Commercial Truck and Bus Safety

Synthesis 3

Highway/Heavy Vehicle Interaction

A Synthesis of Safety Practice

Sponsored by the
Federal Motor Carrier
Safety Administration

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

COMMERCIAL TRUCK AND BUS SAFETY SYNTHESIS PROGRAM

Synthesis 3

Highway/Heavy Vehicle Interaction

DOUGLAS W. HARWOOD
INGRID B. POTTS
DARREN J. TORBIC

AND

WILLIAM D. GLAUZ
Midwest Research Institute
Kansas City, MO

SUBJECT AREAS
Operations and Safety • Public Transit • Freight Transportation

Research Sponsored by the Federal Motor Carrier Safety Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2003
www.TRB.org

COMMERCIAL TRUCK AND BUS SAFETY SYNTHESIS PROGRAM

Safety is a principal focus of government agencies and private-sector organizations concerned with transportation. The Federal Motor Carrier Safety Administration (FMCSA) was established within the Department of Transportation on January 1, 2000, pursuant to the Motor Carrier Safety Improvement Act of 1999. Formerly a part of the Federal Highway Administration, the FMCSA's primary mission is to prevent commercial motor vehicle-related fatalities and injuries. Administration activities contribute to ensuring safety in motor carrier operations through strong enforcement of safety regulations, targeting high-risk carriers and commercial motor vehicle drivers; improving safety information systems and commercial motor vehicle technologies; strengthening commercial motor vehicle equipment and operating standards; and increasing safety awareness. To accomplish these activities, the Administration works with federal, state, and local enforcement agencies, the motor carrier industry, labor, safety interest groups, and others. In addition to safety, security-related issues are also receiving significant attention in light of the terrorist events of September 11, 2001.

Administrators, commercial truck and bus carriers, government regulators, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and underevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information available on nearly every subject of concern to commercial truck and bus safety. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the commercial truck and bus industry, the Commercial Truck and Bus Safety Synthesis Program (CTBSSP) was established by the FMCSA to undertake a series of studies to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern. Reports from this endeavor constitute the CTBSSP Synthesis series, which collects and assembles the various forms of information into single concise documents pertaining to specific commercial truck and bus safety problems or sets of closely related problems

The CTBSSP, administered by the Transportation Research Board, began in early 2002 in support of the FMCSA's safety research programs. The program initiates three to four synthesis studies annually that address concerns in the area of commercial truck and bus safety. A synthesis report is a document that summarizes existing practice in a specific technical area based typically on a literature search and a survey of relevant organizations (e.g., state DOTs, enforcement agencies, commercial truck and bus companies, or other organizations appropriate for the specific topic). The primary users of the syntheses are practitioners who work on issues or problems using diverse approaches in their individual settings. The program is modeled after the successful synthesis programs currently operated as part of the National Cooperative Highway Research Program (NCHRP) and the Transit Cooperative Research Program (TCRP).

This synthesis series reports on various practices, making recommendations where appropriate. Each document is a compendium of the best knowledge available on measures found to be successful in resolving specific problems. To develop these syntheses in a comprehensive manner and to ensure inclusion of significant knowledge, available information assembled from numerous sources, including a large number of relevant organizations, is analyzed.

For each topic, the project objectives are (1) to locate and assemble documented information (2) to learn what practice has been used for solving or alleviating problems; (3) to identify all ongoing research; (4) to learn what problems remain largely unsolved; and (5) to organize, evaluate, and document the useful information that is acquired. Each synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation.

The CTBSSP is governed by a Program Oversight Panel consisting of individuals knowledgeable in the area of commercial truck and bus safety from a number of perspectives—commercial truck and bus carriers, key industry trade associations, state regulatory agencies, safety organizations, academia, and related federal agencies. Major responsibilities of the panel are to (1) provide general oversight of the CTBSSP and its procedures, (2) annually select synthesis topics, (3) refine synthesis scopes, (4) select researchers to prepare each synthesis, (5) review products, and (6) make publication recommendations.

Each year, potential synthesis topics are solicited through a broad industry-wide process. Based on the topics received, the Program Oversight Panel selects new synthesis topics based on the level of funding provided by the FMCSA. In late 2002, the Program Oversight Panel selected two task-order contractor teams through a competitive process to conduct syntheses for Fiscal Years 2003 through 2005.

