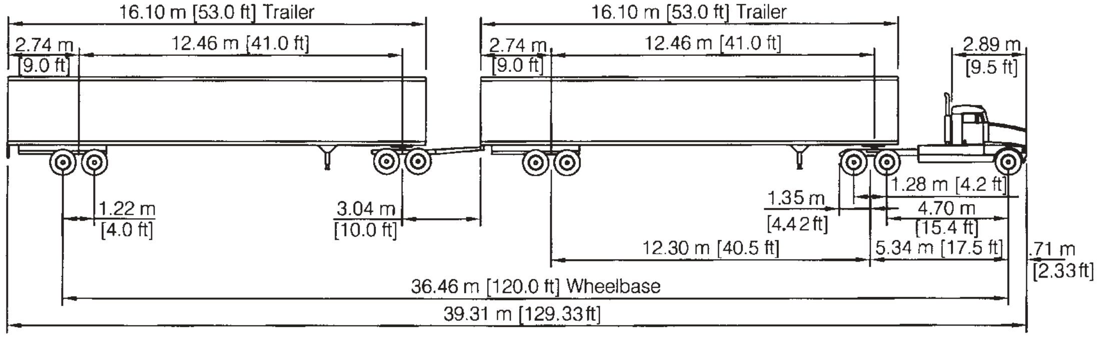


Tractor Width: 8.00 ft
Tractor Track: 8.00 ft

Trailer Width: 8.50 ft
Trailer Track: 8.50 ft

Steering Angle: 15.60°
Articulating Angle: 70.00°

Figure C-11. WB-23D [WB-77D] double trailer combination.

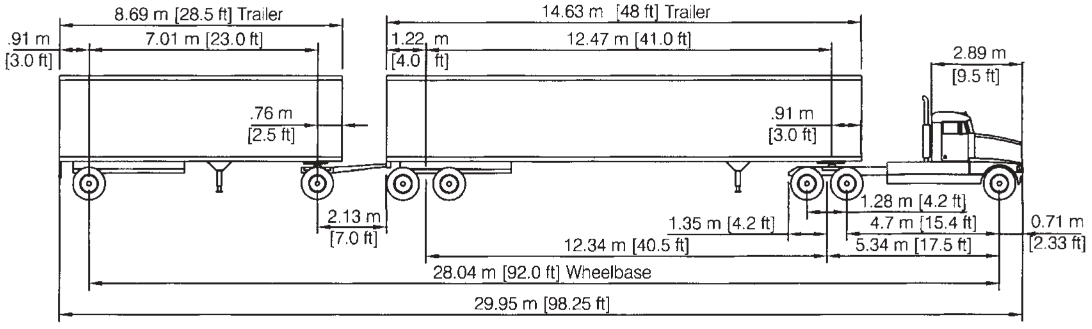


Tractor Width: 8.00 ft
Tractor Track: 8.00 ft

Trailer Width: 8.50 ft
Trailer Track: 8.50 ft

Steering Angle: 12.60°
Articulating Angle: 70.00°

Figure C-12. WB-37D [WB-120D] double trailer combination.



Tractor Width: 8.00 ft
Tractor Track: 8.00 ft

Trailer Width: 8.50 ft
Trailer Track: 8.50 ft

Steering Angle: 12.60°
Articulating Angle: 70.00°

Figure C-13. WB-28D [WB-92D] double trailer combination.

rear of the trailer. It has a minimum centerline turning radius of 23.8 m [78.0 ft].

WB-23BD [WB-75BD]: B-Train Double-Trailer Combination

This B-train double trailer combination for potential future inclusion in the *Green Book* has an overall length of 24.2 m [79.5 ft] (see Figure C-14). A B-train combination has a first trailer with a fifth wheel mounted on a dolly at the rear. The second trailer is a semitrailer that rests on the fifth wheel attached to the first trailer. The length of the first trailer is 8.5 m [28.0 ft], and the length of the second trailer is 9.6 m [31.5 ft]. It has a minimum turning radius of 12.07 m [39.6 ft]. The dimensions of this proposed truck are similar to those found in the Geometric Design Guide for Canadian Roads *(16)*.

SUMMARY OF INPUT PARAMETERS FOR VEHICLES CONSIDERED

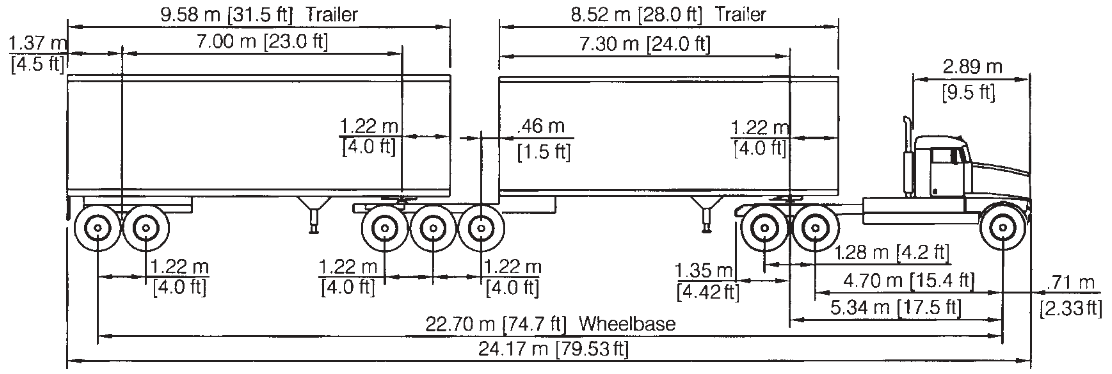
Table C-1 presents a summary of the input parameters of each vehicle modeled within AutoTURN. The top portion of the table provides the input parameters for selected design vehicles from the 2001 *Green Book*, while the bottom portion of the table provides the input parameters for the proposed new design vehicles.

PHASE II—MODELING OF MINIMUM 180-DEGREE TURNS

In Phase II, 180-degree turns with minimum turning radii were modeled for seven vehicles being considered for possible inclusion in the *Green Book*. These vehicles included the seven SU-8 [SU-25], WB-20 [WB-67], WB-22 [WB-71], WB-23D [WB-77D], WB-37D [WB-120D], WB-28D [WB-92D], and WB-23BD [WB-75BD] design vehicles. The capabilities of these seven vehicles to negotiate 180-degree turns at minimum turning radii are presented in Figures C-15 to C-21. The figures show the centerline turning radius of the front axle, the minimum turning radius of the driver's side front tire, the minimum distance between center of the turning radius and the path of the rear axle set, and the maximum distance between the center of the turning radius and the path of the front overhang. Figures C-15 to C-21 can be used in future versions of the *Green Book* if a decision is made to add these design vehicles.

Minimum 180-degree turns were not modeled for two of the proposed new design vehicles presented earlier in this appendix, the WB-20 [WB-67] and WB-22 [WB-71] with KCRT distances of 12.5 m [41 ft]. These trucks have nearly identical turning performance to the very similar turning capabilities of the WB-19 [WB-62] design vehicle, so no separate turning plots are needed. The revised WB-19 [WB-62] design vehicle proposed for future use in the *Green Book* also has a KCRT distance of 12.5 m [41 ft].

Table C-2 summarizes the critical turning parameters shown in Figures C-15 to C-21. For comparative purposes, Table C-2 also summarizes these same critical turning parameters for the single unit truck (SU), WB-19 (WB-62) tractor-semitrailer, WB-20D (WB-67D) double trailer, and WB-33B (WB-109D) double trailer design vehicles from the 2001 *Green Book*. The results are presented by vehicle classification: single unit, tractor-semitrailer, and double trailer combination. When comparing the turning characteristics of the respective vehicles in the different vehicle classes, several points are worth noting:



Tractor Width: 8.00 ft	Trailer Width: 8.50 ft	Steering Angle: 29.50°
Tractor Track: 8.00 ft	Trailer Track: 8.50 ft	Articulating Angle: 70.00°

Figure C-14. WB-23BD [WB-75BD] double trailer combination.

TABLE C-1 Input parameters of vehicles considered in turning performance evaluation

Design Vehicles	Width and Track of Tractor (A)	Width and Track of Trailer (B)	Overall Length (C)	Overall Wheelbase (D)	Cab Length (E)	Front Overhang (F)	Steer Axle to 2nd Axle Set (G)	King Pin to Rear Axle Set (H)	2nd Axle Set to 3rd Axle Set (I)	3rd Axle Set to 4th Axle Set (J)	4th Axle Set To 5th Axle Set (K)	Rear Overhang of 1st Trailer (L)	Rear Overhang of 2nd Trailer (M)	Overall Length of 1st Trailer (N)	Overall Length of 2nd Trailer (O)	Min. Centerline Turning Radius of Front Axle (P)	Max. Steering Angle (Degrees) (Q)	Max. Articulating Angle (Degrees) (R)
AASHTO 2001 Green Book Design Vehicles																		
SU	8		30	20		4	20					6				38.0	31.7	
WB-62	8	8.5	68.5	62	15	4	19.5	40.5	40.5			4.5		48		41.0	28.4	65
WB-67D	8	8.5	72.33	67	6.5	2.33	11	23	23	10	23	3	3	28.5	28.5	41.0	15.7	70
WB-109D	8	8.5	114.03	109.2	6.5	2.33	12.2	40.5	40.0	14.5	40.5	4.5	4.5	48	48	56.0	12.7	70
Possible New Design Vehicles																		
SU-25	8		39.5	25		4	25					10.5				47.5	31.8	
WB-67	8	8.5	73.5	67	15	4	19.5	45.5	45.5			4.5		53		41.0	28.4	75
WB-67 (41 ft KCRT)	8	8.5	73.5	62.5	15	4	19.5	41	41			9		53		41.0	28.4	75
WB-71	8	8.5	77.5	71	15	4	19.5	49.5	49.5			4.5		57		41.5	28.4	75
WB-71 (41 ft KCRT)	8	8.5	77.5	62.5	15	4	19.5	41	41			13		57		41.0	28.4	75
WB-77D	8	8.5	81.50	77.2	6.5	2.33	12.2	26.5	25.5	11	26.5	4	4	33	33	45.0	15.6	70
WB-120D	8	8.5	129.33	120.0	9.5	2.33	17.5	41	40.5	19	41	9	9	53	53	78.0	12.6	70
WB-92D	8	8.5	98.25	92.0	9.5	2.33	17.5	41	40.5	11	23	4	3	48	28.5	78.0	12.6	70
WB-75BD	8	8.5	79.53	74.53	9.5	2.33	17.5	29.5	29.5	31	27.7		4.5	28	31.5	39.6	29.5	70

A – Width and track of tractor or vehicle body if SU.
B – Width and tract of trailer body.
C – Overall length of vehicle, measured from front bumper to rear bumper.
D – Overall length of wheelbase, measured from center of steering axle to center of rear axle.
E – Length of cab, measured from front bumper to rear of cab.
F – Front overhang, measured from front bumper to center of steering axle.
G – Distance between center of steer axle to center of second axle group.
H – Distance from kingpin to center of rear axle group
I – Distance between center of second axle group to center of third axle group.
J – Distance between center of third axle group to center of fourth axle group.
K – Distance between center of fourth axle group to center of fifth axle group.
L – Rear overhang on first trailer or first vehicle, measured from center of rear axle group to rear bumper.
M – Rear overhang on second trailer, measured from center of rear axle group to rear bumper.
N – Overall length of first trailer.
O – Overall length of second trailer.
P – Minimum centerline turning radius of front axle.
Q – Maximum steering angle.
R – Maximum articulating angle.
NOTE: All lengths and widths are in feet.

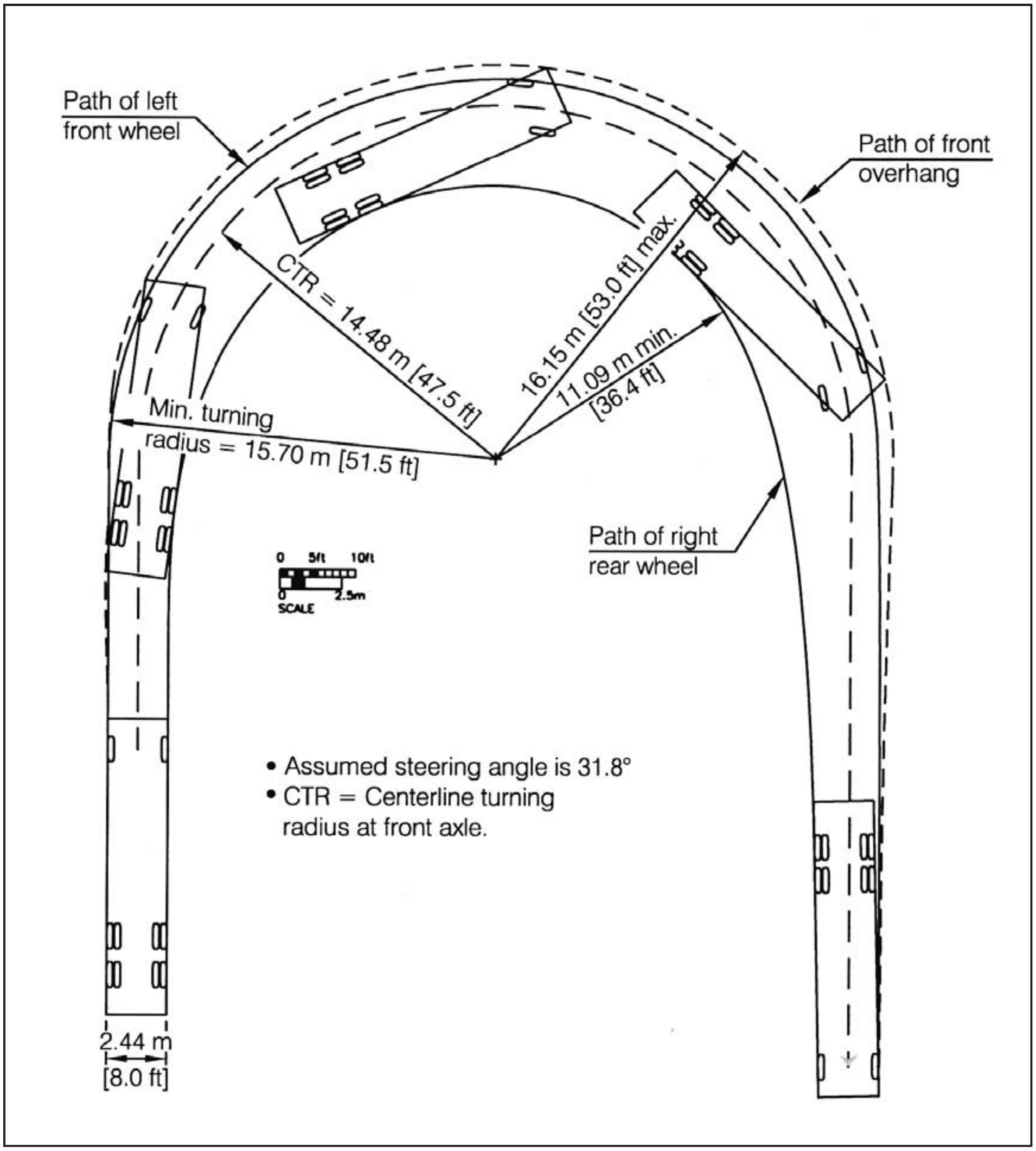


Figure C-15. Minimum 180º turn: single unit truck.

Single Unit Vehicles

- The minimum turning radius of the proposed single unit design vehicle is 2.9 m [9.5 ft] greater than the minimum turning radius of the single unit design vehicle in the 2001 *Green Book*.
- The difference between the minimum turning radius and the maximum distance to the path of the front overhang is equivalent for both vehicles.
- The minimum distance between the path of the rear axle set and the center of the turn is greater for the proposed single unit design vehicle than the single unit design vehicle in the 2001 *Green Book*.
- The difference between minimum turning radius and the minimum distance between the path of the rear axle set and the center of the turn is greater for the proposed single unit design vehicle than for the single unit design vehicle in the 2001 *Green Book* which indicates that the

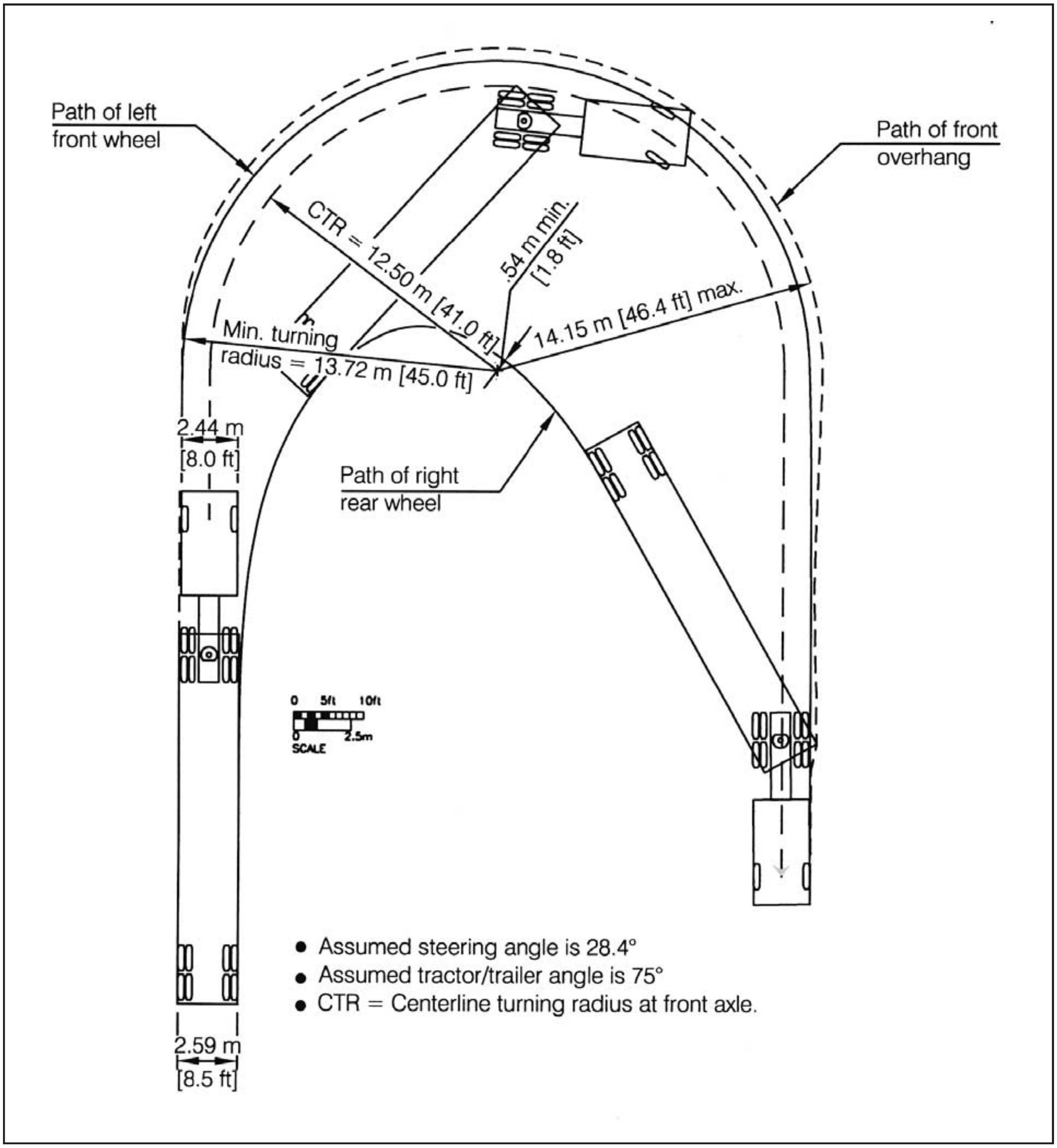
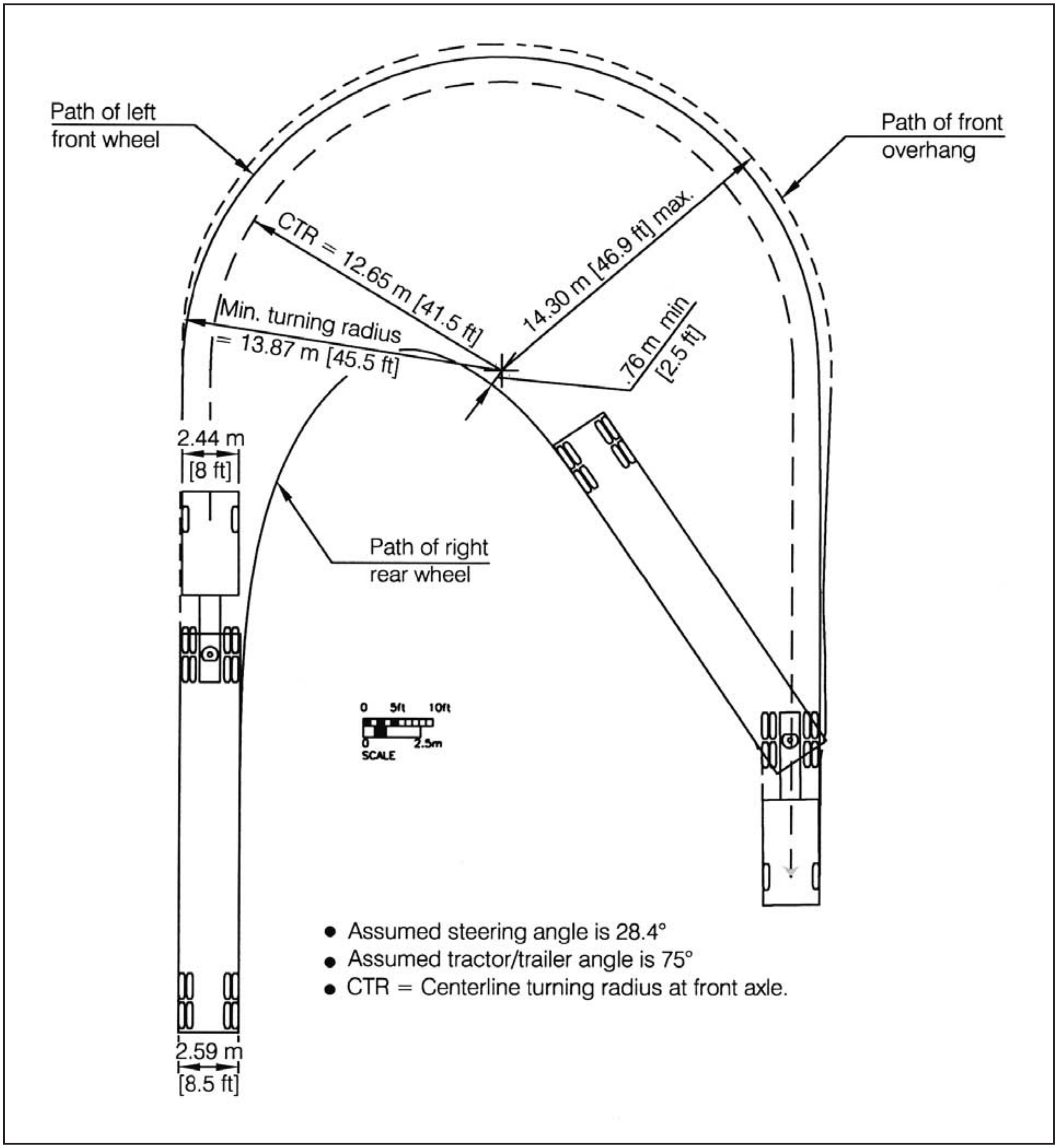


Figure C-16. Minimum 180º turn: WB-20 [WB-67] tractor-semitrailer.

proposed single unit design vehicle has greater offtracking and a wider swept path width than the single unit design vehicle in the 2001 *Green Book*.

Tractor-Semitrailers

- The minimum turning radius of the proposed WB-22 [WB-71] design vehicle is 0.15 m [0.5 ft] greater than the turning radii of the other tractor-semitrailer design vehicles, but for practical purposes the minimum turning radii of all the proposed tractor-semitrailer design vehicles and the WB-19 [WB-62] design vehicle in the 2001 *Green Book* are equivalent. Direct calculations of the minimum turning radii for all tractor-semitrailers (as per Figure C-5) indicates a minimum turning radii of 13.7 m [45 ft] for all tractor-semitrailers.



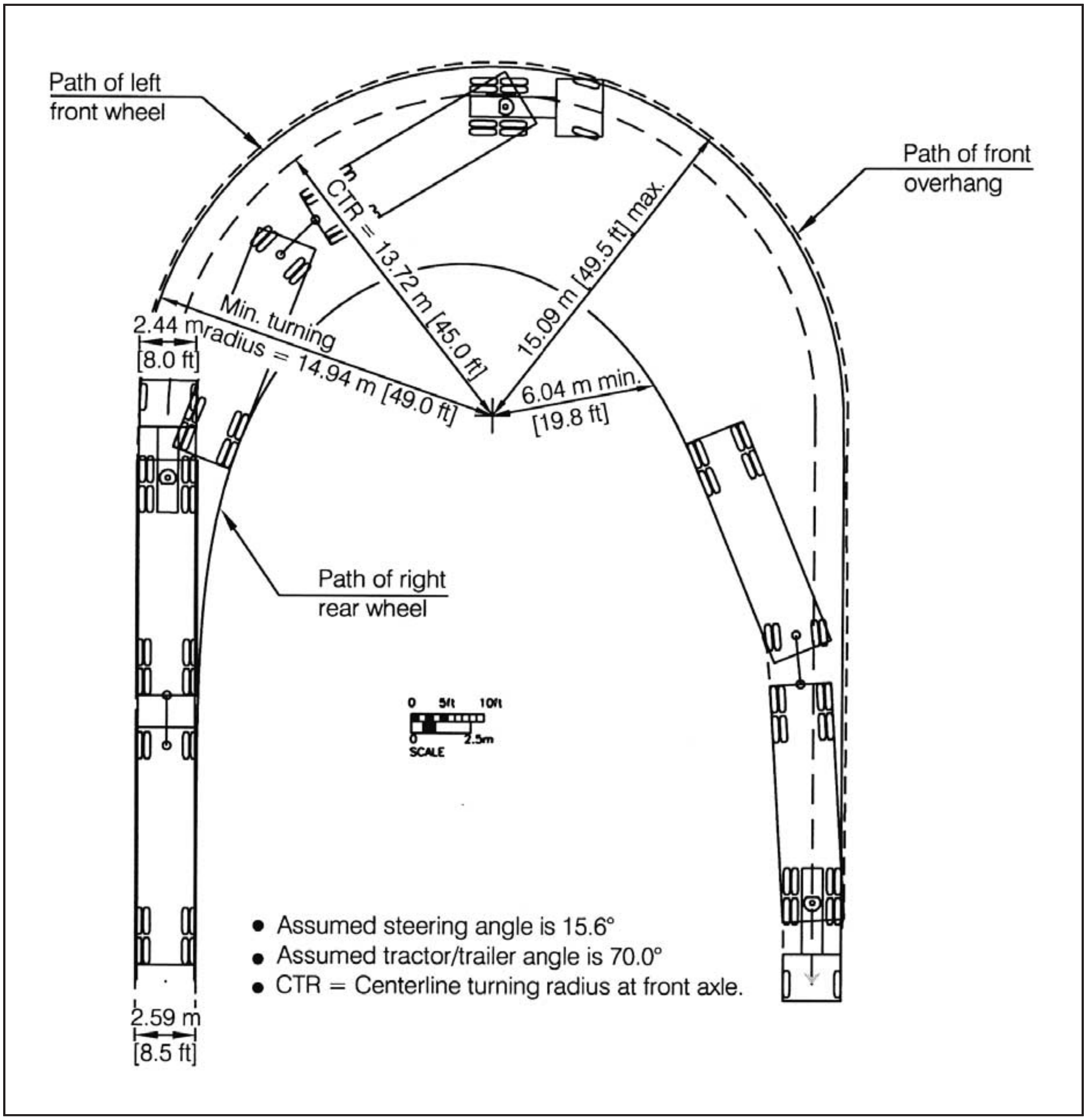
- Assumed steering angle is 28.4°
- Assumed tractor/trailer angle is 75°
- CTR = Centerline turning radius at front axle.

Figure C-17. Minimum 180º turn: WB-22 [WB-71] tractor-semitrailer.

Although the minimum turning radii for all the tractor-semitrailers are approximately equivalent, the longer wheelbases of the WB-20 [WB-67] and the WB-22 [WB-71] proposed design vehicles result in considerably smaller minimum distances between the path of the rear axle set and the center of the turn for these two vehicles compared to the other tractor-semitrailer combinations. In fact, the rear axle set of the WB-22 [WB-71] tracks on the inside of the turning center.

Double Trailer Combinations

- The proposed WB-37D [WB-120D] and WB-28D [WB-92D] design vehicles have significantly greater minimum turning radii compared to the other double trailer combinations.
- There is a wide range in the minimum distances between the path of the rear axle set and the center of the turn for



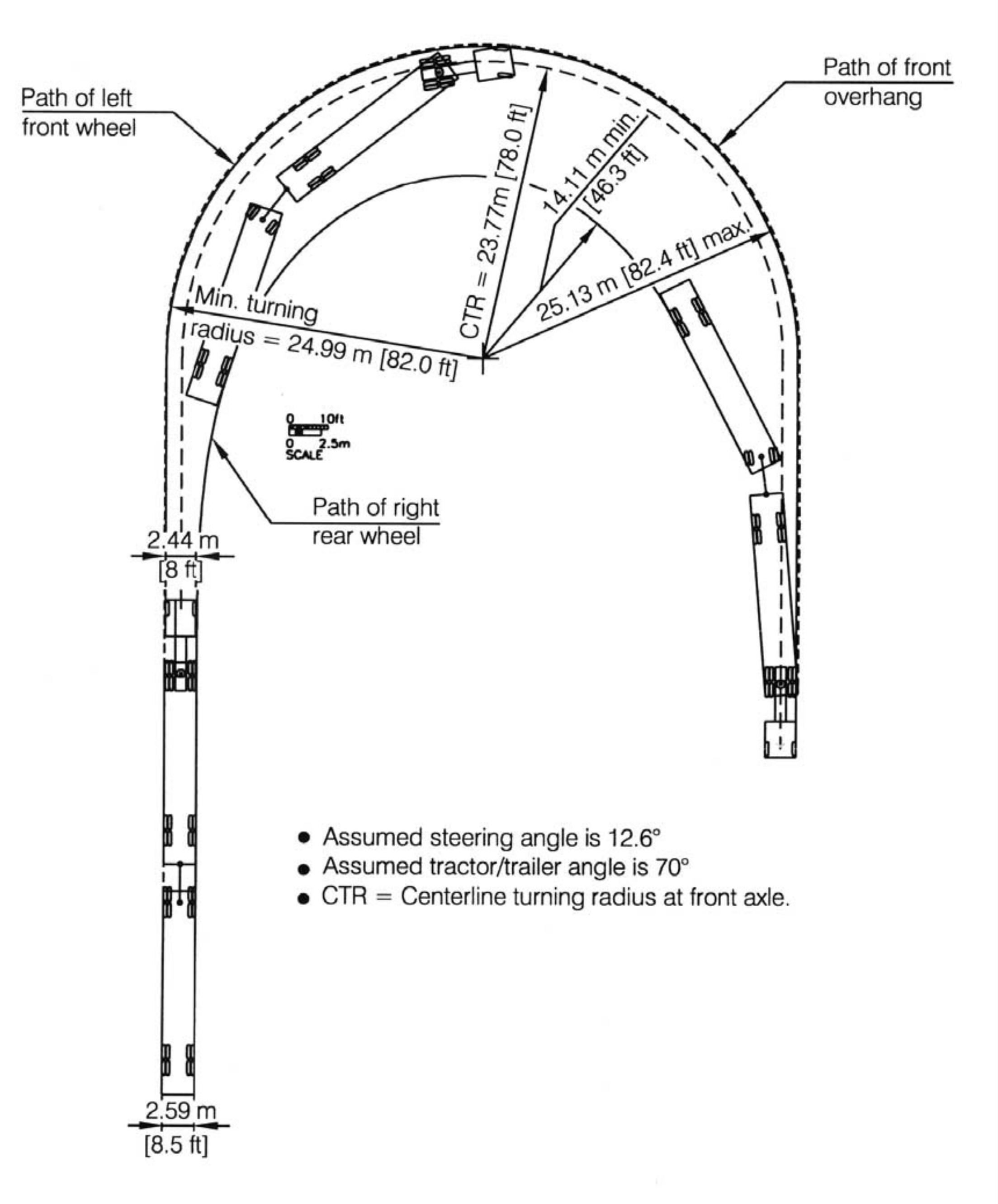
- Assumed steering angle is 15.6°
- Assumed tractor/trailer angle is 70.0°
- CTR = Centerline turning radius at front axle.

Figure C-18. Minimum 180º turn: WB-23D [WB-77D] double trailer combination.

the double trailer combinations, with a minimum of 2.36 m [7.7 ft] and a maximum of 16.9 m [55.4 ft].

PHASE III—MODELING OF 90-DEGREE TURNS

Phase III consisted of modeling 90-degree right turns with centerline turning radii of 15.2, 22.9, 30.5, and 45.7 m (50, 75, 100, and 150 ft) and comparing the capabilities of the proposed design vehicles as they negotiated through the respective turns to the capabilities of similar design vehicles in the 2001 *Green Book*. The parameters of specific interest in this sensitivity analysis included maximum offtracking, swept path width, and rear swingout. These parameters were measured directly from turning path plots generated by AutoTURN. The procedures for measuring the three parameters from the plots are described, and the results are then presented by vehicle classification: single unit, tractor-semitrailer, and double trailer combination.



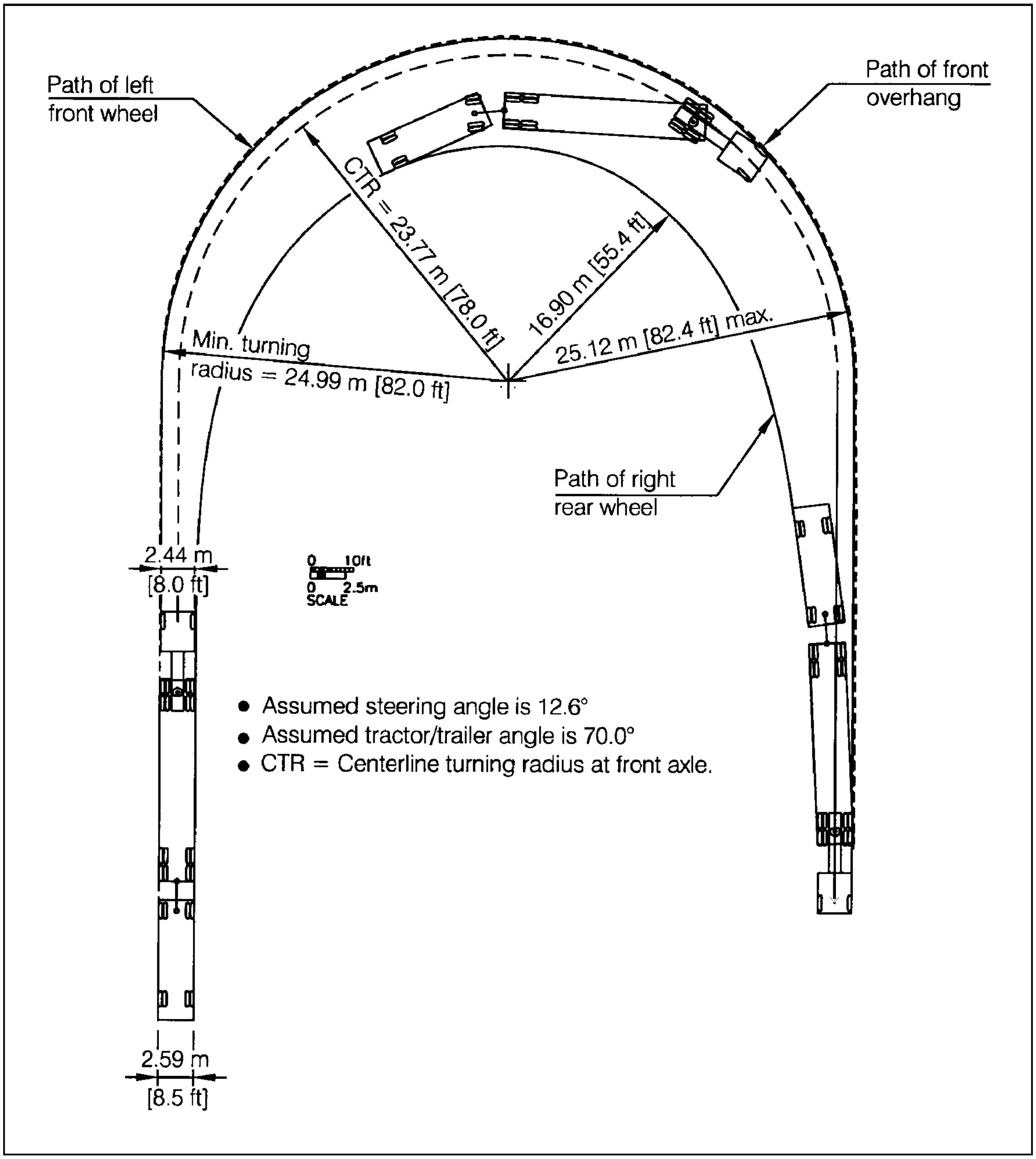
- Assumed steering angle is 12.6°
- Assumed tractor/trailer angle is 70°
- CTR = Centerline turning radius at front axle.

Figure C-19. Minimum 180º turn: WB-37D [WB-120D] double trailer combination.

Estimating Maximum Offtracking

Offtracking is defined as the radial offset between the path of the centerline of the front axle of the tractor and the path of the centerline of the rearmost trailer axle set. There are two types of offtracking, referred to as low-speed and high-speed offtracking. This analysis focuses on low-speed offtracking which occurs as vehicles traverse horizontal curves at low speed.

To estimate the maximum offtracking as a vehicle negotiates a 90-degree right turn, the path of the center of the front tractor axle (steering axle) is specified and the path of the inside rear axle set of the trailer generated by AutoTURN. Figure C-22 provides an example of one of the turning path plots. The example shows the proposed WB-23D [WB-77D] double trailer combination negotiating a 90-degree turn with a 15.2 m [50 ft] turning radius. The figure also shows the paths of other vehicle parts. The offtracking was quantified



- Assumed steering angle is 12.6°
- Assumed tractor/trailer angle is 70.0°
- CTR = Centerline turning radius at front axle.

Figure C-20. Minimum 180° turn: WB-28D [WB-92D] double trailer combination.

by bringing the AutoTURN plot into AutoCAD and scaling the appropriate distances. The largest radial distance between the two paths (that of the center of the front axle and that of the inside rear axle set) was scaled. Measurements were taken along the entire length of the curve until a maximum radial distance was determined. In Figure C-22, several of the actual measurements are displayed with the maximum distance shown with a box around it. Since offtracking is measured to the centerline of both the front and rear axle set, half the width of the rear axle set was subtracted from the measured radial distance to provide an estimate of the maximum offtracking. For example, the tractor-semitrailers and the double trailer combinations had 2.6 m [8.5 ft] wide trailers. Therefore, 1.3 m [4.25 ft] was subtracted from the measured radial distance to determine the maximum offtracking of these vehicle types, while 1.2 m [4.0 ft] was subtracted for the single unit trucks. Thus, for the given example of the proposed WB-23D [WB-77D] design vehicle negotiating a 90-degree turn with a 15.2 m [50 ft] radius, the maximum offtracking is 4.3 m [14.2 ft].

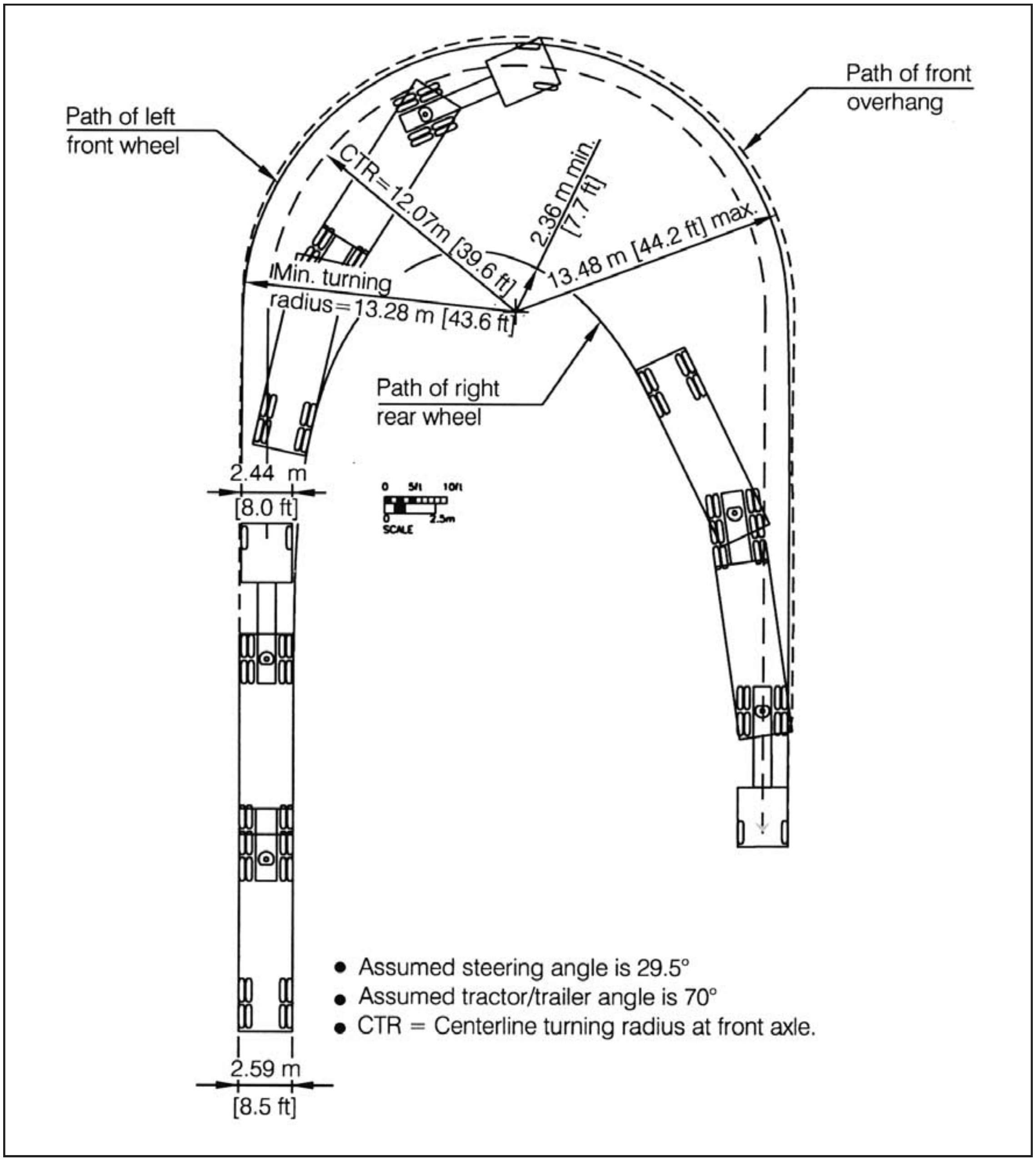


Figure C-21. Minimum 180º turn: WB-23BD [WB-75BD] double trailer combination.

Estimating Maximum Swept Path Width

Swept path width is defined as the radial distance between the two paths of the outside front tractor tire and the inside rear axle set of the trailer. Conceptually, the maximum swept path width of a vehicle negotiating a turn occurs at the same location as the maximum offtracking. Thus, to estimate the maximum swept path width, half the width of the front tractor axle and half the width of the rearmost trailer axle were added to the maximum offtracking estimate. Continuing with the given example of the proposed WB-23D [WB-77D] design vehicle negotiating a 90-degree turn with a 15.2 m [50 ft] radius, the maximum offtracking is 4.3 m [14.2 ft]. Half the width of the front tractor axle is 1.2 m [4.0 ft], and half the width of the rear trailer axle is 1.3 m [4.25 ft]. Thus, the maximum swept path width for the proposed WB-23D [WB-77D] design vehicle under the given scenario is 6.8 m [22.4 ft].