CTBSSP SYNTHESIS 3

Project MC-02 FY'01

ISSN 1544-6808

ISBN 0-309-08756-2

Library of Congress Control Number 2003106789

Price $21.00

NOTICE

The project that is the subject of this report was a part of the Commercial Truck and Bus Safety Synthesis Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical panel, they are not necessarily those of the Transportation Research Board, the National Research Council, or the Federal Motor Carrier Safety Administration of the U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical panel according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

Special Notice

The Transportation Research Board, the National Research Council, and the Federal Motor Carrier Safety Administration (sponsor of the Commercial Truck and Bus Safety Synthesis Program) do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the clarity and completeness of the project reporting.

Published reports of the

COMMERCIAL TRUCK AND BUS SAFETY SYNTHESIS PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet at:
http://www.national-academies.org/trb/bookstore

Printed in the United States of America

Note: The Transportation Research Board of the National Academies, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. William A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both the Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. William A. Wulf are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is a division of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. The Board's mission is to promote innovation and progress in transportation by stimulating and conducting research, facilitating the dissemination of information, and encouraging the implementation of research results. The Board's varied activities annually engage more than 4,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

COOPERATIVE RESEARCH PROGRAMS STAFF FOR CTBSSP SYNTHESIS 3

ROBERT J. REILLY, *Director, Cooperative Research Programs*
CHRISTOPHER W. JENKS, *Manager, Commercial Truck and Bus Safety Synthesis Program*
EILEEN P. DELANEY, *Managing Editor, Cooperative Research Programs*
BETH HATCH, *Assistant Editor*

COMMERCIAL TRUCK AND BUS SAFETY SYNTHESIS PROGRAM OVERSIGHT PANEL

STEPHEN CAMPBELL, *Commercial Vehicle Safety Alliance, Bethesda, MD* (Chair)
REBECCA M. BREWSTER, *American Transportation Research Institute, Smyrna, GA*
KENNETH CAMPBELL, *Oak Ridge National Laboratory, Oak Ridge, TN*
THOMAS M. CORSI, *University of Maryland, College Park, MD*
DENNISON COTTRELL, *New York State DOT, Albany, NY*
MARK L. EDWARDS, *Consultant, Longwood, FL*
NICHOLAS J. GARBER, *University of Virginia, Charlottesville, VA*
THOMAS D. GILLESPIE, *University of Michigan, Ann Arbor, MI*
S. WILLIAM GOUSE, *American Trucking Associations, Alexandria, VA*
ALEX GUARIENTO, *Greyhound Lines, Inc., Dallas, TX*
DAVID HOPPS, *The Service Master Co., Memphis, TN*
SCOTT MADAR, *International Brotherhood of Teamsters, Washington, DC*
WILLIAM MAHORNEY, *American Bus Association, Washington, DC*
JAMES W. McFARLIN, *ABF Freight System, Inc., Fort Smith, AR*
WILLIAM C. ROGERS, *Motor Freight Carriers Association, Washington, DC*
JOHN SIEBERT, *Owner-Operator Independent Drivers Association, Grain Valley, MO*
LARRY F. SUTHERLAND, *Ohio DOT, Columbus, OH*
C. MICHAEL WALTON, *University of Texas at Austin, Austin, TX*
DAVID K. WILLIS, *Texas A&M University, College Station, TX*
DAVID SMITH, *FHWA Liaison*
ALBERT ALVAREZ, *FMCSA Liaison*
DOUG McKELVEY, *FMCSA Liaison*
MARTIN WALKER, *FMCSA Liaison*
DUANE PERRIN, *NHTSA Liaison*
GREG HULL, *APTA Liaison*
MICHELE McMURTRY, *NTSB Liaison*
LEO PENNE, *AASHTO Liaison*
CHRISTOPHER ZEILINGER, *CTAA Liaison*
CHARLES NIESSNER, *TRB Liaison*
RICHARD PAIN, *TRB Liaison*

FOREWORD

By Christopher W. Jenks
CTBSSP Manager
Transportation Research Board

This synthesis will be of use to state agencies, commercial truck and bus carriers, and others interested in improving commercial vehicle safety. Prepared by Midwest Research Institute, this synthesis reports on the safety interactions of commercial trucks and buses with highway features and the highway improvements that can be made to improve the safety of heavy vehicle operations. On the basis of a comprehensive literature review and surveys of state departments of transportation and the trucking industry, this synthesis presents the state of the knowledge and practice concerning the accommodation of heavy vehicles on highways. The synthesis addresses the physical and performance characteristics of heavy vehicles that interact with highways, geometric design criteria based on vehicle characteristics, traffic control devices and traffic regulations, and the use of intelligent transportation systems (ITS) to more effectively communicate with heavy vehicle drivers and provide real-time information concerning safe vehicle operation.