Estimating Maximum Rear Swingout

The rear of a trailer generally overhangs the rear axle set. During a turn the rear of the trailer swings to the outside of

TABLE C-2 Summary of minimum 180-degree turning capabilities

Design vehicles	Minimum turning radius (ft)	Maximum distance to path of front overhang (ft)	Minimum distance between path of rear axle set and center of turn (ft)
Single Unit Vehicles			
SU-25	51.5	53.0	36.4
SU	42.0	43.5	28.3
Tractor-Semitrailers			
WB-67	45.0	46.4	1.8
WB-67* (41 ft KCRT)	45.0	46.4	7.9
WB-71	45.5	46.9	2.5**
WB-71* (41 ft KCRT)	45.0	46.4	7.9
WB-62	45.0	46.4	7.9
Double Trailer Combinations			
WB-77D	49.0	49.5	19.8
WB-120D	82.0	82.4	46.3
WB-92D	82.0	82.4	55.4
WB-75BD	43.6	44.2	7.7
WB-67D	45.0	45.5	19.3
WB-109D	60.0	60.4	14.9

* Measurements same as for WB-62 in 2001 *Green Book*
** Measured to the inside of the center of the turning radius

the path of the rear axle set. This rear swingout is a function of the trailer wheelbases, the radius of the turn, and other dimensions of the vehicle. The procedures for estimating the maximum rear swingout were slightly different than for estimating the maximum offtracking and swept path width. Conceptually, maximum rear swingout is the maximum radial distance between the path of the outside rear axle set and the path of the outside rear corner of the trailer. AutoTURN is able to trace the path of the rear axle set of the trailer as it negotiates a turn but is unable to trace the path of the outside rear portion of the trailer. Therefore, it is not feasible to measure the radial distance between the continuous paths of the respective portions of a vehicle. However, AutoTURN has a function that draws vehicles at different intervals along the curve. Using this function, vehicles were drawn at very small intervals (i.e., 10 percent of the vehicle length) through the entire curve. These drawings showed the location of the outside rear corner of the trailer with respect to the path of the rear axle set and enabled measurement of the rear swingout. This procedure introduces some error in the measurement of the rear swingout because distances are not measured between continuous paths of the respective portions of the vehicle, but drawing the vehicles at very small intervals minimized this error. Figure C-23 illustrates measurement of the rear swingout for the WB-19 [WB-62] design vehicle while negotiating a 90-degree turn with a 15.2-m [50-ft] radius. The upper left portion of the figure shows vehicles drawn at various intervals along the same curve. The bottom right portion of the figure is a close-up of the rear portion of the vehicle at a particular location/instant along the curve and shows the radial distance between the path of the outside rear axle set and the location of the outside rear of the trailer.

Summary of Results

This section presents a summary of the turning performance results. The results are presented by vehicle classification. Table C-3 provides a comparison of turning capabilities of the proposed single unit design vehicle to the single unit design vehicle in the 2001 *Green Book*. Table C-4 provides a comparison of the turning capabilities of the proposed tractor-semitrailer combinations to that of the WB-19 [WB-62] design vehicle. Table C-5 provides a comparison of the turning capabilities of the proposed double trailer combinations to those of the WB-20D [WB-67D] and WB-33D [WB-109D] design vehicles in the 2001 *Green Book.*

When comparing the turning characteristics of the respective vehicles while negotiating 90-degree turns with various turning radii, several points are worth noting:

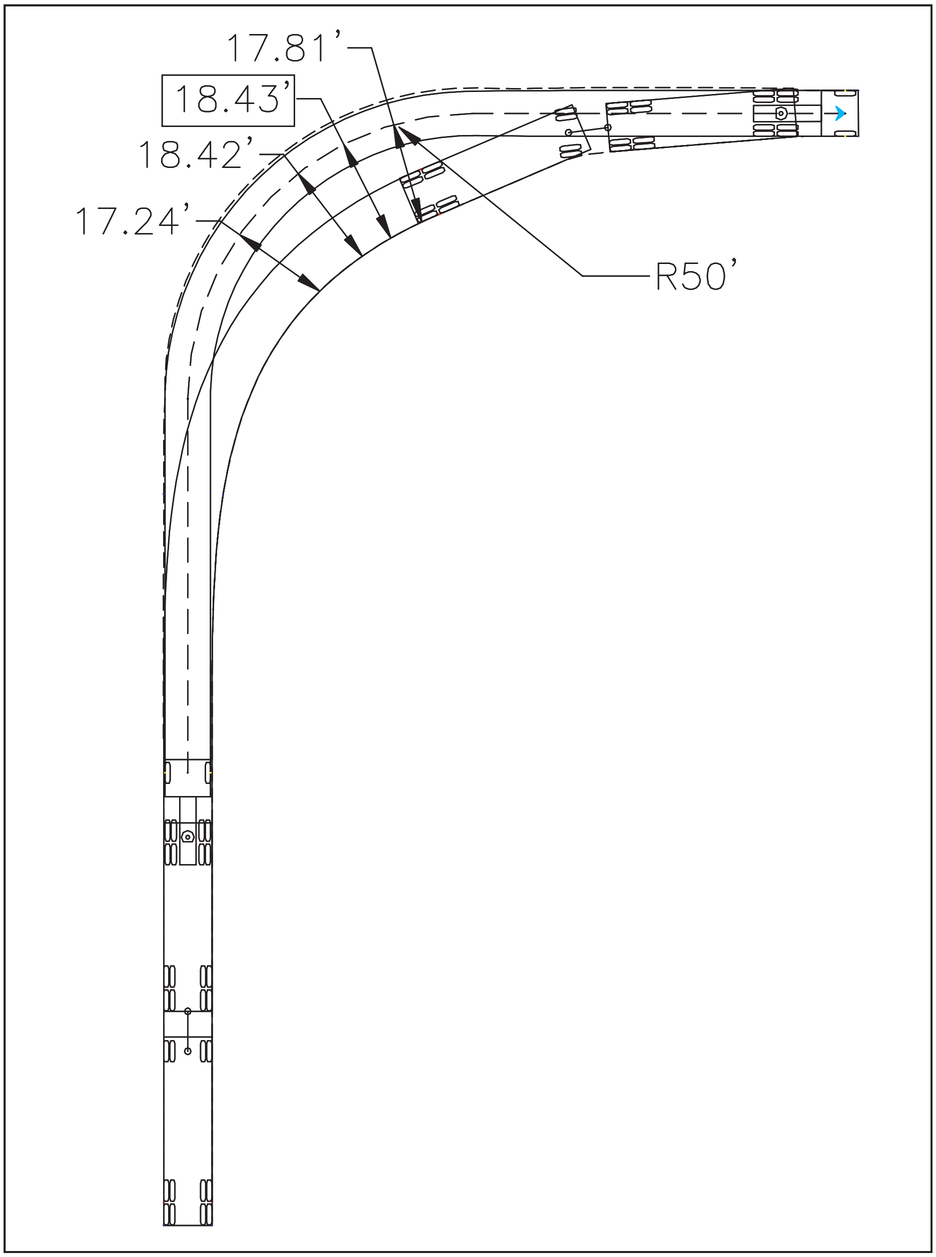


Figure C-22. Sample offtracking estimates.

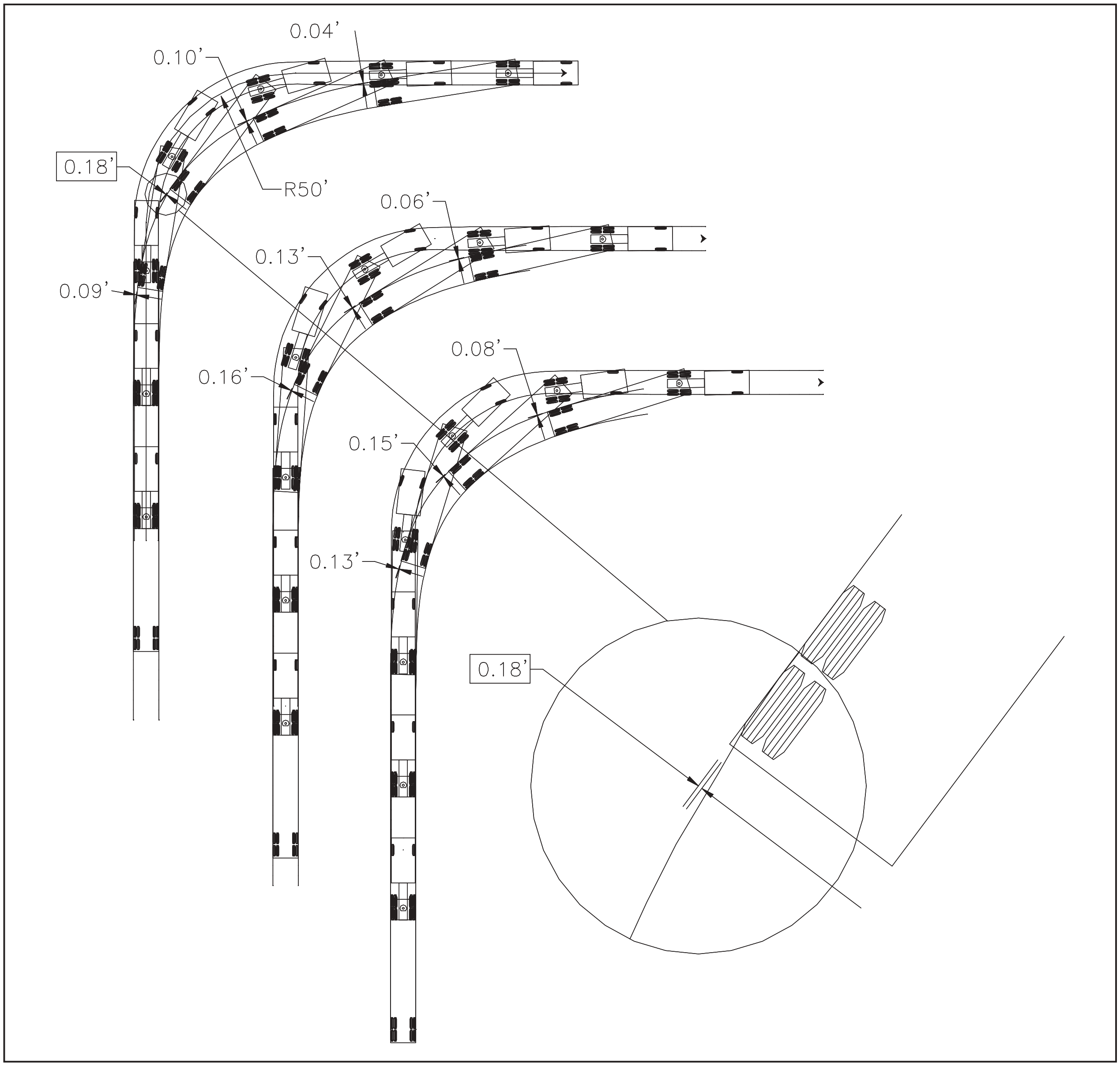


Figure C-23. Sample rear swingout estimates.

TABLE C-3 Turning capabilities of selected single-unit trucks

		Design vehicle	
Turning capabilities		Proposed design vehicle Single Unit (SU) Wheelbase = 25 ft	2001 *Green Book* Single Unit (SU) Wheelbase = 20 ft
Minimum turning radius		47.5 ft	38.0 ft
Maximum Offtracking	50 ft turning radius[a]	6.13 ft	3.80 ft
	75 ft turning radius	4.26 ft	2.74 ft
	100 ft turning radius	3.21 ft	1.81 ft
	150 ft turning radius	2.13 ft	1.12 ft
Maximum Swept Path Width	50 ft turning radius	14.13 ft	11.80 ft
	75 ft turning radius	12.26 ft	10.74 ft
	100 ft turning radius	11.21 ft	9.81 ft
	150 ft turning radius	10.13 ft	9.12 ft
Maximum Rear Swingout	50 ft turning radius	1.07 ft	0.35 ft
	75 ft turning radius	0.73 ft	0.24 ft
	100 ft turning radius	0.53 ft	0.18 ft
	150 ft turning radius	0.35 ft	0.12 ft

[a] Centerline turning radius.

TABLE C-4 Turning capabilities of selected tractor-semitrailer combinations

Turning capabilities		Design vehicle				
		Proposed design vehicle				2001 *Green Book*
		WB-67	WB-67 (41 ft KCRT)	WB-71	WB-71 (41 ft KCRT)	WB-62
Minimum turning radius		41.0 ft	41.0 ft	41.5 ft	41.0 ft	41.0 ft
Maximum Offtracking	50 ft turning radius[a]	19.38 ft	17.02 ft	21.51 ft	17.02 ft	16.76 ft
	75 ft turning radius	15.10 ft	13.06 ft	17.01 ft	13.06 ft	12.83 ft
	100 ft turning radius	12.08 ft	10.32 ft	13.75 ft	10.32 ft	10.12 ft
	150 ft turning radius	8.34 ft	7.04 ft	9.60 ft	7.04 ft	6.90 ft
Maximum Swept Path Width	50 ft turning radius	27.63 ft	25.27 ft	29.76 ft	25.27 ft	25.01 ft
	75 ft turning radius	23.35 ft	21.31 ft	25.26 ft	21.31 ft	21.08 ft
	100 ft turning radius	20.33 ft	18.57 ft	22.00 ft	18.57 ft	18.37 ft
	150 ft turning radius	16.59 ft	15.29 ft	17.85 ft	15.29 ft	15.15 ft
Maximum Rear Swingout	50 ft turning radius	0.17 ft	0.69 ft	0.17 ft	1.45 ft	0.18 ft
	75 ft turning radius	0.14 ft	0.51 ft	0.13 ft	1.08 ft	0.14 ft
	100 ft turning radius	0.10 ft	0.41 ft	0.10 ft	0.84 ft	0.09 ft
	150 ft turning radius	0.07 ft	0.27 ft	0.07 ft	0.61 ft	0.06 ft

[a] Centerline turning radius.

TABLE C-5 Turning capabilities of select double-trailer combinations

Turning capabilities		Design vehicle					
		Proposed design Vehicle				2001 *Green Book*	
		WB-77D	WB-120D	WB-92D	WB-77BD	WB-67D	WB-109D
Minimum turning radius		49.0	82.0 ft	82.0 ft	43.5 ft	45.0 ft	60.0 ft
Maximum Offtracking	50 ft turning radius[a]	14.18 ft	***	***	15.63 ft	11.47 ft	***
	75 ft turning radius	10.56 ft	***	***	11.70 ft	8.31 ft	***
	100 ft turning radius	8.16 ft	17.87 ft	12.71 ft	9.10 ft	6.31 ft	17.05 ft
	150 ft turning radius	5.45 ft	12.59 ft	8.73 ft	6.10 ft	4.20 ft	11.97 ft
Maximum Swept Path Width	50 ft turning radius	22.43 ft	***	***	23.88 ft	19.72 ft	***
	75 ft turning radius	18.81 ft	***	***	19.95 ft	16.56 ft	***
	100 ft turning radius	16.41 ft	26.12 ft	20.96 ft	17.35 ft	14.56 ft	25.30 ft
	150 ft turning radius	13.70 ft	20. 84 ft	16.98 ft	14.35 ft	12.45 ft	19.22 ft
Maximum Rear Swingout	50 ft turning radius	0.13 ft	***	***	0.17 ft	0.08 ft	***
	75 ft turning radius	0.11 ft	***	***	0.12 ft	0.05 ft	***
	100 ft turning radius	0.08 ft	0.37 ft	0.05 ft	0.10 ft	0.05 ft	0.09 ft
	150 ft turning radius	0.06 ft	0.27 ft	0.04 ft	0.07 ft	0.03 ft	0.06 ft

*** Vehicle unable to negotiate a turn with the respective turning radius.

[a] Centerline turning radius.

- The greatest differences in the turning characteristics between the respective vehicles occur along turns with smaller turning radii.
- It appears that rear swingout is not as much of a concern as previously thought by many designers and researchers, for two reasons:
  1. Maximum rear swingout values are relatively small, and
  2. Maximum rear swingout occurs within the boundaries of the swept path width of the vehicle as it negotiates the turn (see Figure C-23), which implies that the path of the front outside of the tractor is more critical to intersection and horizontal curve design than the path of the rear outside corner of the trailer.

APPENDIX D

FIELD ESTIMATES OF TRUCK WEIGHT-TO-POWER RATIOS

A key issue in need of resolution is the distribution of truck characteristics related to performance on upgrades, particularly truck weight-to-power ratios. For over 30 years, from the 1950s through the 1980s, truck weight-to-power ratios decreased dramatically as truck engines became more and more powerful. Trucks with weight-to-power ratios greater than 150 kg/kW [250 lb/hp] have largely disappeared, with the exception of certain bulk haul operations like coal trucks and trucks hauling construction materials. Limited data suggest the distribution of truck weight-to-power ratios may have changed only a little since the mid-1980s, but this is uncertain. For the 2001 *Green Book*, a truck with a weight-to-power ratio of 120 kg/kW [200 lb/hp] was chosen as the basis for computation of critical length of grade. This seems a reasonable choice, but the data currently available could also support a choice in the 90- to 108-kg/kW [150- to 180-lb/hp] range. Therefore, field data were collected to document the actual distribution of truck weight-to-power ratios in the current truck fleet. This appendix describes the alternative approaches that were considered to collect the needed data, the site selection process for data collection locations, the data collection procedures, the data reduction procedures, and the field study results.

DATA COLLECTION APPROACH

Two fundamentally different approaches were considered to collect field data on truck weight-to-power ratios. These are:

- Measure truck weights and record marked engine power (referred to as nameplate horsepower) at weigh scales
- Record crawl speeds of trucks near the top of extended grades whose geometric profiles are known

In the first approach, weight-to-power ratio is computed directly as a ratio. The weight can be determined accurately from weigh scale data. The actual net horsepower (after mechanical losses) must be estimated from the nameplate horsepower. This approach requires substantial cooperation from weigh scale operators, because all trucks (including empty trucks) must be weighed to get a representative sample; many weigh scale operators allow empty trucks to bypass the scales because there is little point in weighing them for enforcement purposes. Cooperation of truckers is needed to determine the engine characteristics of their vehicles. This data collection approach requires a substantial amount of time per truck measured.

In the second approach, weight-to-power ratios are computed from the truck crawl speeds on steep upgrades measured with a radar or lidar device. This computation requires estimates of the frontal area of the truck and its aerodynamic drag coefficient, although for trucks with substantially reduced crawl speeds, aerodynamic drag is relatively unimportant. However, the field measurement—truck speed—is also a quantity of direct interest in highway design, since critical length of grade is based on a speed reduction criterion. The speed measurement approach has the advantages that data can be gathered relatively inexpensively and that no cooperation from weigh scale operators or truckers is needed; the only permission needed is permission from a highway agency to conduct a speed study from the roadside.

In previous research for the Korean Institute of Construction Technology, both field data collection methods described above were shown to provide comparable results in terms of the distribution of weight-to-power ratios. Therefore, the speed measurement approach was employed because it is more efficient.

SITE SELECTION

Data collection locations were selected through a three-step process. It was decided to use both freeway and two-lane highway locations because there were expected to be potential differences in the truck population between these two types of highways. In addition, it was decided to use sites in both eastern and western states to investigate differences in the truck population in different regions of the country.

The first step in site selection was to obtain data that would aid in selection of appropriate states and sites. Highway Performance Monitoring System (HPMS) data were utilized for this purpose. Table D-1 presents the mileage of rural freeways and two-lane highways with grades over 4.5 percent by region of the U.S. Listings of the mileage of grades over 4.5 percent by state were also obtained *(15)*. Based on the HPMS data and the proximity of potential sites within a reasonable traveling distance, a choice was made to collect truck crawl speeds on sustained grades in California, Colorado, and Pennsylvania.

The second step in site selection was to conduct site visits in the respective states to identify and review candidate data collection locations.

A total of 15 freeway sites and 15 two-lane highway sites were visited. In addition, truck crawl speed data from one rural two-lane highway site in California were available from a 1997 field study for NCHRP Project 3-55 (*3*) and were used

TABLE D-1 Roadway mileages with steep grades (*15*)

Region	Length of rural freeway (mi) 4.5-6.4%	Length of rural freeway (mi) > 6.4%	Length of rural two-lane highway (mi) 4.5-6.4%	Length of rural two-lane highway (mi) > 6.4%
Northeast	244.7	19.9	407.3	284.9
Southeast	34.6	9.0	539.6	239.2
Midwest	50.6	16.0	521.2	153.9
West	254.1	15.6	948.8	109.3
California	108.8	4.0	287.6	48.8
TOTAL	692.8	64.5	2,704.5	836.1

in this study. The following criteria were used to evaluate the appropriateness of a grade for purposes of this study. The characteristics of an ideal site include:

- Steep grade (at least 4 percent or more)
- Long grade (at least 1 mile in length)
- No sharp horizontal curves
- Good observation locations
- Relatively constant grade

Figures D-1 to D-4 provide illustrations of several candidate data collection sites in Colorado and Pennsylvania.

The final step in verifying the suitability of sites for data collection was to review the actual values of percent grade from vertical profiles in as-built construction plans or from HPMS data. The actual local percent grade is needed to compute truck weight-to-power ratio from the truck crawl speed. Copies of vertical profile sheets from as-built plans and HPMS data were obtained. Based upon a review of the vertical profiles, 10 sites were selected for data collection: four sites in Colorado, three sites in Pennsylvania, and three sites in California (including the site for which data were already available). Table D-2 summarizes the characteristics of each site. The last three columns of the table present the average grade, the local grade in the vicinity of the data collection location, and the length of the grade from the foot of the

Figure D-1. I-70 WB in Colorado on the approach to the Eisenhower Tunnel.

Figure D-2. U.S. 285 NB (Crow Hill) in Colorado.

Figure D-3. I-80 WB in Pennsylvania.

Figure D-4. State Route 26 SB in Pennsylvania.

TABLE D-2 Site information on data collection locations

State	Route	MP/Segment	Direction	Name of pass/area	Type of site	Dates of data collection	Average grade (%)	Local grade (%)	Length of grade (mi)
CA	I-80	Pla/51	EB	Baxter	Freeway	8/12/02 & 8/14/02	4.8	5.0	2.0
CA	I-80	Nev/3.7	EB	Donner Summit	Freeway	8/13/02	4.2	3.8	4.1
CA	Rt 97			Siskiyou County	Two-Lane	6/9/97 & 6/10/97	4.3		4.3
CO	I-70	MP 210.9	EB	Eisenhower Tunnel	Freeway	8/2/02	6.4	6.5	5.9
CO	I-70	MP 215.8	WB	Eisenhower Tunnel	Freeway	8/5/02 & 8/6/02	4.0	6.5	11.7
CO	US 50	MP 192.7	EB	Monarch Pass	Two-Lane	7/31/02 & 8/1/02	4.6	5.5	2.8
CO	US 285	MP 224	NB	Crow Hill	Two-Lane	7/29/02 & 7/30/02	6.9	7.0	1.9
PA	I-80	Segment 1505	WB	Centre County	Freeway	11/08/02	3	3	1.5
PA	Rt 26	Segment 20	SB	Centre County	Two-Lane	10/11/02 & 11/11/02	6.3	7.44	1.3
PA	Rt 153	Segment 730	NB	Clearfield County	Two-Lane	11/04/02 & 11/05/02	6.3	8	1.2

grade to the data collection location. Several typical data collection sites are illustrated in Figures D-1 through D4.

DATA COLLECTION PROCEDURES

Speed data were collected near the top of each grade to ensure that all or most trucks were operating at crawl speeds (i.e., the maximum speed of which the truck is capable at that point on the grade). Speeds were measured using a lidar gun. Speeds were recorded to the nearest mile per hour, and the configuration or type of each truck was recorded as follows:

- Single unit
- Single unit bulk carrier
- Van semitrailer
- Flat bed semitrailer
- Bulk semitrailer
- Low-boy semitrailer
- Auto carrier semitrailer
- Tank semitrailer
- Log semitrailer
- Single unit truck with trailer
- Double-trailer combination
- Triple-trailer combination
- Other

The goal was to collect the speeds of 100 trucks at each two-lane highway site and 400 trucks at each freeway site. Speeds were measured only for unimpeded trucks; if a truck was traveling behind another vehicle, the truck's speed may have been limited by its leader, so the truck speed was not measured. The speeds of trucks traveling in the through travel lanes were recorded, but the speeds of trucks driving on the shoulders were not recorded.

DATA REDUCTION AND ANALYSIS

The field study database included the truck type and speeds for each truck measured. The site-specific distribution of truck speeds is, in itself, of interest in highway design, but the primary purpose for conducting the field studies was to estimate the distribution of truck weight-to-power ratios in the current truck fleet. Therefore, the speed data were converted into truck weight-to-power estimates.

The conversion of truck speeds to weight-to-power ratios was accomplished using the vehicle performance equations from the TWOPAS model *(85, 86)*. Appendix E presents a truck speed profile model (TSPM) based on the TWOPAS vehicle performance equations. The TSPM can estimate the speed profile for the unimpeded truck on any specified vertical alignment given the truck's weight-to-power ratio. For the analysis of the field data, the TWOPAS model was applied in reverse to estimate the truck weight-to-power ratio that would have produced the observed truck crawl speed on the known vertical alignment.

RESULTS

The distributions of weight-to-power ratios, categorized by type of site and by state, are presented below.

Freeways

Figures D-5, D-6, and D-7 show the distributions of weight-to-power ratios found for California, Colorado, and Pennsylvania freeways, respectively. The cumulative percentiles (by state) are presented in Table D-3. The 85th-percentile weight-to-power ratio from each state ranged from a low of 101 kg/kW [169 lb/hp] in Colorado to a high of 124 kg/kW [207 lb/hp] in Pennsylvania.

Two-Lane Highways

Figures D-8, D-9, and D-10 show the distributions of weight-to-power ratios found on California, Colorado, and Pennsylvania two-lane highways, respectively. The cumulative percentiles (by state) are presented in Table D-4. The 85th-percentile weight-to-power ratio from each state ranged from a low of 108 kg/kW [180 lb/hp] in Colorado to a high of 168 kg/kW [280 lb/hp] in Pennsylvania.

Speed Distributions

Table D-5 presents a summary of the speed distributions as measured at the respective data collection locations. In general, truck crawl speeds were greater on the freeways as compared to the two-lane highways, as would be expected due to the character of service they are intended to provide and the higher criteria to which they are designed.

SUMMARY OF RESULTS

It is difficult to decide whether the truck populations found in the three states differ by state or geographic region (eastern states vs. western states). However, it is clear from the results obtained that the truck population on two-lane highways generally has greater weight-to-power ratios than the truck population on freeways.

Clearly, the best performing truck fleet is in Colorado, and the poorest performing truck fleet is in Pennsylvania. Further, there is much more variability in truck weight-to-power ratios on two-lane highways than on freeways. Long-haul trucks may have the best weight-to-power ratios, and one would expect the long-haul trucks to be more prevalent on the freeways and less so on two-lane highways.

In summary, the 85th-percentile weight-to-power ratio on freeways falls within a fairly narrow range, from 102 to 126 kg/kW [170 to 210 lb/hp] nationally, with California and Colorado at the low end of that range and Pennsylvania at the high end. For design purposes, it appears that a truck with weight-to-power ratio of 102 to 108 kg/kW [170 to 180 lb/hp] would be appropriate for freeways in California and Colorado, while a weight-to-power ratio of 126 kg/kW [210 lb/hp] would be more appropriate in

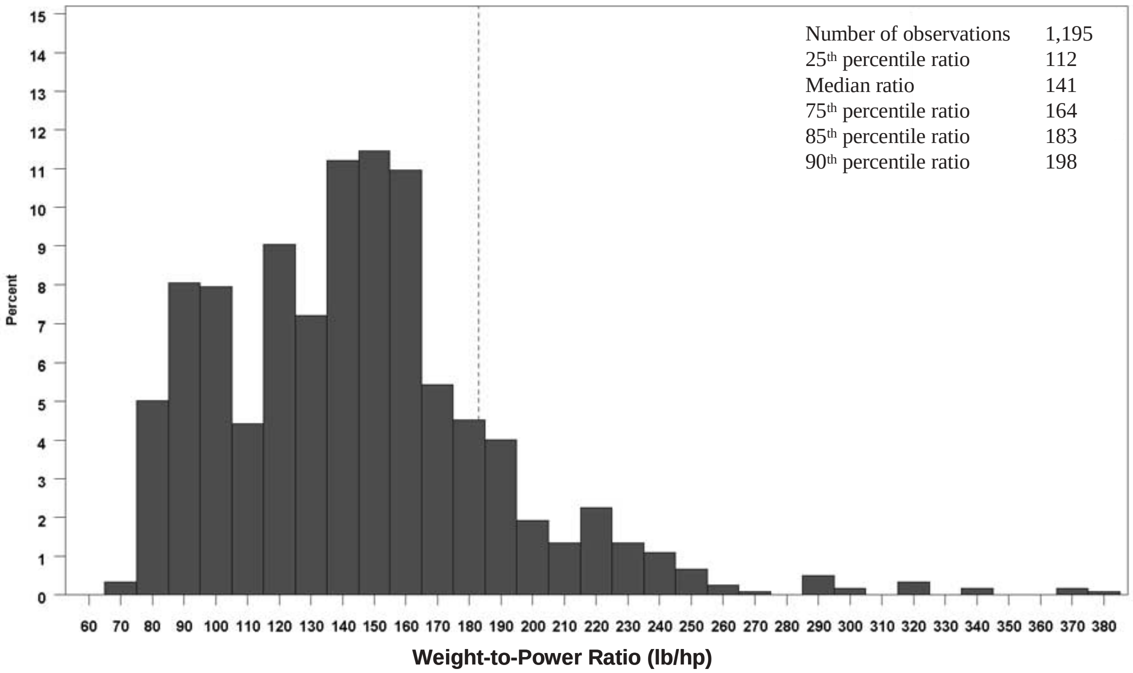
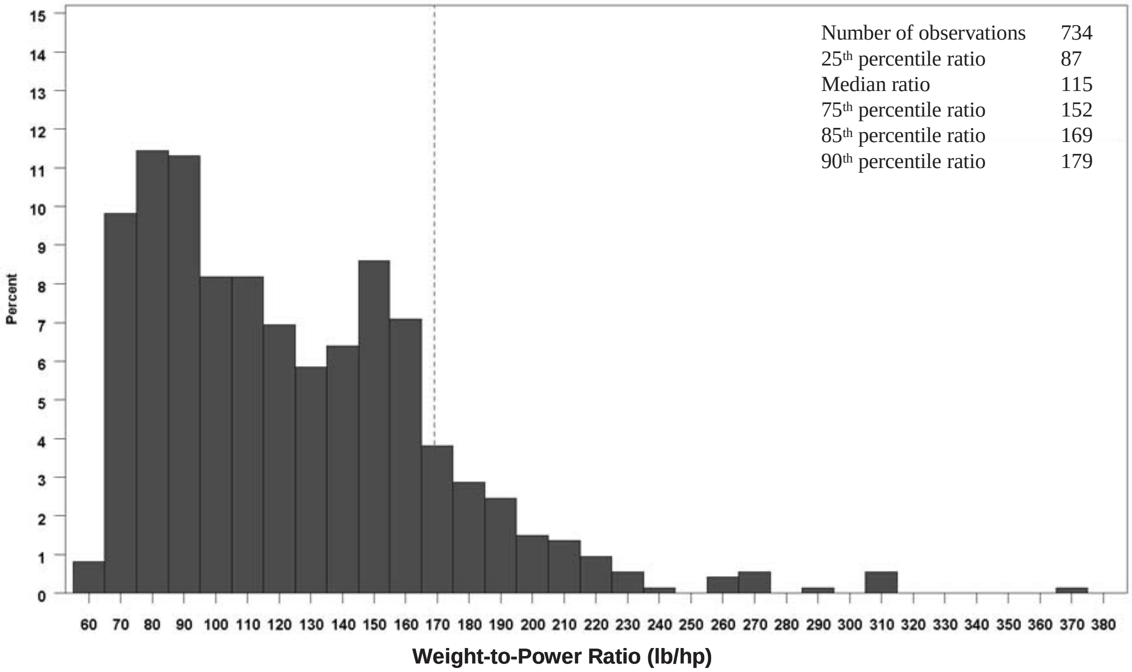
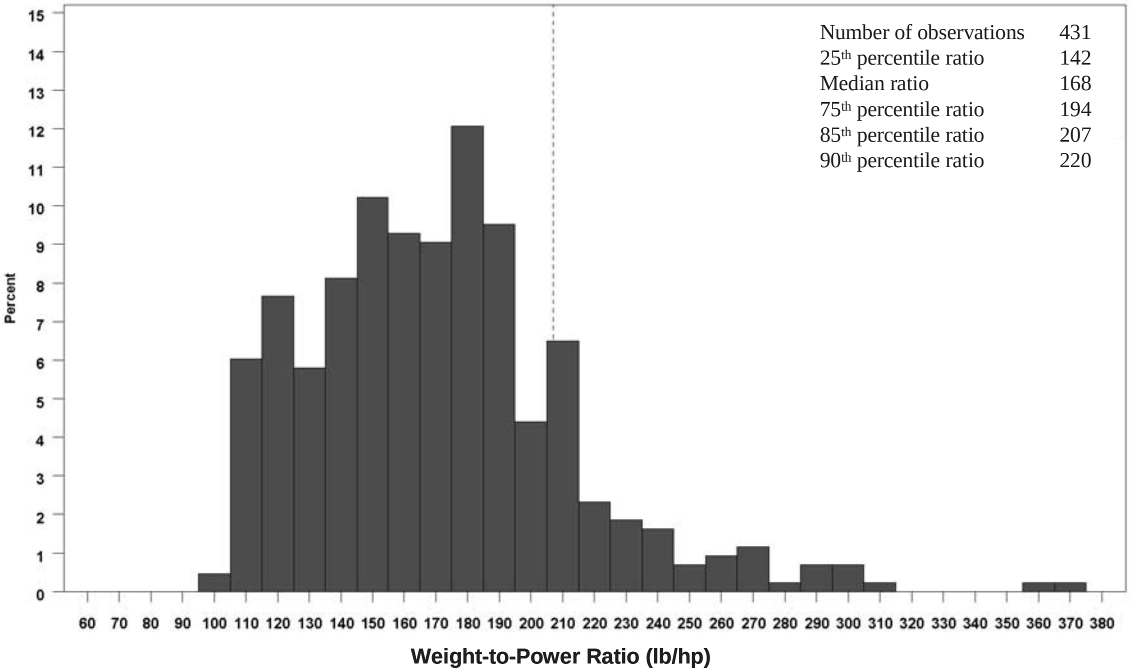


Figure D-5. Distribution of estimated weight-to-power ratios for California freeways.



Number of observations	734
25th percentile ratio	87
Median ratio	115
75th percentile ratio	152
85th percentile ratio	169
90th percentile ratio	179

Figure D-6. Distribution of estimated weight-to-power ratios for Colorado freeways.

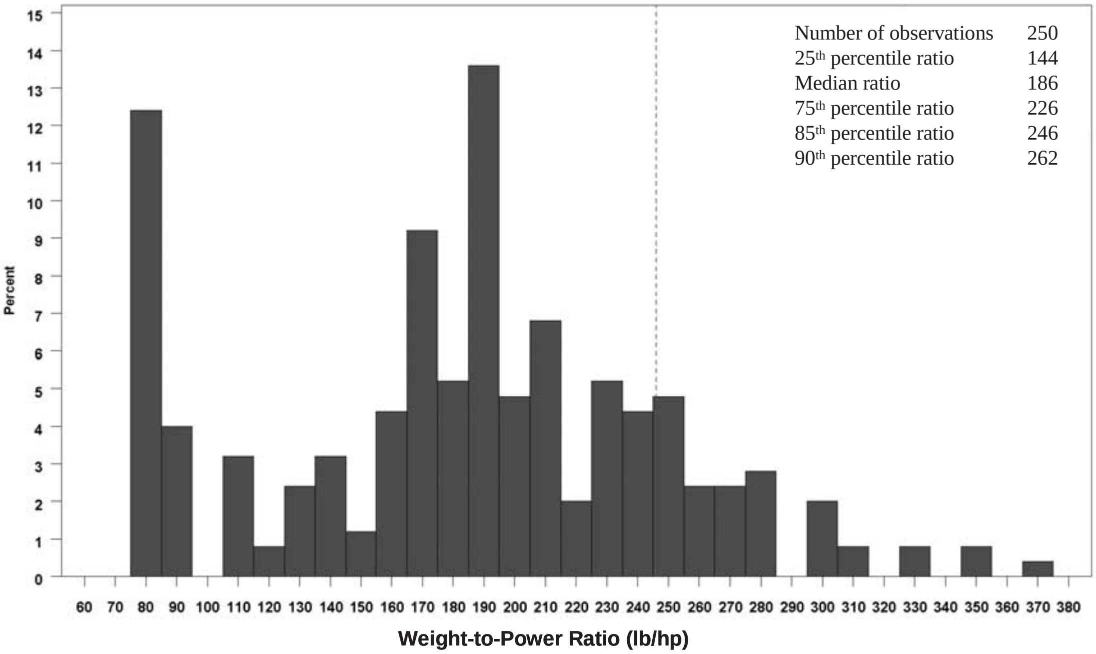


Number of observations	431
25th percentile ratio	142
Median ratio	168
75th percentile ratio	194
85th percentile ratio	207
90th percentile ratio	220

Figure D-7. Distribution of estimated weight-to-power ratios for Pennsylvania freeways.

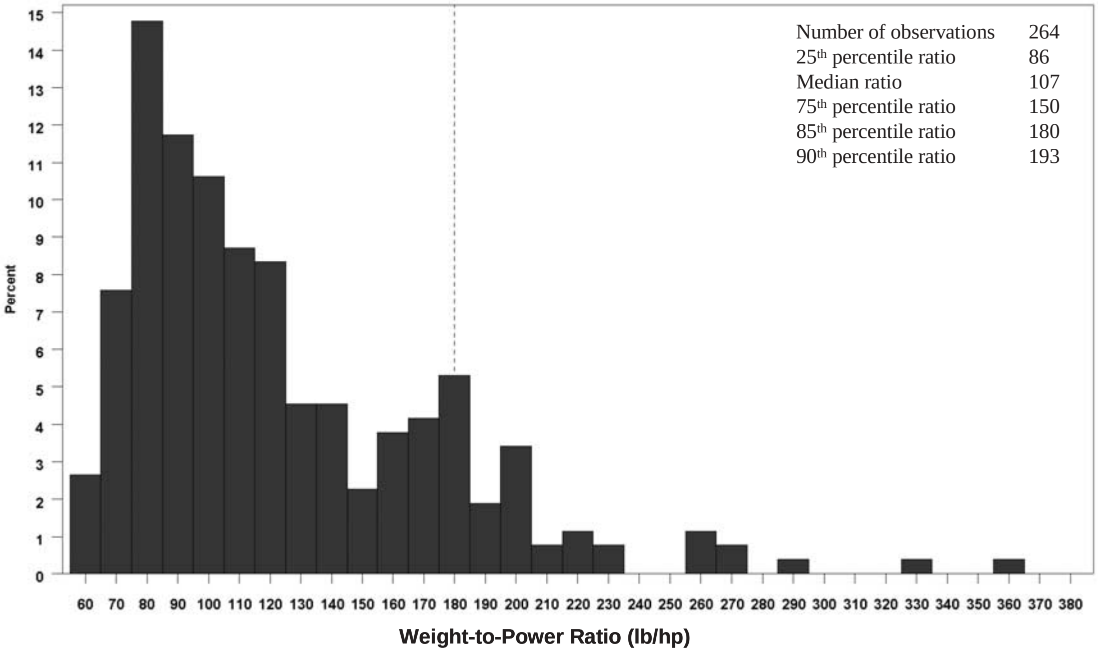
TABLE D-3 Summary of truck weight-to-power ratios for freeway sites

Percentile	Weight-to-power (lb/hp) ratio California	 Colorado	 Pennsylvania
5th	83	69	111
25th	112	87	142
50th	141	115	168
75th	164	152	194
85th	183	169	207
90th	198	179	220
95th	224	199	251



Number of observations	250
25th percentile ratio	144
Median ratio	186
75th percentile ratio	226
85th percentile ratio	246
90th percentile ratio	262

Figure D-8. Distribution of weight-to-power ratios for California two-lane highways.



Number of observations	264
25th percentile ratio	86
Median ratio	107
75th percentile ratio	150
85th percentile ratio	180
90th percentile ratio	193

Figure D-9. Distribution of estimated weight-to-power ratios for Colorado two-lane highways.

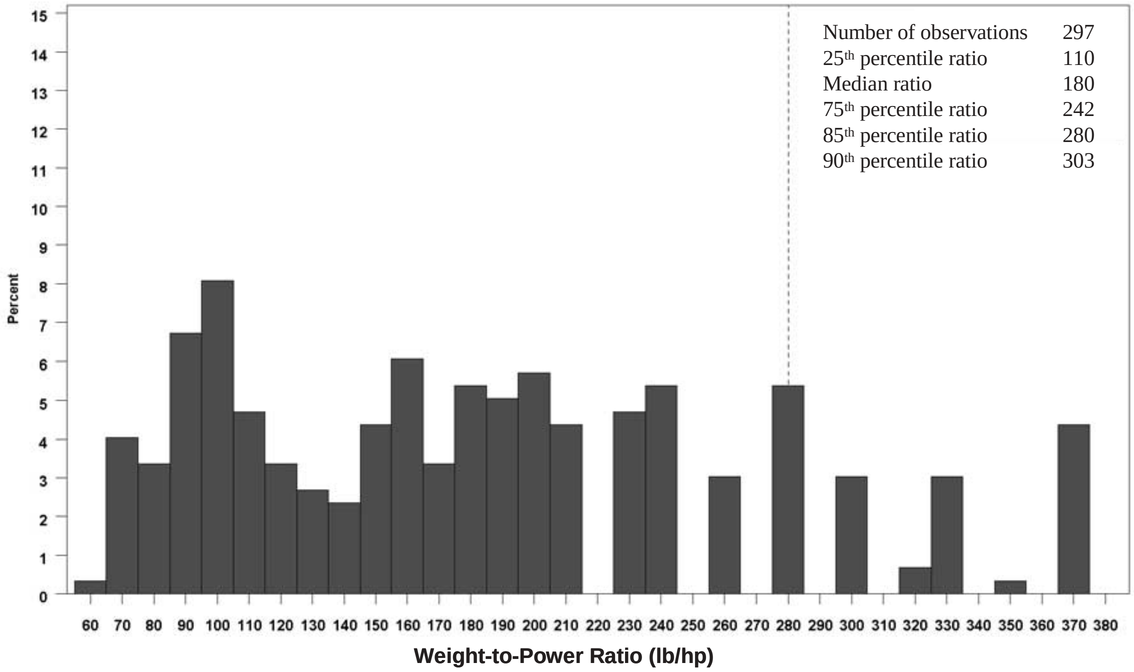


Figure D-10. Distribution of weight-to-power ratios for Pennsylvania two-lane highways.

Pennsylvania. For two-lane highways, a 108-kg/kW [180-lb/hp] design vehicle may be appropriate in Colorado, while less powerful design vehicles in the 150 to 168 kg/kW [250 to 280 lb/hp] range may be appropriate for California and Pennsylvania. All of these design vehicle weight-to-power ratios represent the 85th percentile of the truck population; so, of course, most of the truck population performs substantially better.

TABLE D-4 Summary of truck weight-to-power ratios for two-lane highway sites

	Weight-to-Power (lb/hp) Ratio		
Percentile	California	Colorado	Pennsylvania
5th	79	68	79
25th	144	86	110
50th	186	107	180
75th	226	149	242
85th	246	180	280
90th	262	193	303
95th	281	214	331

TABLE D-5 Speed distributions at data collection locations

						Speed (mph)		
State	Route	MP/Segment	Direction	Type of site	Number of observations	15th percentile	50th percentile	85th percentile
CA	I-80	Pla/51	EB	Freeway	600	29	36	52
CA	I-80	Nev/3.7	EB	Freeway	600	32	41	53
CA	Rt 97			Two-Lane	250	25	32	52
CO	I-70	MP 210.9	EB	Freeway	400	26	39	54
CO	I-70	MP 215.8	WB	Freeway	350	26	36	50
CO	US 50	MP 192.7	EB	Two-Lane	97	27	41	50
CO	US 285	MP 224	NB	Two-Lane	169	22	40	51
PA	I-80	Segment 1505	WB	Freeway	434	38	45	55
PA	Rt 26	Segment 20	SB	Two-Lane	109	17	31	41
PA	Rt 153	Segment 730	NB	Two-Lane	189	12	19	33

APPENDIX E

TRUCK SPEED PROFILE MODEL

A truck speed profile model (TSPM) for truck performance on upgrades has been developed as a design tool to permit highway agencies to anticipate when an added climbing lane may be warranted. TSPM is implemented in a Microsoft Excel spreadsheet. This appendix illustrates how the speed profile model operates and documents the truck performance equations that form the basis for that model.

The current *Green Book* contains several truck speed profile plots (i.e., plots of truck speed versus distance along a grade) for use in determining the critical length of grade that might warrant a climbing lane. These plots are not as useful as they might be because they assume a single initial truck speed, a constant percent grade, and a single truck weight-to-power ratio (120 kg/kW [200 lb/hp]). The TSPM spreadsheet allows the user to input the actual vertical alignment for any site of interest and to choose any appropriate value for initial truck speed and weight-to-power ratio. This flexibility should improve the ability of highway agencies to determine whether the climbing lane criteria are met at any particular site.

INPUT DATA

The input data for the TSPM include both roadway and truck characteristics. The specific input data are as follows:

- Roadway Characteristics:
  - Vertical profile—percent grade for specific ranges of position coordinates
  - Elevation above sea level (ft)
- Truck Characteristics:
  - Desired speed (mph)
  - Initial speed of truck at beginning of analysis section (mph)
  - Weight-to-power ratio (lb/hp)
  - Weight-to-front-area ratio (lb/ft2)

The input data are entered on the first page of the TSPM spreadsheet, which is illustrated in Figure E-1. The grades that constitute the vertical profile of the analysis site are entered for ranges of position coordinates, such as stationing, in units of feet. The profile should begin at coordinate zero and subsequent grade ranges should appear in order of increasing coordinates. The end of each coordinate range should be equal to the beginning of the next coordinate range. Vertical curves have little effect on truck speeds, so grades can be entered as continuous constant grades from one vertical point of intersection (VPI) to the next. Grades for any number of coordinate ranges may be entered.