Administrators, commercial truck and bus carriers, government regulators, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and underevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information available on nearly every subject of concern to commercial truck and bus safety. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day jobs. To provide a systematic means for assembling and evaluating such useful information and to make it available to the commercial truck and bus industry, the Commercial Truck and Bus Safety Synthesis Program (CTBSSP) was established by the Federal Motor Carrier Safety Administration to undertake a series of studies to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in selected areas of concern. Reports from this endeavor constitute the CTBSSP Synthesis series, which collects and assembles information into single concise documents pertaining to specific commercial truck and bus safety issues.

The CTBSSP, administered by the Transportation Research Board, was authorized in late 2001 and began in 2002 in support of the FMCSA's safety research programs. The program initiates three to four synthesis studies annually that address issues in the area of commercial truck and bus safety. A synthesis report is a document that summarizes existing practice in a specific technical area based typically on a literature search and a survey of relevant organizations (e.g., state DOTs, enforcement agencies, commercial truck and bus companies, or other organizations appropriate for the specific topic). The primary users of the syntheses are practitioners who work on issues or problems using diverse approaches in their individual settings.

This synthesis series reports on various practices; each document is a compendium of the best knowledge available on measures found to be successful in resolving specific problems. To develop these syntheses in a comprehensive manner and to ensure inclusion of significant knowledge, available information assembled from numerous sources is analyzed.

For each topic, the project objectives are (1) to locate and assemble documented information; (2) to learn what practices have been used for solving or alleviating problems; (3) to identify relevant, ongoing research; (4) to learn what problems remain largely unsolved; and (5) to organize, evaluate, and document the useful information that is acquired. Each synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation.

CONTENTS

SUMMARY

1 **CHAPTER ONE Introduction**

Background, 1
Problem Statement, 1
Scope of Synthesis, 1
Organization of this Synthesis, 2

3 **CHAPTER TWO Physical and Performance Characteristics of Heavy Vehicles**

Vehicle Types and Configurations, 3
Vehicle Weights and Dimensions, 3
Turning Radius, 6
Offtracking and Swept Path Width, 6
Trailer Swingout, 10
Braking Distance, 14
Driver Eye Height, 15
Truck Acceleration Characteristics, 16
Rearward Amplification, 18
Suspension Characteristics, 18
Load Transfer Ratio, 19
Rollover Threshold, 19

21 **CHAPTER THREE Role of Roadway Geometric Design in Safely Accommodating Heavy Vehicles on the Highway**

Design Vehicles, 21
Sight Distance, 21
Upgrades, 27
Downgrades, 27
Acceleration Lanes, 28
Horizontal Curves, 28
Intersection Design, 28
Interchange Ramp Design, 29
Roadside Design, 29

31 **CHAPTER FOUR Role of Traffic Control Devices and Traffic Regulations in Safely Accommodating Heavy Vehicles on the Highway**

Differential Speed Limits for Passenger Cars and Heavy Vehicles, 31
Lane Use Restrictions for Heavy Vehicles, 36
Heavy Vehicle Prohibitions, 38
Exclusive Lanes or Roadways for Heavy Vehicles, 39
Signing and Marking of Interchange Ramps, 40
Restriction of Sign Visibility by Heavy Vehicles, 41
Signal Timing to Accommodate Heavy Vehicles, 43
Safety Improvements for Night Driving, 43

45 **CHAPTER FIVE ITS Initiatives for Improving Safety in Highway/Heavy Vehicle Interactions**

ITS Commercial Vehicle Operations (CVO) Program, 45
Warning Systems for Long Downgrades, 46
Dynamic Curve Warning Systems, 48
Weigh Stations, 52
Collision Avoidance Warning Systems, 53

55 **CHAPTER SIX Conclusions and Recommendations**

59 **REFERENCES**

63 **APPENDIX A Design Vehicles**

73 **APPENDIX B Highway Agency Survey**

85 **APPENDIX C Industry Survey**

HIGHWAY/HEAVY VEHICLE INTERACTION

SUMMARY

Trucks and buses are larger, heavier, and less maneuverable than passenger cars and make up an increasingly larger proportion of the traffic on U.S. highways. This synthesis addresses the safety interactions of commercial trucks and buses with highway features and the highway improvements that can be made to improve the safety of heavy vehicle operations. This synthesis presents the state of knowledge and the state of practice concerning the accommodation of heavy vehicles on the highway. The synthesis is based on a comprehensive literature review and a survey of highway agencies and the trucking industry.