The desired speed of the truck, entered in miles per hour, is the speed that the truck driver would prefer to travel where not limited by the presence of an upgrade. The TSPM logic will never show the trucks as traveling faster than this speed.

The initial speed of the truck, entered in miles per hour, is the speed of the truck at coordinate zero. This speed typically represents the truck speed prior to entering the grade and can be any speed greater than or equal to zero. If the truck is entering the grade from level terrain, the initial speed may be equal to the desired speed. If the truck is entering the grade from a stopped position, the initial speed may be zero.

The weight-to-power ratio, entered in lb/hp, represents the performance ability of the truck. The lower the weight-to-power ratio, the better will be the truck performance on any grade and the greater will be the truck's final crawl speed.

The weight-to-frontal-area ratio, entered in lb/ft^2, represents the ability of the truck to overcome aerodynamic resistance. If the cell representing weight-to-frontal-area ratio is left blank or set equal to zero, the spreadsheet will estimate a typical default value of weight-to-frontal-area ratio, based on the weight-to-power ratio. In general, aerodynamic resistance has limited effect on truck speed profiles, so it is best in most cases to use the typical default value. However, the TSPM permits the user to include a specific value for weight-to-frontal-area ratio where this is available.

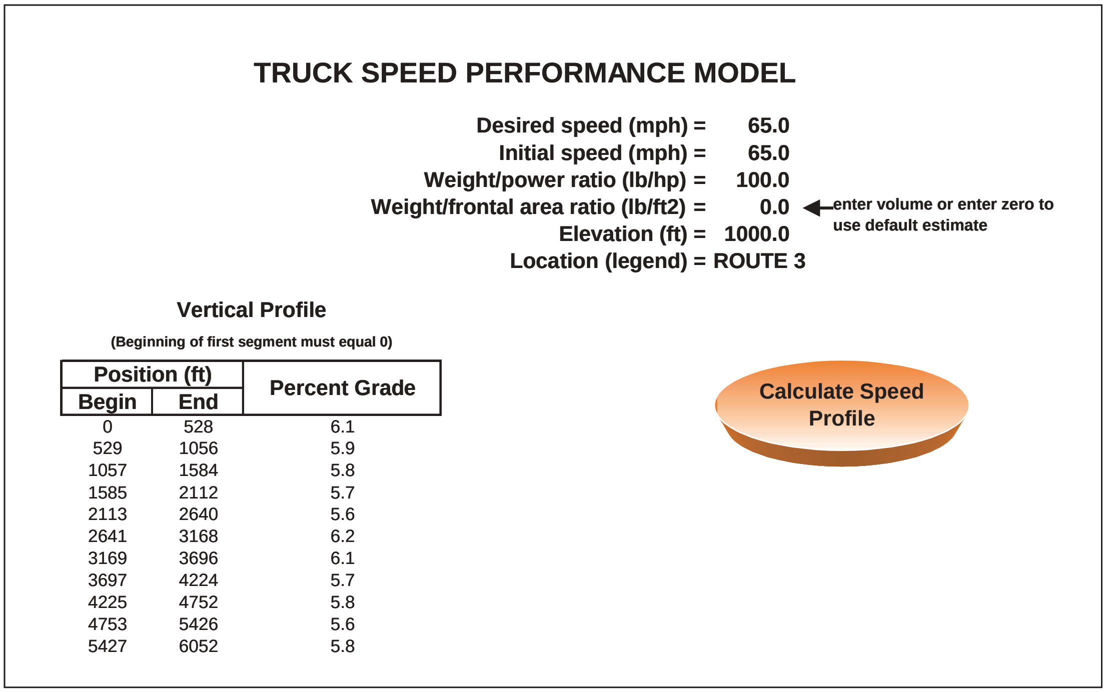
The elevation above sea level, in feet, of the site being evaluated is also entered for the site being evaluated. The elevation of the site influences the aerodynamic resistance. However, as noted above, the effect of aerodynamic resistance on truck performance is minimal, so the accuracy of the elevation used is not critical.

TSPM is applicable to diesel trucks, so there is no horsepower correction for elevation as there would be for gasoline engines.

When all input data for a problem have been entered, the user should click the button marked "Calculate Speed Profile" to generate output data.

OUTPUT DATA

TSPM generates two types of output data. On the sheet labeled "Results," TSPM displays the speed profile calculations for each second of elapsed time after the truck passes coordinate zero. The tabulated values include all position coordinates from zero to the maximum coordinate specified in the input data. This detailed, second-by-second output is illustrated in Figure E-2. The individual columns in the spreadsheet are defined in the next section of this appendix.



TRUCK SPEED PERFORMANCE MODEL

Desired speed (mph) =	65.0
Initial speed (mph) =	65.0
Weight/power ratio (lb/hp) =	100.0
Weight/frontal area ratio (lb/ft2) =	0.0
Elevation (ft) =	1000.0
Location (legend) =	ROUTE 3

enter volume or enter zero to use default estimate

Vertical Profile

(Beginning of first segment must equal 0)

Position (ft)		Percent Grade
Begin	End	
0	528	6.1
529	1056	5.9
1057	1584	5.8
1585	2112	5.7
2113	2640	5.6
2641	3168	6.2
3169	3696	6.1
3697	4224	5.7
4225	4752	5.8
4753	5426	5.6
5427	6052	5.8

Figure E-1. Input screen for TSPM.

The speed profile spreadsheet includes the minimum and maximum truck speeds computed by the spreadsheet and their difference. If the maximum speed represents the truck speed in advance of the upgrade, then the difference between the maximum and minimum speeds represents the speed reduction on the grade. If the speed reduction is 16 km/h [10 mph] or more, a climbing lane may be warranted.

The sheet labeled “Chart1” presents a speed versus distance plot that illustrates the truck speed profile. The speed profile plot is simply a graph of Columns 17 and 19. A typical plot is illustrated in Figure E-3. Such a plot allows the user to review the expected speed of the truck at each location along the specified grade.

SPEED PROFILE COMPUTATIONS

The speed profile computations are conducted as follows, using the truck performance equations from the TWOPAS model *(85, 86)*:

- Column 1 represents the elapsed time, in seconds, since the vehicle passed coordinate zero.
- Columns 2 and 3 represent the user-specified desired speed, in units of miles per hour and feet per second, for the truck in question.
- Columns 4 and 5 represent the actual speed of the truck, in miles per hour and feet per second, at the time shown in Column 1.
- Column 6 represents the position of the truck (distance from coordinate zero) at the time shown in Column 1.
- Columns 8 through 10 represent the coasting acceleration, horsepower-limited-acceleration, and effective acceleration, respectively, during the 1-s interval beginning at the time shown in Column 1. The accelerations are determined as follows:

$$a_c = -0.2445 - 0.004V' - \frac{0.021C_{de}(V')^2}{(W/A)} - \frac{222.6C_{pe}}{(W/NHP)V'} - gG \tag{1}$$

$$a_p = \frac{\dfrac{15368C_{pe}}{(W/NHP)V'}}{1 + \dfrac{14080}{(W/NHP)V'^2}} \tag{2}$$

$$a_e = \frac{0.4V'a_o}{0.4V' + \dfrac{1.5a_o}{|a_o|}(a_p - a_c)}, \quad V \geq 10 \text{ ft/s} \tag{3}$$

$$a_e = \frac{10a_o}{10 + \dfrac{1.5a_o}{|a_o|}(a_p - a_c)}, \quad V < 10 \text{ ft/s} \tag{4}$$

where

a_c = coasting acceleration (ft/s^2) during gear shifts
a_p = horsepower-limited acceleration (ft/s^2)
a_e = effective acceleration (ft/s^2) including an allowance of 1.5 s for gear shift delays

TRUCK SPEED PROFILE FOR ROUTE 3

Desired speed (mph) = 65.0
Initial speed (mph) = 65.0
Weight/horsepower ratio (lb/hp) = 100.0
Weight/frontal area ratio (lb/ft2) = 221.0
Elevation (ft) = 1000.0
Horsepower correction factor for elevation = 1.0000
Aerodynamic drag correction factor for elevation = 0.9710

Maximum speed (mph) = 63.9
Minimum speed (mph) = 41.9
Speed difference (mph) = 22.0

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)
Elapsed time (sec)	Desired speed		Start of 1-sec Interval			Local grade (%)	Limiting acceleration (ft/sec2)			New speed based on vehicle performance		Limiting acceleration and speed based on driver preferences			Actual acceleration (ft/sec2)	End of 1-sec Interval		
			Speed		Position (ft)							Speed		Acceleration (ft/sec2)		New speed		New position (ft)
	(mph)	(ft/sec)	(mph)	(ft/sec)			Coasting	Power	Effective	(mph)	(ft/sec)	(mph)	(ft/sec)			(mph)	(ft/sec)	
0.0	65.0	95.3	65.0	95.3	0.0	6.1	-3.11	-1.47	-1.57	63.9	93.8	65.0	95.3	0.00	-1.57	63.9	93.8	94.5
1.0	65.0	95.3	63.9	93.8	94.5	6.1	-3.08	-1.42	-1.52	62.9	92.2	64.9	95.1	1.37	-1.52	62.9	92.2	187.5
2.0	65.0	95.3	62.9	92.2	187.5	6.1	-3.05	-1.36	-1.46	61.9	90.8	63.9	93.8	1.53	-1.46	61.9	90.8	279.1
3.0	65.0	95.3	61.9	90.8	279.1	6.1	-3.03	-1.31	-1.41	60.9	89.4	63.0	92.5	1.69	-1.41	60.9	89.4	369.1
4.0	65.0	95.3	60.9	89.4	369.1	6.1	-3.00	-1.26	-1.36	60.0	88.0	62.2	91.2	1.84	-1.36	60.0	88.0	457.8
5.0	65.0	95.3	60.0	88.0	457.8	6.1	-2.98	-1.21	-1.31	59.1	86.7	61.4	90.0	1.99	-1.31	59.1	86.7	545.2
6.0	65.0	95.3	59.1	86.7	545.2	5.9	-2.90	-1.10	-1.20	58.3	85.5	60.6	88.8	2.13	-1.20	58.3	85.5	631.2
7.0	65.0	95.3	58.3	85.5	631.2	5.9	-2.88	-1.06	-1.15	57.5	84.3	59.8	87.8	2.26	-1.15	57.5	84.3	716.2
8.0	65.0	95.3	57.5	84.3	716.2	5.9	-2.86	-1.02	-1.11	56.8	83.2	59.1	86.7	2.39	-1.11	56.8	83.2	800.0
9.0	65.0	95.3	56.8	83.2	800.0	5.9	-2.84	-0.98	-1.07	56.0	82.2	58.5	85.7	2.51	-1.07	56.0	82.2	882.7
10.0	65.0	95.3	56.0	82.2	882.7	5.9	-2.83	-0.94	-1.02	55.3	81.1	57.8	84.8	2.62	-1.02	55.3	81.1	964.3
11.0	65.0	95.3	55.3	81.1	964.3	5.9	-2.81	-0.90	-0.98	54.7	80.2	57.2	83.9	2.73	-0.98	54.7	80.2	1045.0
12.0	65.0	95.3	54.7	80.2	1045.0	5.9	-2.80	-0.86	-0.94	54.0	79.2	56.6	83.0	2.84	-0.94	54.0	79.2	1124.7
13.0	65.0	95.3	54.0	79.2	1124.7	5.8	-2.75	-0.79	-0.87	53.4	78.3	56.0	82.2	2.94	-0.87	53.4	78.3	1203.4
14.0	65.0	95.3	53.4	78.3	1203.4	5.8	-2.74	-0.76	-0.84	52.8	77.5	55.5	81.4	3.03	-0.84	52.8	77.5	1281.4
15.0	65.0	95.3	52.8	77.5	1281.4	5.8	-2.72	-0.72	-0.80	52.3	76.7	55.0	80.6	3.13	-0.80	52.3	76.7	1358.5
16.0	65.0	95.3	52.3	76.7	1358.5	5.8	-2.71	-0.69	-0.77	51.8	75.9	54.5	79.9	3.21	-0.77	51.8	75.9	1434.8
17.0	65.0	95.3	51.8	75.9	1434.8	5.8	-2.70	-0.66	-0.74	51.3	75.2	54.0	79.2	3.29	-0.74	51.3	75.2	1510.4
18.0	65.0	95.3	51.3	75.2	1510.4	5.8	-2.69	-0.63	-0.70	50.8	74.5	53.6	78.6	3.37	-0.70	50.8	74.5	1585.2
19.0	65.0	95.3	50.8	74.5	1585.2	5.7	-2.65	-0.57	-0.64	50.4	73.9	53.1	77.9	3.45	-0.64	50.4	73.9	1659.4
20.0	65.0	95.3	50.4	73.9	1659.4	5.7	-2.64	-0.55	-0.61	49.9	73.2	52.8	77.4	3.52	-0.61	49.9	73.2	1732.9
21.0	65.0	95.3	49.9	73.2	1732.9	5.7	-2.63	-0.52	-0.58	49.5	72.7	52.4	76.8	3.59	-0.58	49.5	72.7	1805.9
22.0	65.0	95.3	49.5	72.7	1805.9	5.7	-2.63	-0.50	-0.56	49.2	72.1	52.0	76.3	3.65	-0.56	49.2	72.1	1878.3
23.0	65.0	95.3	49.2	72.1	1878.3	5.7	-2.62	-0.47	-0.53	48.8	71.6	51.7	75.8	3.71	-0.53	48.8	71.6	1950.1
24.0	65.0	95.3	48.8	71.6	1950.1	5.7	-2.61	-0.45	-0.51	48.5	71.1	51.4	75.3	3.77	-0.51	48.5	71.1	2021.4
25.0	65.0	95.3	48.5	71.1	2021.4	5.7	-2.60	-0.43	-0.48	48.1	70.6	51.1	74.9	3.82	-0.48	48.1	70.6	2092.2
26.0	65.0	95.3	48.1	70.6	2092.2	5.7	-2.60	-0.41	-0.46	47.8	70.1	50.8	74.5	3.87	-0.46	47.8	70.1	2162.6
27.0	65.0	95.3	47.8	70.1	2162.6	5.6	-2.56	-0.36	-0.41	47.5	69.7	50.5	74.0	3.92	-0.41	47.5	69.7	2232.5
28.0	65.0	95.3	47.5	69.7	2232.5	5.6	-2.55	-0.34	-0.39	47.3	69.3	50.2	73.7	3.97	-0.39	47.3	69.3	2302.0
29.0	65.0	95.3	47.3	69.3	2302.0	5.6	-2.55	-0.32	-0.37	47.0	69.0	50.0	73.3	4.01	-0.37	47.0	69.0	2371.2
30.0	65.0	95.3	47.0	69.0	2371.2	5.6	-2.54	-0.31	-0.35	46.8	68.6	49.8	73.0	4.05	-0.35	46.8	68.6	2439.9
31.0	65.0	95.3	46.8	68.6	2439.9	5.6	-2.54	-0.29	-0.33	46.6	68.3	49.6	72.7	4.09	-0.33	46.6	68.3	2508.4
32.0	65.0	95.3	46.6	68.3	2508.4	5.6	-2.54	-0.28	-0.32	46.3	68.0	49.4	72.4	4.12	-0.32	46.3	68.0	2576.5
33.0	65.0	95.3	46.3	68.0	2576.5	5.6	-2.53	-0.26	-0.30	46.1	67.7	49.2	72.1	4.16	-0.30	46.1	67.7	2644.3
34.0	65.0	95.3	46.1	67.7	2644.3	6.2	-2.72	-0.44	-0.50	45.8	67.2	49.0	71.8	4.19	-0.50	45.8	67.2	2711.7
35.0	65.0	95.3	45.8	67.2	2711.7	6.2	-2.72	-0.41	-0.48	45.5	66.7	48.7	71.4	4.24	-0.48	45.5	66.7	2778.6
36.0	65.0	95.3	45.5	66.7	2778.6	6.2	-2.71	-0.39	-0.45	45.2	66.2	48.4	71.0	4.29	-0.45	45.2	66.2	2845.1
37.0	65.0	95.3	45.2	66.2	2845.1	6.2	-2.70	-0.37	-0.43	44.9	65.8	48.1	70.6	4.34	-0.43	44.9	65.8	2911.1
38.0	65.0	95.3	44.9	65.8	2911.1	6.2	-2.70	-0.35	-0.41	44.6	65.4	47.9	70.2	4.39	-0.41	44.6	65.4	2976.7
39.0	65.0	95.3	44.6	65.4	2976.7	6.2	-2.69	-0.33	-0.39	44.3	65.0	47.6	69.8	4.43	-0.39	44.3	65.0	3041.9
40.0	65.0	95.3	44.3	65.0	3041.9	6.2	-2.69	-0.31	-0.36	44.1	64.6	47.4	69.5	4.47	-0.36	44.1	64.6	3106.8
41.0	65.0	95.3	44.1	64.6	3106.8	6.2	-2.68	-0.30	-0.35	43.8	64.3	47.2	69.2	4.51	-0.35	43.8	64.3	3171.2
42.0	65.0	95.3	43.8	64.3	3171.2	6.1	-2.65	-0.25	-0.29	43.6	64.0	46.9	68.9	4.55	-0.29	43.6	64.0	3235.4
43.0	65.0	95.3	43.6	64.0	3235.4	6.1	-2.65	-0.24	-0.28	43.5	63.7	46.8	68.6	4.58	-0.28	43.5	63.7	3299.3
44.0	65.0	95.3	43.5	63.7	3299.3	6.1	-2.64	-0.22	-0.26	43.3	63.5	46.6	68.3	4.61	-0.26	43.3	63.5	3362.9
45.0	65.0	95.3	43.3	63.5	3362.9	6.1	-2.64	-0.21	-0.25	43.1	63.2	46.4	68.1	4.64	-0.25	43.1	63.2	3426.2
46.0	65.0	95.3	43.1	63.2	3426.2	6.1	-2.64	-0.20	-0.23	43.0	63.0	46.3	67.9	4.67	-0.23	43.0	63.0	3489.3
47.0	65.0	95.3	43.0	63.0	3489.3	6.1	-2.63	-0.19	-0.22	42.8	62.8	46.2	67.7	4.69	-0.22	42.8	62.8	3552.2
48.0	65.0	95.3	42.8	62.8	3552.2	6.1	-2.63	-0.18	-0.21	42.7	62.6	46.0	67.5	4.72	-0.21	42.7	62.6	3614.9

Figure E-2. Tabular printout from TSPM.

TRUCK SPEED PROFILE FOR ROUTE 3

Desired speed (mph) = 65.0
Initial speed (mph) = 65.0
Weight/horsepower ratio (lb/hp) = 100.0
Weight/frontal area ratio (lb/ft2) = 221.0
Elevation (ft) = 1000.0
Horsepower correction factor for elevation = 1.0000
Aerodynamic drag correction factor for elevation = 0.9710

Maximum speed (mph) = 63.9
Minimum speed (mph) = 41.9
Speed difference (mph) = 22.0

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)
Elapsed time	Desired speed		Start of 1-sec Interval			Local grade	Limiting acceleration (ft/sec2)			New speed based on vehicle performance		Limiting acceleration and speed based on driver preferences			Actual acceleration	End of 1-sec Interval		
			Speed		Position							Speed		Acceleration		New speed		New position
(sec)	(mph)	(ft/sec)	(mph)	(ft/sec)	(ft)	(%)	Coasting	Power	Effective	(mph)	(ft/sec)	(mph)	(ft/sec)	(ft/sec2)	(ft/sec2)	(mph)	(ft/sec)	(ft)
49.0	65.0	95.3	42.7	62.6	3614.9	6.1	-2.63	-0.17	-0.20	42.5	62.4	45.9	67.3	4.74	-0.20	42.5	62.4	3677.4
50.0	65.0	95.3	42.5	62.4	3677.4	6.1	-2.63	-0.16	-0.18	42.4	62.2	45.8	67.1	4.76	-0.18	42.4	62.2	3739.7
51.0	65.0	95.3	42.4	62.2	3739.7	5.7	-2.50	-0.02	-0.03	42.4	62.2	45.7	67.0	4.78	-0.03	42.4	62.2	3801.8
52.0	65.0	95.3	42.4	62.2	3801.8	5.7	-2.50	-0.02	-0.03	42.4	62.1	45.6	66.9	4.78	-0.03	42.4	62.1	3864.0
53.0	65.0	95.3	42.4	62.1	3864.0	5.7	-2.50	-0.02	-0.02	42.3	62.1	45.6	66.9	4.79	-0.02	42.3	62.1	3926.1
54.0	65.0	95.3	42.3	62.1	3926.1	5.7	-2.49	-0.02	-0.02	42.3	62.1	45.6	66.9	4.79	-0.02	42.3	62.1	3988.2
55.0	65.0	95.3	42.3	62.1	3988.2	5.7	-2.49	-0.02	-0.02	42.3	62.1	45.6	66.9	4.79	-0.02	42.3	62.1	4050.3
56.0	65.0	95.3	42.3	62.1	4050.3	5.7	-2.49	-0.02	-0.02	42.3	62.0	45.6	66.9	4.79	-0.02	42.3	62.0	4112.3
57.0	65.0	95.3	42.3	62.0	4112.3	5.7	-2.49	-0.02	-0.02	42.3	62.0	45.6	66.8	4.80	-0.02	42.3	62.0	4174.4
58.0	65.0	95.3	42.3	62.0	4174.4	5.7	-2.49	-0.02	-0.02	42.3	62.0	45.6	66.8	4.80	-0.02	42.3	62.0	4236.4
59.0	65.0	95.3	42.3	62.0	4236.4	5.8	-2.53	-0.05	-0.05	42.2	62.0	45.6	66.8	4.80	-0.05	42.2	62.0	4298.4
60.0	65.0	95.3	42.2	62.0	4298.4	5.8	-2.53	-0.04	-0.05	42.2	61.9	45.5	66.8	4.80	-0.05	42.2	61.9	4360.3
61.0	65.0	95.3	42.2	61.9	4360.3	5.8	-2.52	-0.04	-0.05	42.2	61.9	45.5	66.7	4.81	-0.05	42.2	61.9	4422.2
62.0	65.0	95.3	42.2	61.9	4422.2	5.8	-2.52	-0.04	-0.05	42.1	61.8	45.5	66.7	4.82	-0.05	42.1	61.8	4484.0
63.0	65.0	95.3	42.1	61.8	4484.0	5.8	-2.52	-0.04	-0.04	42.1	61.8	45.4	66.6	4.82	-0.04	42.1	61.8	4545.8
64.0	65.0	95.3	42.1	61.8	4545.8	5.8	-2.52	-0.03	-0.04	42.1	61.7	45.4	66.6	4.83	-0.04	42.1	61.7	4607.6
65.0	65.0	95.3	42.1	61.7	4607.6	5.8	-2.52	-0.03	-0.04	42.1	61.7	45.4	66.6	4.83	-0.04	42.1	61.7	4669.3
66.0	65.0	95.3	42.1	61.7	4669.3	5.8	-2.52	-0.03	-0.04	42.0	61.7	45.4	66.5	4.83	-0.04	42.0	61.7	4730.9
67.0	65.0	95.3	42.0	61.7	4730.9	5.8	-2.52	-0.03	-0.03	42.0	61.6	45.3	66.5	4.84	-0.03	42.0	61.6	4792.6
68.0	65.0	95.3	42.0	61.6	4792.6	5.6	-2.46	0.04	0.03	42.0	61.7	45.3	66.5	4.84	0.03	42.0	61.7	4854.2
69.0	65.0	95.3	42.0	61.7	4854.2	5.6	-2.46	0.03	0.03	42.1	61.7	45.3	66.5	4.84	0.03	42.1	61.7	4915.9
70.0	65.0	95.3	42.1	61.7	4915.9	5.6	-2.46	0.03	0.03	42.1	61.7	45.4	66.5	4.83	0.03	42.1	61.7	4977.6
71.0	65.0	95.3	42.1	61.7	4977.6	5.6	-2.46	0.03	0.03	42.1	61.7	45.4	66.5	4.83	0.03	42.1	61.7	5039.3
72.0	65.0	95.3	42.1	61.7	5039.3	5.6	-2.46	0.03	0.03	42.1	61.8	45.4	66.6	4.83	0.03	42.1	61.8	5101.1
73.0	65.0	95.3	42.1	61.8	5101.1	5.6	-2.46	0.03	0.02	42.1	61.8	45.4	66.6	4.83	0.02	42.1	61.8	5162.8
74.0	65.0	95.3	42.1	61.8	5162.8	5.6	-2.46	0.03	0.02	42.1	61.8	45.4	66.6	4.82	0.02	42.1	61.8	5224.6
75.0	65.0	95.3	42.1	61.8	5224.6	5.6	-2.46	0.03	0.02	42.2	61.8	45.4	66.6	4.82	0.02	42.2	61.8	5286.5
76.0	65.0	95.3	42.2	61.8	5286.5	5.6	-2.46	0.02	0.02	42.2	61.9	45.4	66.7	4.82	0.02	42.2	61.9	5348.3
77.0	65.0	95.3	42.2	61.9	5348.3	5.6	-2.46	0.02	0.02	42.2	61.9	45.5	66.7	4.82	0.02	42.2	61.9	5410.2
78.0	65.0	95.3	42.2	61.9	5410.2	5.6	-2.46	0.02	0.02	42.2	61.9	45.5	66.7	4.81	0.02	42.2	61.9	5472.0
79.0	65.0	95.3	42.2	61.9	5472.0	5.8	-2.52	-0.04	-0.05	42.2	61.8	45.5	66.7	4.81	-0.05	42.2	61.8	5533.9
80.0	65.0	95.3	42.2	61.8	5533.9	5.8	-2.52	-0.04	-0.04	42.1	61.8	45.5	66.7	4.82	-0.04	42.1	61.8	5595.7
81.0	65.0	95.3	42.1	61.8	5595.7	5.8	-2.52	-0.04	-0.04	42.1	61.8	45.4	66.6	4.82	-0.04	42.1	61.8	5657.5
82.0	65.0	95.3	42.1	61.8	5657.5	5.8	-2.52	-0.03	-0.04	42.1	61.7	45.4	66.6	4.83	-0.04	42.1	61.7	5719.3
83.0	65.0	95.3	42.1	61.7	5719.3	5.8	-2.52	-0.03	-0.04	42.1	61.7	45.4	66.6	4.83	-0.04	42.1	61.7	5781.0
84.0	65.0	95.3	42.1	61.7	5781.0	5.8	-2.52	-0.03	-0.04	42.0	61.7	45.4	66.5	4.83	-0.04	42.0	61.7	5842.6
85.0	65.0	95.3	42.0	61.7	5842.6	5.8	-2.52	-0.03	-0.03	42.0	61.6	45.3	66.5	4.84	-0.03	42.0	61.6	5904.3
86.0	65.0	95.3	42.0	61.6	5904.3	5.8	-2.52	-0.03	-0.03	42.0	61.6	45.3	66.5	4.84	-0.03	42.0	61.6	5965.9
87.0	65.0	95.3	42.0	61.6	5965.9	5.8	-2.52	-0.02	-0.03	42.0	61.6	45.3	66.4	4.84	-0.03	42.0	61.6	6027.5
88.0	65.0	95.3	42.0	61.6	6027.5	5.8	-2.52	-0.02	-0.03	42.0	61.5	45.3	66.4	4.85	-0.03	42.0	61.5	6089.0
89.0	65.0	95.3	42.0	61.5	6089.0	5.8	-2.52	-0.02	-0.03	41.9	61.5	45.3	66.4	4.85	-0.03	41.9	61.5	6150.5

Figure E-2. Tabular printout from TSPM (continued).

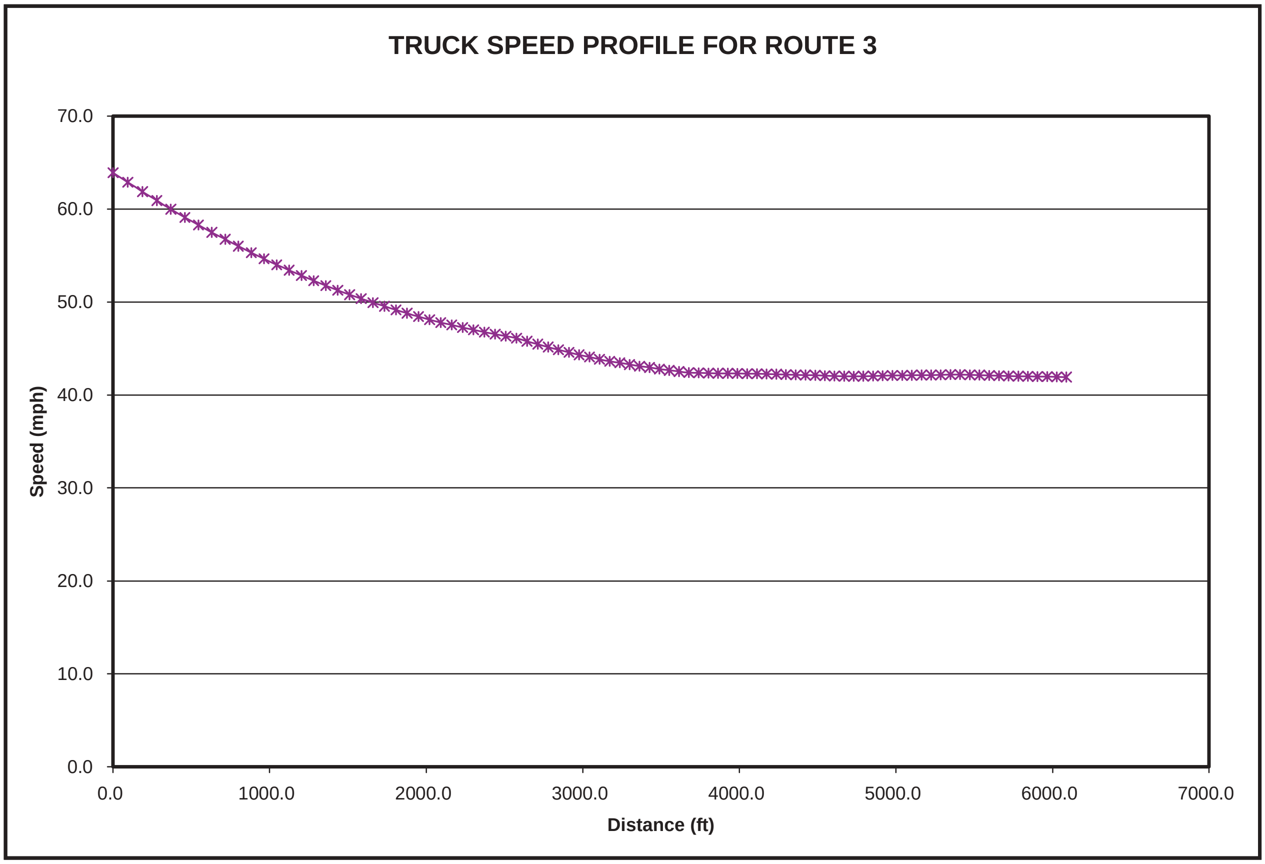


Figure E-3. Example of TSPM speed profile plot.

V' = larger of speed at beginning of interval (V) and 10 ft/s
C_{de} = correction factor for converting sea-level aerodynamic drag to local elevation = $(1 - 0.000006887E)^{4.255}$
C_{pe} = altitude correction factor for converting sea-level net horsepower to local elevation = 1 for diesel engines
E = local elevation (ft)
W/A = weight to projected frontal area ratio (lb/ft^2)
W/NHP = weight to net horsepower ratio (lb/hp)

Equation 1 represents the coasting acceleration of the truck. Equation 2 represents the acceleration as limited by engine horsepower. Equations 3 and 4 combine the coasting and horsepower-limited accelerations into an effective acceleration that allows the truck to use maximum horsepower, except during gear shift delays of 1.5 s, during which the truck is coasting (with no power supplied by the engine). This model of truck performance is based on SAE truck-performance equations which were adapted by St. John and Kobett to incorporate gear shift delays (*86*). There are no driver restraints on using maximum acceleration or maximum speed on upgrades because, unlike passenger car engines, truck engines are designed to operate at full power for sustained periods.

- Columns 11 and 12 represent the calculated speed at the end of the 1-s interval in units of miles per hour and feet per second, based on vehicle performance. The speed in feet per second shown in Column 12 is simply the sum of the speed shown in Column 6 and change in speed computed as the acceleration shown in Column 12, multiplied by the interval duration of 1 s.
- Columns 13 through 15 show the limiting speed, in units of miles per hour and feet per second, and the limiting acceleration, in units of ft/s^2, based on driver preferences. These driver preference limitations are based on research which shows that, even when drivers are not limited by vehicle performance, the driver's preferred acceleration rate will be limited as a function of the magnitude of the difference between the driver's current speed and the desired speed (*64*). Such driver preferences generally come into play only when the acceleration rate that would need to be used by the driver in returning to desired speed exceeds 1.2 ft/s^2. The following three equations represent limitations on new speed

based on maximum preferred accelerations (or decelerations) for drivers for three specific cases:

If $|V_d - V| \leq 1.2$ then,

$$V_n = V_d \tag{5}$$

If $|V_d - V| > 1.2$ and $Vd - V > 0$ then,

$$V_n = V + (1.2 + 0.108\,|V_d - V|)\,t \tag{6}$$

If $|V_d - V| > 1.2$ and $Vd - V < 0$ then,

$$V_n = V - 1.2\,t \tag{7}$$

where

V_d = driver desired speed
V = vehicle speed (ft/s) at the start of time interval t
V_n = new speed (ft/s) at the end of time interval t
t = duration of time interval (sec) (generally, $t = 1$ s)

- Columns 16 through 18 show the actual acceleration over the 1-s interval and the new vehicle speed at the end of the 1-s interval considering both vehicle performance limitations and driver preferences. The new speed, in feet per second, shown in Column 18 is the minimum of the speeds shown in Columns 12 and 14. In other words, if the new speed (based on Equations 5, 6, or 7, as appropriate) is lower than the new speed based on Equations 1 through 4, then the lower speed based on Equations 5, 6, or 7 will govern. The maximum acceleration preferences of drivers generally govern speed choices on the level, on downgrades, and on minor upgrades, but not on steep upgrades.

  Once the speed at the end of the 1-s interval is known, the acceleration during the interval shown in Column 16 can be computed as follows:

$$a = \frac{V_n - V}{t} \tag{8}$$

- Column 19 presents the new position of the vehicle at the end of the 1-s interval, expressed as a distance in feet from coordinate zero. The new position is determined as follows:

$$X_n = X_o + Vt + 0.5\,a\,t^2 \tag{9}$$

where

X_n = position at end of time interval of length t
X_o = position at beginning of time interval of length t

- The new speed in Columns 17 and 18 and the new position in Column 19 on one line of the spreadsheet become the speed at the start of the interval in Columns 4 and 5 and the position at the start of the interval in Column 6 on the next line of the spreadsheet.

APPENDIX F

RECOMMENDED CHANGES TO THE AASHTO *POLICY ON GEOMETRIC DESIGN OF HIGHWAYS AND STREETS*

This appendix presents recommended changes in the AASHTO *Policy on Geometric Design of Highways and Streets* (*1*), commonly known as the *Green Book*, based on the research presented in this report. The appendix presents appropriate changes to the text of the *Green Book* and suggested modification to *Green Book* exhibits. For key recommended changes to the *Green Book*, the modified text is presented in redline format, with additions underlined and deletions indicated with strikethroughs. The rationale for these changes is presented in Chapters 4 and 6 of this report. The appendix is arranged by *Green Book* chapters, in page-order sequence based on the 2001 edition of the *Green Book*.

Chapter 1—Highway Functions

No changes recommended.

Chapter 2—Design Controls and Criteria

The text of the sections on general characteristics and minimum turning radius of design vehicles from p. 15 to 43 should be revised as follows:

GENERAL CHARACTERISTICS

Key controls in geometric highway design are the physical characteristics and the proportions of vehicles of various sizes using the highway. Therefore, it is appropriate to examine all vehicle types, establish general class groupings, and select vehicles of representative size within each class for design use. These selected vehicles, with representative weight, dimensions, and operating characteristics, used to establish highway design controls for accommodating vehicles of designated classes, are known as design vehicles. For purposes of geometric design, each design vehicle has larger physical dimensions and a larger minimum turning radius than most vehicles in its class. The largest design vehicles are usually accommodated in freeway design.

Four general classes of design vehicles have been established, including: (1) passenger cars, (2) buses, (3) trucks, and (4) recreational vehicles. The passenger-car class includes passenger cars of all sizes, sport/utility vehicles, minivans, vans, and pick-up trucks. Buses include inter-city (motor coaches), city transit, school, and articulated buses. The truck class includes single-unit trucks, truck tractor-semitrailer combinations, and truck tractors with semitrailers in combination with full trailers. Recreational vehicles include motor homes, cars with camper trailers, cars with boat trailers, motor homes with boat trailers, and motor homes pulling cars. In addition, the bicycle should also be considered a design vehicle where bicycle use is allowed on a highway.

Dimensions for 20 design vehicles representing vehicles within these general classes are given in Exhibit 2-1. In the design of any highway facility, the designer should consider the largest design vehicle likely to use that facility with considerable frequency or a design vehicle with special characteristics appropriate to a particular intersection in determining the design of such critical features as radii at intersections and radii of turning roadways. In addition, as a general guide, the following may be considered when selecting a design vehicle:

- A passenger car may be selected when the main traffic generator is a parking lot or series of parking lots.
- A two-axle single-unit truck may be used for intersection design of residential streets and park roads.
- A three-axle single-unit truck may be used for design of collector streets and other facilities where larger single-unit trucks are likely.
- A city transit bus may be used in the design of state highway intersections with city streets that are designated bus routes and that have relatively few large trucks using them.
- Depending on expected usage, a large school bus (84 passengers) or a conventional school bus (65 passengers) may be used for the design of intersections of highways with low-volume county highways and township/local roads under 400 ADT. The school bus may also be appropriate for the design of some subdivision street intersections.

The WB-20 [WB-67] truck should generally be the minimum size design vehicle considered for intersections of freeway ramp terminals with arterial crossroads and for other intersections on state highways and industrialized streets that carry high volumes of traffic and/or that provide local access for large trucks. In many cases, operators of WB-20 [WB-67] and larger vehicles pull the rear axles of the vehicle forward to maintain a kingpin-to-rear-axle distance of 12.5 m [41 ft], which makes the truck more maneuverable for the operator and is required by law in many jurisdictions. Where this practice is prevalent, the WB-19 [WB-62] may be used in the design of turning maneuvers, but the WB-20 [WB-67] should be used in design situations where the overall length of the vehicle is considered, such as for sight distance at railroad-highway grade crossings.

In addition to the 20 design vehicles, dimensions for a typical farm tractor are shown in Exhibit 2-1, and the minimum turning radius for a farm tractor with one wagon is shown in Exhibit 2-2. Turning paths of design vehicles can be determined from the dimensions shown in Exhibit 2-1 and 2-2 and through the use of commercially available computer programs.

Metric

		Dimensions (m)											
		Overall			Overhang								Typical Kingpin to Center of Rear Axle
Design Vehicle Type	Symbol	Height	Width	Length	Front	Rear	WB$_1$	WB$_2$	S	T	WB$_3$	WB$_4$	
Passenger Car	P	1.3	2.1	5.8	0.9	1.5	3.4	–	–	–	–	–	–
Single Unit Truck	SU	3.4-4.1	2.4	9.2	1.2	1.8	6.1	–	–	–	–	–	–
Single Unit Truck (three-axle)	SU-8	3.4-4.1	2.4	12.0	1.3	3.2	25.0	–	–	–	–	–	–
Buses													
Inter-city Bus (Motor Coaches)	BUS-12	3.7	2.6	12.2	1.8	1.9[a]	7.3	1.1	–	–	–	–	–
	BUS-14	3.7	2.6	13.7	1.8	2.6[a]	8.1	1.2	–	–	–	–	–
City Transit Bus	CITY-BUS	3.2	2.6	12.2	2.1	2.4	7.6	–	–	–	–	–	–
Conventional School Bus (65 pass.)	S-BUS 11	3.2	2.4	10.9	0.8	3.7	6.5	–	–	–	–	–	–
Large School Bus (84 pass.)	S-BUS 12	3.2	2.4	12.2	2.1	4.0	6.1	–	–	–	–	–	–
Articulated Bus	A-BUS	3.4	2.6	18.3	2.6	3.1	6.7	5.9	1.9[a]	4.0[a]	–	–	–
Combination Trucks													
Rocky Mountain Double-Semitrailer/Trailer	WB-28D	4.1	2.6	13.9	0.7	0.9	5.3	12.3	0.9[b]	2.1[b]	7.0	–	13.0
Intermediate Semitrailer	WB-12	4.1	2.4	16.8	0.9	0.8[a]	3.8	8.4	–	–	–	–	7.8
Interstate Semitrailer	WB-19*	4.1	2.6	20.9	1.2	0.8[a]	6.6	12.3	–	–	–	–	12.5
Interstate Semitrailer	WB-20**	4.1	2.6	22.4	1.2	1.4-0.8[a]	6.6	13.2-13.8	–	–	–	–	13.9
“Double-Bottom”-Semitrailer/Trailer	WB-20D	4.1	2.6	22.4	0.7	0.9	3.4	7.0	0.9[b]	2.1[b]	7.0	–	6.4
Triple-Semitrailer/ Trailers	WB-30T	4.1	2.6	32.0	0.7	0.9	3.4	6.9	0.9[c]	2.1[c]	7.0	7.0	6.4
Turnpike Double-Semitrailer/Trailer	WB-33D*	4.1	2.6	34.8	0.7	0.8[a]	4.4	12.2	0.8[d]	3.1[d]	13.6	–	12.3
Recreational Vehicles													
Motor Home	MH	3.7	2.4	9.2	1.2	1.8	6.1	–	–	–	–	–	–
Car and Camper Trailer	P/T	3.1	2.4	14.8	0.9	3.1	3.4	–	1.5	5.8	–	–	–
Car and Boat Trailer	P/B	–	2.4	12.8	0.9	2.4	3.4	–	1.5	4.6	–	–	–
Motor Home and Boat Trailer	MH/B	3.7	2.4	16.2	1.2	2.4	6.1	–	1.8	4.6	–	–	–
Farm Tractor[f]	TR	3.1	2.4-3.1	4.9[g]	–	–	3.1	2.7	0.9	2.0	–	–	–

NOTE: Since vehicles are manufactured in U.S. Customary dimensions and to provide only one physical size for each design vehicle, the values shown in the design vehicle drawings have been soft converted from numbers listed in feet, and then the numbers in this table have been rounded to the nearest tenth of a meter.

* = Design vehicle with 14.63 m trailer as adopted in 1982 Surface Transportation Assistance Act (STAA).
** = Design vehicle with 16.16 m trailer as grandfathered in with 1982 Surface Transportation Assistance Act (STAA).
[a] = Combined dimension is 5.91 m and articulating section is 1.22 m wide.
[b] = Combined dimension is typically 3.05 m.
[c] = Combined dimension is typically 3.05 m.
[d] = Combined dimension is typically 3.81 m.
[e] = This is overhang from the back axle of the tandem axle assembly.
[f] = Dimensions are for a 150-200 hp tractor excluding any wagon length.
[g] = To obtain the total length of tractor and one wagon, add 5.64 m to tractor length. Wagon length is measured from front of drawbar to rear of wagon, and drawbar is 1.98 m long.

- WB$_1$, WB$_2$, and WB$_4$ are the effective vehicle wheelbases, or distances between axle groups, starting at the front and working towards the back of each unit.
- S is the distance from the rear effective axle to the hitch point or point of articulation.
- T is the distance from the hitch point or point of articulation measured back to the center of the next axle or center of tandem axle assembly.