A wide variety of heavy vehicle types—including single-unit trucks, combination trucks with one, two, or three trailers, and buses—operate on U.S. highways. The physical and performance characteristics of heavy vehicles that interact with highways include vehicle types and configurations, weights and dimensions, turning radius, offtracking and swept path width, trailer swingout, braking distance, driver eye height, truck acceleration characteristics, rearward amplification, suspension characteristics, load transfer ratio, and rollover threshold.

Many highway geometric design criteria are based on vehicle characteristics. In many cases, truck and buses are the most critical characteristics used in defining these design criteria or assessing their appropriateness. Highway geometric design features whose design is based on consideration of vehicle characteristics include sight distance, upgrades, downgrades, acceleration lanes, horizontal curves, intersection design, interchange ramps, and roadside features.

Traffic control devices and traffic regulations have an important role in safely accommodating heavy vehicles on the highway and can be used by highway agencies to better accommodate trucks at locations where safety problems have occurred or are anticipated. The traffic control device strategies that have been used, or are being considered, to better accommodate heavy vehicles on the highway include differential speed limits for passenger cars and heavy vehicles, heavy vehicle prohibitions on particular roads, lane use restrictions for heavy vehicles, exclusive lanes and exclusive roadways for heavy vehicles, signing for long downgrades, signing and marking of interchange ramps, mitigating the restriction of sign visibility by heavy vehicles, and modifying signal timing to better accommodate heavy vehicles.

Highway agencies are increasingly using intelligent transportation system (ITS) initiatives to more effectively communicate with heavy vehicle drivers and provide real-time information concerning safe vehicle operation. The types of ITS systems in current use by highway agencies include warning systems for long downgrades, dynamic curve warning systems, and improved weigh station operations. ITS initiatives related to heavy vehicle safety also include on-board vehicle technology such as collision avoidance systems for buses.

CHAPTER ONE

INTRODUCTION

BACKGROUND

Trucks and buses are larger, heavier, and less maneuverable than passenger cars and make up an increasingly larger proportion of the traffic on U.S. highways. For example, on many rural Interstate highways, commercial trucks and buses now make up more than one-third of the traffic stream. Many of the established criteria for highway design and operation used by highway agencies are based on interactions between highway features and the vehicles that use the highways. For most of these criteria, larger and heavier vehicles, such a commercial trucks and buses, have more critical interactions with highway features than passenger cars. Safe design and operation of highway facilities requires that these interactions be understood and incorporated in the formulation of highway agency policies and in the planning of safety improvements that highway agencies make to the highway system.

PROBLEM STATEMENT

The objective of this synthesis is to summarize and present information concerning the safety interaction of highways with commercial trucks and buses and the highway improvements that can be made to improve the safety of heavy vehicle operations. This synthesis presents the state of knowledge and the state of practice concerning the accommodation of heavy vehicles on the highway. The synthesis describes current highway design features, operational practices, and other initiatives of importance to commercial truck and bus safety. The synthesis includes issues such as roadway type and design, ramp design, exclusive roadways or lanes for commercial trucks and buses, restrictions on commercial truck and bus roadway/lane use, differential speed limits for commercial trucks and buses, roadside devices to minimize road departures and crashes, and signage for drivers. It also identifies the key physical characteristics of commercial vehicles (such as length, width, roll stability, low- and high-speed offtracking, and braking) and the ability of these vehicles to operate within existing highway designs. The synthesis also discusses intelligent transportation system (ITS) impacts and identifies needed research relevant to commercial truck and bus safety.

This synthesis is based on a comprehensive review of relevant literature as well as surveys of and interviews with representatives of state departments of transportation and the commercial truck and bus industry. The synthesis has been prepared as part of the Commercial Truck and Bus Safety Synthesis Program (CTBSSP), sponsored by the Federal Motor Carrier Safety Administration (FMCSA) and managed by the Transportation Research Board (TRB). The FMCSA will likely use information collected to identify collaborative safety research and technology transfer activities, as well as initiatives that FMCSA could undertake on its own to better inform the commercial motor vehicle industry about highway-related safety factors. The information will also be of interest to a variety of other organizations involved in the design of highway facilities and the manufacture and operation of vehicles.