EXHIBIT 2-1 Design vehicle Dimensions—REVISED

US Customary

Design Vehicle Type	Symbol	Dimensions (ft)											
		Overall			Overhang								Typical Kingpin to Center of Rear Tandem Axle
		Height	Width	Length	Front	Rear	WB_1	WB_2	S	T	WB_3	WB_4	
Passenger Car	P	4.25	7	19	3	5	11	–	–	–	–	–	–
Single Unit Truck	SU	11-13.5	8.0	30	4	6	20	–	–	–	–	–	–
Single Unit Truck (three-axle)	SU-25	11-13.5	8.0	39.5	4	10.5	25	–	–	–	–	–	–
Buses													
Inter-city Bus (Motor Coaches)	BUS-40	12.0	8.5	40	6	6.3[a]	24	3.7	–	–	–	–	–
	BUS-45	12.0	8.5	45	6	8.5[a]	26.5	4.0	–	–	–	–	–
City Transit Bus	CITY-BUS	10.5	8.5	40	7	8	25	–	–	–	–	–	–
Conventional School Bus (65 pass.)	S-BUS 36	10.5	8.0	35.8	2.5	12	21.3	–	–	–	–	–	–
Large School Bus (84 pass.)	S-BUS 40	10.5	8.0	40	7	13	20	–	–	–	–	–	–
Articulated Bus	A-BUS	11.0	8.5	60	8.6	10	22.0	19.4	6.2[a]	13.2[a]	–	–	–
Combination Trucks													
Rocky Mountain Double-Semitrailer/Trailer	WB-92D	13.5	8.5	98.3	2.33	3	17.5	40.5	3.0[b]	7.0[b]	23.0	–	42.5
Intermediate Semitrailer	WB-40	13.5	8.0	45.5	3	2.5[a]	12.5	27.5	–	–	–	–	25.5
Interstate Semitrailer	WB-62*	13.5	8.5	68.5	4	2.5[a]	21.6	40.4	–	–	–	–	41.0
Interstate Semitrailer	WB-67**	13.5	8.5	73.5	4	4.5-2.5[a]	21.6	43.4-45.4	–	–	–	–	45.5
“Double-Bottom”-Semitrailer/Trailer	WB-67D	13.5	8.5	73.3	2.33	3	11.0	23.0	3.0[b]	7.0[b]	23.0	–	21.0
Triple-Semitrailer/ Trailers	WB-100T	13.5	8.5	104.8	2.33	3	11.0	22.5	3.0[c]	7.0[c]	23.0	23.0	21.0
Turnpike Double-Semitrailer/Trailer	WB-109D*	13.5	8.5	114	2.33	2.5[e]	14.3	39.9	2.5[d]	10.0[d]	44.5	–	40.5
Recreational Vehicles													
Motor Home	MH	12	8	30	4	6	20	–	–	–	–	–	–
Car and Camper Trailer	P/T	10	8	48.7	3	10	11	–	5	19	–	–	–
Car and Boat Trailer	P/B	–	8	42	3	8	11	–	5	15	–	–	–
Motor Home and Boat Trailer	MH/B	12	8	53	4	8	20	–	6	15	–	–	–
Farm Tractorf	TR	10	8-10	16[g]	–	–	10	9	3	6.5	–	–	–

* = Design vehicle with 48 ft trailer as adopted in 1982 Surface Transportation Assistance Act (STAA).
** = Design vehicle with 53 ft trailer as grandfathered in with 1982 Surface Transportation Assistance Act (STAA).
[a] = Combined dimension is 19.4 ft and articulating section is 4 ft wide.
[b] = Combined dimension is typically 10.0 ft.
[c] = Combined dimension is typically 10.0 ft.
[d] = Combined dimension is typically 12.5 ft.
[e] = This is overhang from the back axle of the tandem axle assembly.
[f] = Dimensions are for a 150-200 hp tractor excluding any wagon length.
[g] = To obtain the total length of tractor and one wagon, add 18.5 ft to tractor length. Wagon length is measured from front of drawbar to rear of wagon, and drawbar is 6.5 ft long.

- WB_1, WB_2, and WB_4 are the effective vehicle wheelbases, or distances between axle groups, starting at the front and working towards the back of each unit.
- S is the distance from the rear effective axle to the hitch point or point of articulation.
- T is the distance from the hitch point or point of articulation measured back to the center of the next axle or center of tandem axle assembly.

EXHIBIT 2-1 Design vehicle Dimensions—REVISED *(continued)*

Metric

Design Vehicle Type	Passenger Car	Single Unit Truck	Single Unit Truck (Three Axle)	Inter-city Bus (Motor Coach)		City Transit Bus	Conventional School Bus (65 pass.)	Large[2] School Bus (84 pass.)	Articulated Bus	Intermediate Semi-trailer
Symbol	P	SU	SU-8	BUS-12	BUS-14	CITY-BUS	S-BUS11	S-BUS12	A-BUS	WB-12
Minimum Design Turning Radius (ft)	7.3	12.8	15.7	13.7	13.7	12.8	11.9	12.0	12.1	12.2
Center-line[1] Turning Radius (CTR)	6.4	11.6	14.5	12.4	12.4	11.5	10.6	10.8	10.8	11.0
Minimum Inside Radius (ft)	4.4	8.6	11.1	8.4	7.8	7.5	7.3	7.7	6.5	5.9

Design Vehicle Type	Interstate Semi-trailer		"Double Bottom" Combination	Rocky Mtn Double	Triple Semi-trailer/ trailers	Turnpike Double Semi-trailer/ trailer	Motor Home	Car and Camper Trailer	Car and Boat Trailer	Motor Home and Boat Trailer	Farm[3] Tractor w/One Wagon
Symbol	WB-19*	WB-20** or WB-20	WB-20D	WB-28D	WB-30T	WB-33D*	MH	P/T	P/B	MH/B	TR/W
Minimum Design Turning Radius (ft)	13.7	13.7	13.7	25.0	13.7	18.3	12.2	10.1	7.3	15.2	5.5
Center-line[1] Turning Radius (CTR)	12.5	12.5	12.5	23.8	12.5	17.1	11.0	9.1	6.4	14.0	4.3
Minimum Inside Radius (ft)	2.4	1.3	5.9	25.1	3.0	4.5	7.9	5.3	2.8	10.7	3.2

NOTE: Numbers in table have been rounded to the nearest tenth of a meter.

* = Design vehicle with 14.63 m trailer as adopted in 1982 Surface Transportation Assistance Act (STAA).

** = Design vehicle with 16.16 m trailer as grandfathered in with 1982 Surface Transportation Assistance Act (STAA).

[1] = The turning radius assumed by a designer when investigating possible turning paths and is set at the centerline of the front axle of a vehicle. If the minimum turning path is assumed, the CTR approximately equals the minimum design turning radius minus one-half the front width of the vehicle.

[2] = School buses are manufactured from 42 passenger to 84 passenger sizes. This corresponds to wheelbase lengths of 3,350 mm to 6,020 mm, respectively. For these different sizes, the minimum design turning radii vary from 8.78 m to 12.01 m and the minimum inside radii vary from 4.27 m to 7.74 m.

[3] = Turning radius is for 150-200 hp tractor with one 5.64 m long wagon attached to hitch point. Front wheel drive is disengaged and without brakes being applied.

EXHIBIT 2-2 Minimum turning radii of design vehicles—REVISED

Recent research has developed several design vehicles larger than those presented here, with overall lengths up to 39.3 m [129.3 ft]. These larger design vehicles are not generally needed for design to accommodate the current truck fleet. However, if needed to address conditions at specific sites, their dimensions and turning performance can be found in NCHRP Report 505.

MINIMUM TURNING PATHS OF DESIGN VEHICLES

Exhibits 2-3 through 2-23 present the minimum turning paths for 20 typical design vehicles. The principal dimensions affecting design are the

US Customary

Design Vehicle Type	Passenger Car	Single Unit Truck	Single Unit Truck (Three Axle)	Inter-city Bus (Motor Coach)		City Transit Bus	Conventional School Bus (65 pass.)	Large[2] School Bus (84 pass.)	Articulated Bus	Intermediate Semi-trailer
Symbol	P	SU	SU-25	BUS-40	BUS-45	CITY-BUS	S-BUS36	S-BUS40	A-BUS	WB-40
Minimum Design Turning Radius (ft)	24	42	51.5	45	45	42.0	38.9	39.4	39.8	40
Center-line[1] Turning Radius (CTR)	21	38	47.5	40.8	40.8	37.8	34.9	35.4	35.5	36
Minimum Inside Radius (ft)	14.4	28.3	36.4	27.6	25.5	24.5	23.8	25.4	21.3	19.3

Design Vehicle Type	Interstate Semi-trailer		"Double Bottom" Combination	Rocky Mtn Double	Triple Semi-trailer/ trailers	Turnpike Double Semi-trailer/ trailer	Motor Home	Car and Camper Trailer	Car and Boat Trailer	Motor Home and Boat Trailer	Farm[3] Tractor w/One Wagon
Symbol	WB-62*	WB-65** or WB-67	WB-67D	WB-92D	WB-100T	WB-109D*	MH	P/T	P/B	MH/B	TR/W
Minimum Design Turning Radius (ft)	45	45	45	82.0	45	60	40	33	24	50	18
Center-line[1] Turning Radius (CTR)	41	41	41	78.0	41	56	36	30	21	46	14
Minimum Inside Radius (ft)	7.9	4.4	19.3	82.4	9.9	14.9	25.9	17.4	8.0	35.1	10.5

NOTE: Numbers in table have been rounded to the nearest tenth of a meter.

* = Design vehicle with 14.63 m trailer as adopted in 1982 Surface Transportation Assistance Act (STAA).

** = Design vehicle with 16.16 m trailer as grandfathered in with 1982 Surface Transportation Assistance Act (STAA).

[1] = The turning radius assumed by a designer when investigating possible turning paths and is set at the centerline of the front axle of a vehicle. If the minimum turning path is assumed, the CTR approximately equals the minimum design turning radius minus one-half the front width of the vehicle.

[2] = School buses are manufactured from 42 passenger to 84 passenger sizes. This corresponds to wheelbase lengths of 3,350 mm to 6,020 mm, respectively. For these different sizes, the minimum design turning radii vary from 8.78 m to 12.01 m and the minimum inside radii vary from 4.27 m to 7.74 m.

[3] = Turning radius is for 150-200 hp tractor with one 5.64 m long wagon attached to hitch point. Front wheel drive is disengaged and without brakes being applied.

EXHIBIT 2-2 Minimum turning radii of design vehicles—REVISED *(continued)*

minimum centerline turning radius (CTR), the out-to-out track width, the wheelbase, and the path of the inner rear tire. Effects of driver characteristics (such as the speed at which the driver makes a turn) and of the slip angles of wheels are minimized by assuming that the speed of the vehicle for the minimum turning radius is less than 15 km/h [10 mph].

The boundaries of the turning paths of each design vehicle for its sharpest turns are established by the outer trace of the front overhang and the path of the inner rear wheel. This turn assumes that the outer front wheel follows the circular arc defining the minimum centerline turning radius as determined by the vehicle steering mechanism. The minimum radii of the outside and inside wheel paths and the centerline turning radii (CTR) for specific design vehicles are given in Exhibit 2-2.

Trucks and buses generally require more generous geometric designs than do passenger vehicles. This is largely because trucks and buses are wider and have longer wheelbases and greater minimum turning radii, which are the principal vehicle dimensions affecting horizontal alignment and cross section. Single-unit trucks and buses have smaller minimum turning radii than most combination vehicles, but because of their greater offtracking, the longer combination vehicles need greater turning path widths. Exhibit 2-11 defines the turning characteristics of a typical tractor/semitrailer combination. Exhibit 2-12 defines the lengths of tractors commonly used in tractor/semitrailer combinations.

A combination truck is a single-unit truck with a full trailer, a truck tractor with a semitrailer, or a truck tractor with a semitrailer and one or more full trailers. Because combination truck sizes and turning characteristics vary widely, there are several combination truck design vehicles. These combination trucks are identified by the designation WB, together with the wheel base or another length dimension in both metric and U.S. customary units. The combination truck design vehicles are: (1) the WB-12 [WB-40] design vehicle representative of intermediate size tractor-semitrailer combinations, (2) the WB-19 [WB-62] design vehicle representative of larger tractor semitrailer combinations allowed on selected highways by the Surface Transportation Assistance Act of 1982, (3) the WB-20 [WB-67] design vehicle representative of a larger tractor-semitrailer allowed to operate on selected highways by “grandfather” rights under the Surface Transportation Assistance Act of 1982, (4) the WB-20D [WB-67D] design vehicle representative of a tractor-semitrailer/full trailer (doubles or twin trailer) combination commonly in use, (5) the WB-28D [WB-92D] Rocky Mountain double tractor-semitrailer/full trailer combination with one longer and one shorter trailer used extensively in a number of Western states, (6) the WB-30T [WB-100T] design vehicle representative of tractor-semitrailer/full trailer/full trailer combinations (triples) selectively in use, and (7) the WB-33D [WB-109D] design vehicle representative of larger tractor-semitrailer/full trailer combinations (turnpike double) selectively in use. Although Rocky Mountain doubles, turnpike doubles, and triple trailers are not permitted on many highways, their occurrence does warrant inclusion in this publication.

The minimum turning radii and transition lengths shown in the exhibits are for turns at less than 15 km/h [10 mph]. Longer transition curves and larger curve radii are needed for roadways with higher speeds. The radii shown are considered appropriate minimum values for use in design, although skilled drivers might be able to turn with a slightly smaller radius.

The dimensions of the design vehicles take into account recent trends in motor vehicle sizes manufactured in the United States and represent a composite of vehicles currently in operation. However, the design vehicle dimensions are intended to represent vehicle sizes that are critical to geometric design and thus are larger than nearly all vehicles belonging to their corresponding vehicle classes.

The turning paths shown in Exhibits 2-3 through 2-10 and Exhibits 2-13 through 2-23 were derived by using commercially available computer programs.

The P design vehicle, with the dimensions and turning characteristics shown in Exhibit 2-3, represents a larger passenger car.

The SU design vehicle represents a larger single-unit truck. The control dimensions indicate the minimum turning path for most single-unit trucks now in operation (see Exhibit 2-4). On long-distance facilities serving large over-the-road truck traffic or inter-city buses (motor coaches), the design vehicle should generally be either a combination truck or an inter-city bus (see Exhibit 2-5 or Exhibit 2-6).

For intra-city or city transit buses, a design vehicle designated as CITY-BUS is shown in Exhibit 2-7. This design vehicle has a wheel base of 7.62 m [25 ft] and an overall length of 12.20 m [40 ft]. Buses serving particular urban areas may not conform to the dimensions shown in Exhibit 2-7. For example, articulated buses, which are now used in certain cities, are longer than a conventional bus, with a permanent hinge near the vehicle’s center that allows more maneuverability. Exhibit 2-10 displays the critical dimensions for the A-BUS design vehicle. Also, due to the importance of school buses, two design vehicles designated as S-BUS 11 [S-BUS 36] and S-BUS 12 [S-BUS 40] are shown in Exhibits 2-8 and 2-9, respectively. The larger design vehicle is an 84-passenger bus and the smaller design vehicle is a 65-passenger bus. The highway designer should also be aware that for certain buses the combination of ground clearance, overhang, and vertical curvature of the roadway may present problems in hilly areas.

Exhibits 2-13 through 2-19 show dimensions and the minimum turning paths of the design vehicles that represent various combination trucks. For local roads and streets, the WB-12 [WB-40] is often considered an appropriate design vehicle. The larger combination trucks are appropriate for design of facilities that serve over-the-road trucks.

Exhibits 2-20 through 2-23 indicate minimum turning paths for typical recreational vehicles.

In addition to the vehicles shown in Exhibits 2-3 through 2-10 and Exhibits 2-13 through 2-23, other vehicles may be used for selected design applications, as appropriate. With the advent of computer programs that can derive turning path plots, the designer can determine the path characteristics of any selected vehicle if it differs from those shown (**1**).

Exhibit 2-1 (Design Vehicle Dimensions) and Exhibit 2-2 (Minimum Turning Radii of Design Vehicles) should be revised as shown to incorporate the recommended SU-8 [SU-25] and WB-28D [WB-92D] design vehicles and to delete the WB-15 [WB-50] design vehicle. In Exhibit 2-1, it is recommended that the rightmost column be changed from KCRA distance to KCRT distance for two reasons. First, most states that regulate the kingpin-to-rear-axle distance regulate the KCRT distance rather than the KCRA distance. Second, the KCRT distance, rather than the KCRA distance, is illustrated in Exhibits 2-13 through 2-19.

Exhibit 2-14 (Minimum Turning Path for Intermediate Semitrailer WB-15 [WB-50] Design Vehicle) should be deleted. New minimum turning path exhibits for the recommended SU-8 [SU-25] and WB-28D [WB-92D] design vehicles should be added. The new exhibits to be used are shown in Figures C-15 and C-20 of this report.

Exhibit 2-15 (Minimum Turning Path for Intermediate Semitrailer WB-19 [WB-62] Design Vehicle) needs to be updated to change the KCRT distance from 12.3 to 12.5 m [40.5 to 41.0 ft]. The updated exhibit is presented in Figure 10 in this report.

Exhibit 2-16 (Minimum Turning Path for Intermediate Semitrailer WB-20 [WB-65 or WB-67] Design Vehicle) should be modified to apply onto a WB-20 [WB-67] design vehicle with a KCRT distance of 13.9 m [45.5 ft]. The applicable truck is shown in Figure C-7 and the applicable turning plot is shown in Figure C-16.

Chapter 3—Elements of Design

In Exhibit 3-47 (Track Width for Widening of Traveled Way at Horizontal Curves), it is recommended that the WB-15 [WB-50] design vehicle be deleted and the WB-19 [WB-62] design vehicle be added.

In Exhibit 3-48 (Front Overhang for Widening of Traveled Way on Curves), delete the reference to the WB-15 [WB-50] in the legend for Line P and add a reference to the WB-28D [WB-92D] in the legend for Line P and a reference to the SU-8 [SU-25] design vehicle in the legend for Line SU.

In the text for Design Values for Traveled Way Widening on p. 214, replace the reference to the WB-15 [WB-50] design vehicle with a reference to the WB-19 [WB-62] design vehicle. In addition, replace Exhibit 3-51 (Calculated and Design Values for Traveled Way Widening on Open Highway Curves [Two-Lane Highways, One-Way or Two-Way]) and Exhibit 3-52 (Adjustments for Traveled Way Widening Values on Open Highway Curves [Two-Lane Highways, One-Way or Two-Way]) with the revised versions presented here. These exhibits have been revised to use the WB-19 [WB-62] design vehicle, rather than the WB-15 [WB-50] design vehicle, as the base.

In Exhibit 3-54 (Derived Pavement Widths for Turning Roadways for Different Design Vehicles), delete the column for the WB-15 [WB-50] design vehicle and add columns for the SU-8 [SU-25] and WB-28D [WB-92D] design vehicles.

Metric																		
Radius of curve (m)	Roadway width = 7.2 m						Roadway width = 6.6 m						Roadway width = 6.0 m					
	Design speed (km/h)						Design speed (km/h)						Design speed (km/h)					
	50	60	70	80	90	100	50	60	70	80	90	100	50	60	70	80	90	100
3000	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.3	0.3	0.3	0.3	0.5	0.5	0.6	0.6	0.6	0.6
2500	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.3	0.3	0.3	0.3	0.3	0.5	0.6	0.6	0.6	0.6	0.6
2000	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.3	0.3	0.3	0.3	0.4	0.6	0.6	0.6	0.6	0.6	0.7
1500	0.0	0.0	0.1	0.1	0.1	0.1	0.3	0.3	0.4	0.4	0.4	0.4	0.6	0.6	0.7	0.7	0.7	0.7
1000	0.2	0.2	0.2	0.3	0.3	0.3	0.5	0.5	0.5	0.6	0.6	0.6	0.8	0.8	0.8	0.9	0.9	0.9
900	0.2	0.2	0.3	0.3	0.3	0.4	0.5	0.5	0.6	0.6	0.6	0.7	0.8	0.8	0.9	0.9	0.9	1.0
800	0.2	0.3	0.3	0.3	0.4	0.4	0.5	0.6	0.6	0.6	0.7	0.7	0.8	0.9	0.9	0.9	1.0	1.0
700	0.3	0.3	0.3	0.4	0.4	0.5	0.6	0.6	0.6	0.7	0.7	0.8	0.9	0.9	0.9	1.0	1.0	1.1
600	0.3	0.4	0.4	0.4	0.5	0.5	0.6	0.7	0.7	0.7	0.8	0.8	0.9	1.0	1.0	1.0	1.1	1.1
500	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.2	1.2
400	0.6	0.6	0.7	0.7	0.8	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.2	1.2	1.3	1.3	1.4	1.4
300	0.7	0.8	0.8	0.9	1.0	1.0	1.0	1.1	1.1	1.2	1.3	1.3	1.3	1.4	1.4	1.5	1.6	1.6
250	0.8	0.9	1.0	1.0	1.1		1.1	1.2	1.3	1.3	1.4		1.4	1.5	1.6	1.6	1.7	
200	1.1	1.2	1.3	1.3			1.4	1.5	1.6	1.6			1.7	1.8	1.9	1.9		
150	1.5	1.6	1.7	1.7			1.8	1.9	2.0	2.0			2.1	2.2	2.3	2.3		
140	1.6	1.7					1.9	2.0					2.2	2.3				
130	1.8	1.9					2.1	2.2					2.4	2.5				
120	1.9	2.0					2.2	2.3					2.5	2.6				
110	2.1	2.2					2.4	2.5					2.7	2.8				
100	2.2	2.3					2.5	2.6					2.8	2.9				
90	2.5						2.8						3.1					
80	2.8						3.1						3.4					
70	3.2						3.5						3.8					

NOTES: Values shown are for WB-19 design vehicle and represent widening in meters. For other design vehicles, use adjustments in Exhibit 3-52.
Values less than 0.6 m may be disregarded.
For 3-lane roadways, multiply above values by 1.5.
For 4-lane roadways, multiply above values by 2.

EXHIBIT 3-51 Calculated and design values for traveled way widening on open highway curves (two-lane highways, one-way, or two-way)—REVISED

In the text for Widths for Turning Roadways at Intersections on p. 225, in the discussion of design values for Traffic Condition C, delete the reference to the WB-15 [WB-50] truck. In the box at the top of p. 226, replace the references to the WB-15 [WB-50] with the WB-12 [WB-40]. The note in the second to last paragraph on p. 223 addresses the applicability of larger design vehicles to the cases discussed here.