SCOPE OF SYNTHESIS

The synthesis addresses the safety interactions between highways and heavy vehicles. For purposes of this synthesis, heavy vehicles are defined to include commercial trucks and buses. Commercial trucks are defined to include motor vehicles with gross vehicle weight ratings in excess of 4,550 kg (10,000 lb). Commercial buses are defined to include any vehicle designed and used to transport 15 or more passengers (including the driver). Only intercity and charter buses are considered. School buses and local transit buses are not addressed by this synthesis, although many of the issues discussed may also apply to these vehicles.

The issues considered in the synthesis are those that (1) have a direct relationship to interactions between heavy vehicles and roadway features, roadside design features, traffic control devices, or traffic regulations and (2) have a direct relationship to safety. The scope of the synthesis does not include issues related exclusively to driver behavior or human factors, except when those issues also involve interaction with the roadway. For example, hours-of-service regulations or in-vehicle alarms to rouse drowsy drivers are considered to be outside the scope of the synthesis. ITS initiatives intended to improve safety are addressed in the synthesis, but commercial vehicle operations initiatives that are related exclusively to reducing delays or minimizing costs are not. Issues related to structural design of bridges, pavement design, and pavement wear are outside the scope of the synthesis, even though they involve interactions with heavy vehicles, because they are primarily cost issues rather than safety issues.

ORGANIZATION OF THIS SYNTHESIS

The remainder of this synthesis is organized as follows. Chapter Two presents the physical and performance characteristics of heavy vehicles that are related to their interactions with highways. Chapter Three reviews the role of roadway geometric design in safely accommodating heavy vehicles on the highway. The role of traffic control devices and traffic regulations in safely accommodating heavy vehicles on the highway is reviewed in Chapter Four. Chapter Five describes ITS initiatives intended to improve the safety of highway/heavy vehicle interactions. The conclusions and recommendations of the synthesis are presented in Chapter Six.

Appendix A presents drawings of typical heavy vehicle types that are considered in the design of highways. The drawings in Appendix A illustrate the various vehicle types that are mentioned throughout the synthesis. Appendix B present the results of the survey of highway agencies conducted for this synthesis and Appendix C presents the results of the survey of the commercial trucking industry.

CHAPTER TWO

PHYSICAL AND PERFORMANCE CHARACTERISTICS OF HEAVY VEHICLES

A wide variety of heavy vehicle types—including single-unit trucks, combination trucks with one, two, or three trailers, and buses—operate on U.S. highways. These heavy vehicle types each have unique physical and performance characteristics that interact with highway features. This chapter summarizes the physical and performance characteristics of heavy vehicles. The issues addressed in this chapter are as follows:

- Vehicle weights and dimensions
- Turning radius
- Offtracking and swept path width
- Trailer swingout
- Braking distance
- Driver eye height
- Acceleration characteristics
- Rearward amplification
- Suspension characteristics
- Load transfer ratio
- Rollover threshold

The relationship of these vehicle characteristics to the safety of highway/heavy vehicle interactions is discussed in later chapters.

VEHICLE TYPES AND CONFIGURATIONS

Table 1 identifies common truck and bus configurations that operate on U.S. highways. Table 2 identifies the primary truck and bus configurations that constitute the U.S. heavy vehicle fleet. The configurations identified in the table are those used as design vehicles in the American Association of State Highway and Transportation Officials (AASHTO) *Policy on Geometric Design of Highways and Streets (1)*, commonly known as the *Green Book*. The table also includes some additional vehicles recommended in *NCHRP Report 505 (2)* for future use in geometric design, but not currently included in AASHTO policy.

VEHICLE WEIGHTS AND DIMENSIONS

Current federal law sets the following limits on heavy vehicle weights and dimensions:

- 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
  - 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 bridge formula established in federal law 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 Secretary of Transportation in consultation with the states. The NN includes the Interstate System plus other selected routes. The extent of the NN on noninterstate routes varies by region of the country. Typically, the noninterstate routes in the NN are fairly limited in the Eastern states and more extensive in the Western states.

States set the truck size and weight limits on their facilities within the framework set by the federal limits discussed above. Many states have

Table 1. 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.
Intercity Bus	3	50,000	Used to transport passengers and their luggage on scheduled routes and on tours and charter trips.
Tractor-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 (*3*)

Table 2. Design vehicle dimensions, adapted from the 2001 *Green Book* (1) and *NCHRP Report 505* (2)

		Dimensions (ft)											
		Overall			Overhang								
Design vehicle type	**Symbol**	**Height**	**Width**	**Length**	**Front**	**Rear**	**WB_1**	**WB_2**	**S**	**T**	**WB_3**	**WB_4**	**Typical kingpin to center of rear tandem axle[6]**
Passenger Car	P	4.25	7	19	3	5	11	–	–	–	–	–	–
Single Unit Truck (two-axle)	SU	11-13.5	8.0	30	4	6	20	–	–	–	–	–	–
Single Unit Truck (three-axle)[6]	SU-25	11-13.5	8.0	39.5	4	10.5	25	–	–	–	–	–	–
Buses													
Intercity Bus (Motor Coach)	BUS-40	12.0	8.5	40	6	6.3[5]	24	3.7	–	–	–	–	–
	BUS-45	12.0	8.5	45	6	8.5[5]	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[1]	13.2[1]	–	–	–
Combination Trucks													
Intermediate Semitrailer	WB-40	13.5	8.0	45.5	3	2.5[5]	12.5	27.5	–	–	–	–	25.5
Intermediate Semitrailer	WB-50	13.5	8.5	55	3	2[5]	14.6	35.4	–	–	–	–	35.5
Interstate Semitrailer[6]	WB-62*	13.5	8.5	68.5	4	2.5[5]	21.6	41.0	–	–	–	–	41.0
Interstate Semitrailer	WB-67	13.5	8.5	73.5	4	2.5[5]	21.6	45.5	–	–	–	–	45.5
"Double-Bottom"-Semitrailer/Trailer	WB-67D	13.5	8.5	73.3	2.33	3	11.0	23.0	3.0[2]	7.0[2]	23.0	–	21.0
Rocky Mountain Double-Semitrailer/Trailer[6]	WB-92D	13.5	8.5	98.3	2.33	3	17.5	40.5	3.0[2]	7.0[1]	23.0	–	42.5
Triple-Semitrailer/ Trailers	WB-100T	13.5	8.5	104.8	2.33	3	11.0	22.5	3.0[3]	7.0[3]	23.0	23.0	21.0
Turnpike Double-Semitrailer/Trailer	WB-109D*	13.5	8.5	114	2.33	2.5[5]	14.3	39.9	2.5[4]	10.0[4]	44.5	–	40.5

* = 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 = Combined dimension is 19.4 ft and articulating section is 4 ft wide.
2 = Combined dimension is typically 10.0 ft.
3 = Combined dimension is typically 10.0 ft.
4 = Combined dimension is typically 12.5 ft.
5 = This is overhang from the back axle of the tandem axle assembly.
6 = Modified from 2001 *Green Book* as recommended in Reference 2.

- 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.

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 through federal law requires only that 14.6-m (48-ft) trailers be permitted. The maximum trailer length currently permitted by any state for single semitrailer trucks is 18.3 m (60 ft).

A number of states also permit multiple trailer trucks with greater weights and trailer lengths than allowed under federal law, to operate on specific highways either under permit and/or under specified conditions. Such trucks are generally known as Longer Combination Vehicles (LCVs). The 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) instituted a freeze on increases in state size and weight limits for LCVs. State limits in effect were allowed to remain in place ("grandfathered"), but no further increases in those limits are 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.

Table 3 summarizes which states permit LCVs to operate with weights over 36,400 kg (80,000 lb).

Table 2 includes the dimensions of the AASHTO design vehicles. Appendix A presents drawings of these design vehicles to illustrate the most common types of trucks and buses that make up the U.S. heavy vehicle fleet. While the trucks in Appendix A are shown with van-type cargo areas, other cargo-area types in common use include flatbeds, bulk carriers (dump trucks), tankers, automobile carriers, and other special-purpose vehicles. The vehicle dimensions shown in Table 2 and Appendix A, and particularly the spacing between axles and hitch points and the front and rear overhang distances, are the primary determinants of the turning radius, offtracking, and swept path width of heavy vehicles, which are discussed below. These performance characteristics, in turn, are key factors in the design of intersections and horizontal curves to safely accommodate heavy vehicles.

The weight of a truck is not, by itself, a factor in its