The text of the section on Critical Lengths of Grade for Design on pp. 242 to 247 should be modified as follows:

Critical Lengths of Grade for Design

Maximum grade in itself is not a complete design control. It is also appropriate to consider the length of a particular grade in relation to desirable vehicle operation. The term “critical length of grade” is used to indicate the maximum length of a designated upgrade on which a loaded truck can operate without an unreasonable reduction in speed. For a given grade, lengths less than critical result in acceptable operation in the desired range of speeds. If the desired freedom of operation is to be maintained on grades longer than critical, design adjustments such as changes in location to reduce grades or addition of extra lanes should be considered. The data for critical lengths of grade should be used with other pertinent factors

Radius of curve (ft)	US Customary																				
	Roadway width = 24 ft							Roadway width = 22 ft							Roadway width = 20 ft						
	Design speed (mph)							Design speed (mph)							Design speed (mph)						
	30	35	40	45	50	55	60	30	35	40	45	50	55	60	30	35	40	45	50	55	60
7000	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.7	0.7	0.8	0.8	0.9	1.0	1.0	1.7	1.7	1.8	1.8	1.9	2.0	2.0
6500	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.7	0.8	0.8	0.9	0.9	1.0	1.1	1.7	1.8	1.8	1.9	1.9	2.0	2.1
6000	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.7	0.8	0.9	0.9	1.0	1.1	1.1	1.7	1.8	1.9	1.9	2.0	2.1	2.1
5500	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.8	0.8	0.9	1.0	1.0	1.1	1.2	1.8	1.8	1.9	2.0	2.0	2.1	2.2
5000	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.8	0.9	1.0	1.0	1.1	1.2	1.2	1.8	1.9	2.0	2.0	2.1	2.2	2.2
4500	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.9	0.9	1.0	1.1	1.2	1.2	1.3	1.9	1.9	2.0	2.1	2.2	2.2	2.3
4000	0.2	0.2	0.2	0.3	0.4	0.4	0.5	1.0	1.1	1.2	1.3	1.4	1.4	1.5	2.0	2.1	2.2	2.3	2.4	2.4	2.5
3500	0.2	0.2	0.3	0.4	0.5	0.5	0.6	1.1	1.2	1.3	1.4	1.5	1.5	1.6	2.1	2.2	2.3	2.4	2.5	2.5	2.6
3000	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.2	1.3	1.4	1.5	1.6	1.7	1.8	2.2	2.3	2.4	2.5	2.6	2.7	2.8
2500	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.5	2.6	2.7	2.8	2.9	3.0	3.1
2000	0.7	0.8	0.9	1.0	1.1	1.3	1.4	1.7	1.8	1.9	2.0	2.1	2.3	2.4	2.7	2.8	2.9	3.0	3.1	3.3	3.4
1800	0.9	1.0	1.2	1.3	1.4	1.5	1.6	1.9	2.0	2.2	2.3	2.4	2.5	2.6	2.9	3.0	3.2	3.3	3.4	3.5	3.6
1600	1.1	1.2	1.3	1.4	1.6	1.7	1.8	2.1	2.2	2.3	2.4	2.6	2.7	2.8	3.1	3.2	3.3	3.4	3.6	3.7	3.8
1400	1.3	1.5	1.6	1.7	1.9	2.0	2.1	2.3	2.5	2.6	2.7	2.9	3.0	3.1	3.3	3.5	3.6	3.7	3.9	4.0	4.1
1200	1.6	1.7	1.9	2.0	2.2	2.3	2.4	2.6	2.7	2.9	3.0	3.2	3.3	3.4	3.6	3.7	3.9	4.0	4.2	4.3	4.4
1000	2.0	2.2	2.3	2.5	2.6	2.8	3.0	3.0	3.2	3.3	3.5	3.6	3.8	4.0	4.0	4.2	4.3	4.5	4.6	4.8	5.0
900	2.3	2.5	2.7	2.8	3.0	3.2		3.3	3.5	3.7	3.8	4.0	4.2		4.3	4.5	4.7	4.8	5.0	5.2	
800	2.7	2.9	3.0	3.2	3.4	3.6		3.7	3.9	4.0	4.2	4.4	4.6		4.7	4.9	5.0	5.2	5.4	5.6	
700	3.1	3.3	3.5	3.7	3.9			4.1	4.3	4.5	4.7	4.9			5.1	5.3	5.5	5.7	5.9		
600	3.8	4.0	4.2	4.4	4.6			4.8	5.0	5.2	5.4	5.6			5.8	6.0	6.2	6.4	6.6		
500	4.6	4.8	5.0	5.2				5.6	5.8	6.0	6.2				6.6	6.8	7.0	7.2			
450	5.1	5.3	5.5					6.1	6.3	6.5					7.1	7.3	7.5				
400	5.8	6.0	6.3					6.8	7.0	7.3					7.8	8.0	8.3				
350	6.7	7.0	7.2					7.7	8.0	8.2					8.7	9.0	9.2				
300	7.8	8.1						8.8	9.1						9.8	10.1					
250	9.4							10.4							11.4						
200	11.8							12.8							13.8						

NOTES: Values shown are for WB-62 design vehicle and represent widening in feet. For other design vehicles, use adjustments in Exhibit 3-52.
Values less than 2.0 ft may be disregarded.
For 3-lane roadways, multiply above values by 1.5.
For 4-lane roadways, multiply above values by 2.

EXHIBIT 3-51 Calculated and design values for traveled way widening on open highway curves (two-lane highways, one-way, or two-way)—REVISED *(continued)*

(such as traffic volume in relation to capacity) to determine where added lanes are warranted.

To establish design values for critical lengths of grade for which gradeability of trucks is the determining factor, data, or assumptions are needed for the following:

1. Size and power of a representative truck or truck combination to be used as a design vehicle along with the gradeability data for this vehicle:

   Recent data show that the 85th percentile weight/power ratios for trucks on main highways are typically in the range from 102 to 126 kg/kW [170 to 210 lb/hp] NCHRP Report 505. A typical loaded truck, powered so that the weight/power ratio is about 120 kg/kW [200 lb/hp], is representative of the size and type of vehicle normally used as a design control for main highways. Data in Exhibits 3-59 and 3-60 apply to such a vehicle. More powerful trucks with weight/power ratios in the range from 102 to 108 kg/kW may be appropriate in some Western states, while some two-lane highways that are not major intercity routes may have distinctly different truck populations with weight/power ratios higher than 126 kg/kW [210 lb/hp].

Metric							US customary						
Radius of curve (m)	Design vehicle						Radius of curve (ft)	Design vehicle					
	SU	WB-12	WB-20	WB-20D	WB-30T	WB-33D		SU	WB-40	WB-67	WB-67D	WB-100T	WB-109D
3000	–0.3	–0.3	0.0	0.0	0.0	0.1	7000	–1.2	–1.2	0.0	–0.1	–0.1	0.2
2500	–0.3	–0.3	0.0	0.0	0.0	0.1	6500	–1.2	–1.2	0.0	–0.1	0.0	0.2
2000	–0.3	–0.3	0.0	0.0	0.0	0.1	6000	–1.3	–1.2	0.1	–0.1	0.0	0.2
1500	–0.4	–0.3	0.1	0.0	0.0	0.1	5500	–1.3	–1.2	0.1	–0.1	0.0	0.3
1000	–0.5	–0.5	0.0	0.0	–0.1	0.1	5000	–1.3	–1.2	0.1	–0.1	0.0	0.3
900	–0.5	–0.5	0.0	0.0	–0.1	0.1	4500	–1.3	–1.2	0.1	–0.1	0.0	0.4
800	–0.5	–0.5	0.0	0.0	–0.1	0.1	4000	–1.4	–1.4	0.0	–0.3	–0.1	0.3
700	–0.5	–0.5	0.0	0.0	–0.1	0.2	3500	–1.5	–1.4	0.1	–0.3	–0.1	0.4
600	–0.6	–0.5	0.0	0.0	0.0	0.2	3000	–1.5	–1.4	0.1	–0.3	–0.1	0.5
500	–0.6	–0.5	0.1	0.0	0.0	0.3	2500	–1.7	–1.5	0.1	–0.4	–0.2	0.5
400	–0.7	–0.6	0.0	0.0	–0.1	0.3	2000	–1.8	–1.6	0.2	–0.4	–0.1	0.7
300	–0.8	–0.7	0.1	–0.3	–0.1	0.4	1800	–1.9	–1.7	0.1	–0.5	–0.2	0.7
250	–0.9	–0.7	0.1	–0.3	–0.1	0.6	1600	–2.0	–1.8	0.2	–0.5	–0.2	0.9
200	–1.1	–0.9	0.1	–0.4	–0.1	0.7	1400	–2.2	–1.9	0.1	–0.7	–0.3	1.0
150	–1.3	–1.1	0.2	–0.5	–0.2	0.9	1200	–2.3	–2.0	0.3	–0.7	–0.2	1.2
140	–1.3	–1.1	0.2	–0.5	–0.2	1.0	1000	–2.6	–2.2	0.3	–0.8	–0.3	1.4
130	–1.5	–1.2	0.1	–0.7	–0.3	1.0	900	–2.8	–2.4	0.3	–0.9	–0.3	1.6
120	–1.6	–1.3	0.2	–0.7	–0.2	1.1	800	–3.0	–2.6	0.3	–1.1	–0.4	1.8
110	–1.7	–1.4	0.2	–0.8	–0.3	1.1	700	–3.3	–2.8	0.4	–1.2	–0.4	2.0
100	–1.8	–1.5	0.2	–0.8	–0.3	1.3	600	–3.7	–3.1	0.4	–1.5	–0.5	2.3
90	–2.0	–1.6	0.2	–0.9	–0.4	1.4	500	–4.2	–3.5	0.5	–1.7	–0.6	2.8
80	–2.2	–1.8	0.3	–1.0	–0.4	1.6	450	–4.6	–3.8	0.6	–1.9	–0.7	3.2
70	–2.5	–2.0	0.3	–1.2	–0.4	1.9	400	–5.0	–4.1	0.7	–2.1	–0.8	3.5
							350	–5.7	–4.7	0.7	–2.5	–0.9	4.0
							300	–6.5	–5.2	0.8	–2.9	–1.1	4.7
							250	–7.5	–6.1	1.1	–3.5	–1.2	5.7
							200	–9.2	–7.4	1.3	–4.4	–1.6	7.2

NOTES: Adjustments are applied by adding to or subtracting from the values in Exhibit 3-51.
Adjustments depend only on radius and design vehicle; they are independent of roadway width and design speed.
For 3-lane roadways, multiply above values by 1.5.
For 4-lane roadways, multiply above values by 2.0.

EXHIBIT 3-52 Adjustments for traveled way widening values on open highway curves (two-lane highways, one-way, or two-way)—REVISED

2. Speed at entrance to critical length of grade:

The average running speed as related to design speed can be used to approximate the speed of vehicles beginning an uphill climb. This estimate is, of course, subject to adjustment as approach conditions may determine. Where vehicles approach on nearly level grades, the running speed can be used directly. For a downhill approach it should be increased somewhat, and for an uphill approach it should be decreased.

3. Minimum speed on the grade below in which interference to following vehicles is considered unreasonable:

No specific data are available on which to base minimum tolerable speeds of trucks on upgrades. It is logical to assume that such minimum speeds should be in direct relation to the design speed. Minimum truck speeds of about 40 to 60 km/h [25 to 40 mph] for the majority of highways (on which design speeds are about 60 to 100 km/h [40 to 60 mph]) probably are not unreasonably annoying to following drivers unable to pass on two-lane roads, if the time interval during which they are unable to pass is not too long. The time interval is not likely to be annoying on two-lane roads with volumes well below their capacities, whereas it is likely to be annoying on two-lane roads with volumes near capacity. Lower minimum truck speeds can probably be tolerated on multilane highways rather than on two-lane roads because there is more opportunity for and less difficulty in passing. Highways should be designed so that the speeds of trucks will not be reduced enough to cause intolerable conditions for following drivers.

Studies show that, regardless of the average speed on the highway, the more a vehicle deviates from the average speed, the greater its chances of becoming involved in a crash. One such study (**41**) used the speed distribution of vehicles traveling on highways in one state, and related it to the crash involvement rate to obtain the rate for trucks of four or more axles operating on level grades. The crash involvement rates for truck speed reductions of 10, 15, 25, and 30 km/h [5, 10, 15, and 20 mph] were developed assuming the reduction in the average speed for all vehicles on a grade was 30 percent of the truck speed reduction on the same grade. The results of this analysis are shown in Exhibit 3-62.

A common basis for determining critical length of grade is based on a reduction in speed of trucks below the average running speed of traffic. The ideal would be for all traffic to operate at the average speed. This, however, is not practical. In the past, the general practice has been to use a reduction in truck speed of 25 km/h [15 mph] below the average running speed of all traffic to identify the critical length of grade. As shown in Exhibit 3-62, the crash involvement rate increases significantly when the truck speed reduction exceeds 15 km/h [10 mph] with the involvement rate being 2.4 times greater for a 25-km/h [15-mph] reduction than for a 15-km/h [10-mph] reduction. On the basis of these relationships, it is recommended that a 15-km/h [10-mph] reduction criterion be used as the general guide for determining critical lengths of grade.

The length of any given grade that will cause the speed of a representative truck (120 kg/kW [200 lb/hp]) entering the grade at 110 km/h [70 mph] to be reduced by various amounts below the average running speed of all traffic is shown graphically in Exhibit 3-63, which is based on the truck performance data presented in Exhibit 3-59. The curve showing a 15-km/h [10-mph] speed reduction is used as the general design guide for determining the critical lengths of grade. Similar information on the critical length of grade for recreational vehicles may be found in Exhibit 3-64, which is based on the recreational vehicle performance data presented in Exhibit 3-61.

Where the entering speed is less than 110 km/h [70 mph], as may be the case where the approach is on an upgrade, the speed reductions shown in Exhibits 3-63 and 3-64 will occur over shorter lengths of grade. Conversely, where the approach is on a downgrade, the probable approach speed is greater than 110 km/h [70 mph] and the truck or recreational vehicle will ascend a greater length of grade than shown in the exhibits before the speed is reduced to the values shown.

The method of using Exhibit 3-63 to determine critical lengths of grade is demonstrated in the following examples.

Assume that a highway is being designed for 100 km/h [60 mph] and has a fairly level approach to a 4 percent upgrade. The 15-km/h [10-mph] speed reduction curve in Exhibit 3-63 shows the critical length of grade to be 350 m [1,200 ft]. If, instead, the design speed was 60 km/h [40 mph], the initial and minimum tolerable speeds on the grade would be different, but for the same permissible speed reduction the critical length would still be 360 m [1,200 ft].

In another instance, the critical length of a 5 percent upgrade approached by a 500-m [1,650-ft] length of 2 percent upgrade is unknown. Exhibit 3-63 shows that a 2 percent upgrade of 500 m [1,650 ft] in length would result in a speed reduction of about 9 km/h [6 mph]. The chart further shows that the remaining tolerable speed reduction of 6 km/h [4 mph] would occur on 100 m [325 ft] of the 5 percent upgrade.

Where an upgrade is approached on a momentum grade, heavy trucks often increase speed, sometimes to a considerable degree in order to make the climb in the upgrade at as high a speed as practical. This factor can be recognized in design by increasing the tolerable speed reduction. It remains for the designer to judge to what extent the speed of trucks would increase at the bottom of the momentum grade above that generally found on level approaches. It appears that a speed increase of about 10 km/h [5 mph] can be considered for moderate downgrades and a speed increase of 15 km/h [10 mph] for steeper grades of moderate length or longer. On this basis, the tolerable speed reduction with momentum grades would be 25 or 30 km/h [15 or 20 mph]. For example, where there is a moderate length of 4 percent downgrade in advance of a 6 percent upgrade, a tolerable speed reduction of 25 km/h [15 mph] can be assumed. For this case, the critical length of the 6 percent upgrade is about 300 m [1,000 ft].

The critical length of grade in Exhibit 3-63 is derived as the length of tangent grade. Where a vertical curve is part of a critical length of grade, an approximate equivalent tangent grade length should be used. Where the condition involves vertical curves of Types II and IV shown later in this chapter in Exhibit 3-73 and the algebraic difference in grades is not too great, the measurement of critical length of grade may be made between the vertical points of intersection (VPI). Where vertical curves of Types I and III in Exhibit 3-73 are involved, about one-quarter of the vertical curve length should be considered as part of the grade under consideration.

In many design situations, Exhibit 3-63 may not be directly applicable to the determination of the critical length of grade for one of several reasons. First, the truck population for a given site may be such that a weight/power ratio either less than or greater than the value of 120 kg/kW assumed in Exhibit 3-63 may be appropriate as a design control. Second, for the reasons described above, the truck speed at the entrance to the grade may differ from the value of 110 km/h [70 mph] assumed in Exhibit 3-63. Third, the profile may not consist of a constant percent grade. In such situations, a spreadsheet program, known as the Truck Speed Profile Model (TSPM), is available and may be used to generate speed truck profiles for any specified truck weight/power ratio, any specified initial truck speed, and any specified sequence of grades.

Steep downhill grades can also have a detrimental effect on the capacity and safety of facilities with high traffic volumes and numerous heavy trucks. Some downgrades are long and steep enough that some heavy vehicles travel at crawl speeds to avoid loss of control on the grade. Slow-moving vehicles of this type may impede other vehicles. Therefore, there are instances where consideration should be given to providing a truck lane for downhill traffic. Procedures have been developed in the HCM (**14**) to analyze this situation.

The suggested design criterion for determining the critical length of grade is not intended as a strict control but as a guideline. In some instances, the terrain or other physical controls may preclude shortening or flattening grades to meet these controls. Where a speed reduction greater than the suggested design guide cannot be avoided, undesirable type of operation may result on roads with numerous trucks, particularly on two-lane roads with volumes approaching capacity and in some instances on multilane highways. Where the length of critical grade is exceeded, consideration should be given to providing an added uphill lane for slow-moving vehicles, particularly where volume is at or near capacity and the truck volume is high. Data in Exhibit 3-63 can be used along with other pertinent considerations, particularly volume data in relation to capacity and volume data for trucks, to determine where such added lanes are warranted.

Chapter 4—Cross Section Elements

No changes recommended.

Chapter 5—Local Roads and Streets

No changes recommended.

Chapter 6—Collector Roads and Streets

No changes recommended.

Chapter 7—Rural and Urban Arterials

No changes recommended.

Chapter 8—Freeways

No changes recommended.

Chapter 9—Intersections

In the discussion on Minimum Edge-of-Traveled-Way Designs on p. 587, eliminate the reference to the WB-50 design vehicle and add references to the SU-8 [SU-25] and WB-28D [WB-92D] design vehicles. Also, change the references to Exhibits 2-3 through 2-23, as appropriate, to reflect the recommended changes in Chapter 2.

In Exhibit 9-19 (Edge-of-Traveled-Way Designs for Turns at Intersections) and Exhibit 9-20 (Edge of Traveled Way for Turns at Intersections), delete the rows for the WB-15 [WB-50] design vehicles and add rows for the SU-8 [SU-25] and WB-28D [WB-92D] design vehicles.

In the section on Design for Specific Conditions (Right-Angle Turns) on p. 596 to 625, delete references to the WB-15 [WB-50] design vehicle and add references to the SU-8 [SU-25] design vehicle. References to the WB-15 [WB-50] design vehicle should be replaced with the WB-12 [WB-40] design vehicle or the WB-19 [WB-62] design vehicle, as appropriate.

Add a new exhibit after Exhibit 9-22 to present minimum traveled way designs for the new SU-8 [SU-25 design vehicle].

Delete Exhibit 9-24 (Minimum Edge-of-Traveled-Way Designs WB-15 [WB-50] Design Vehicle Path).

In Exhibit 9-29 (Effect of Curb Radii on Right Turning Paths of Various Design Vehicles) and Exhibit 9-30 (Effect of Curb Radii on Right Turning Paths of Various Design Vehicles), delete the line for the WB-15 [WB-50] design vehicle and use the WB-19 [WB-62] design vehicle instead.

In Exhibit 9-31 (Cross Street Width Occupied by Turning Vehicle for Various Angles of Intersection and Curb Radii) and Exhibit 9-32 (Effect of Curb Radii and Parking on Right Turning Paths), delete the rows for the WB-15 [WB-50] design vehicle and add rows for the SU-8 [SU-12] design vehicle.

The fourth paragraph on p. 625 should be edited as follows:

> The WB-19 [WB-62] and larger trucks generally are used principally for “over-the-road” transportation between trucking terminals or industrial or commercial areas. Ideally, such destinations are located near

> major highway facilities that are designed to accommodate the larger combination units. Such trucks may be present on urban arterials, but seldom turn into or out of local urban streets.

Exhibit 9-41 (Minimum Turning Roadway Designs with Corner Islands at Urban Locations) should be modified to replace the WB-15 [WB-50] with the WB-19 [WB-62] design vehicle.

In Exhibit 9-42 (Exhibit 9-42. Typical Designs for Turning Roadways), Design Classification C should be modified to address the WB-19 [WB-62] design vehicle rather than the WB-15 [WB-50] design vehicle.

Exhibit 9-76 (Control Radii at Intersections for 90-Degree Left Turns) should be modified to replace the WB-15 [WB-50] and WB-20 [WB-67] design vehicles with the WB-19 [WB-62] design vehicle. The text on p. 697 should be modified accordingly.

Exhibit 9-78 (Minimum Design of Median Openings—P Design Vehicle, Control Radius of 12 m [40 ft]), Exhibit 9-81 (Minimum Design of Median Openings—SU Design Vehicle, Control Radius of 15 m [50 ft]), Exhibit 9-82 (Minimum Design of Median Openings—WB-12 [WB-40] Design Vehicle, Control Radius of 23 m [75 ft]), and Exhibit 9-83 (Minimum Design of Median Openings—Radius of 30 m [100 ft]) should be modified to replace the WB-15 [WB-50] design vehicle with the WB-19 [WB-62] design vehicle.

In the sections on Median Openings Based on Control Radii for Design Vehicles and Effect of Skew on p. 702 through 706, delete the references to the WB-15 [WB-50] design vehicle.

In Exhibit 9-92 (Minimum Designs for U-turns), delete the column for the WB-15 [WB-50] design vehicle. Add a column for the SU-8 [SU-25] design vehicle and replace the WB-18 [WB-60] design vehicle with the WB-19 [WB-62] design vehicle.

On p. 726, insert the following new section after the fourth full paragraph:

Double or Triple Left-Turn Lanes

> Offtracking and swept path width are important factors in designing double and triple left-turn lanes. At such locations, vehicles should be able to turn side-by-side without encroaching upon the adjacent turn lane. A desirable turning radius for double or triple left-turn lane is 27 m [90 ft] which will accommodate the P, SU, SU12 [SU40], and WB-12 [WB-40] design vehicles within a swept path width of 3.6 m [12 ft]. Larger vehicles need greater widths to negotiate double or triple left-turn lanes constructed with a 27 m [90 ft] turning radius without encroaching on the paths of vehicles in the adjacent lane. Exhibit 9-## illustrates the swept path widths for specific design vehicles making 90° left turns. Exhibit 9-## can be used to determine width needed at the center of a turn where the maximum vehicle offtracking typically occurs. To help drivers maintain their vehicles within the proper lanes, it is recommended that the longitudinal lane line markings of double or triple left-turn lanes be extended through the

Centerline Turning Radius (m)	Swept Path Width (m) for Specific Design Vehicles			
	SU	SU-8	WB-19	WB-20D
23	3.3	3.7	6.4	5.1
30	3.0	3.4	5.6	4.4
46	2.8	3.1	4.6	3.8

Centerline Turning Radius (ft)	Swept Path Width (ft) for Specific Design Vehicles			
	SU	SU-25	WB-62	WB-67D
75	10.7	12.3	21.1	16.6
100	9.8	11.2	18.4	14.7
150	9.1	10.1	15.2	12.5

EXHIBIT 9-## Swept path widths for 90º left turns

intersection area to provide positive guidance. This type of pavement marking extension provides a visual cue for lateral positioning of the vehicle as the driver makes a turning maneuver.

Chapter 10—Grade Separations and Interchanges

No changes recommended. It is recommended that minimum acceleration lengths for trucks be considered in future research.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation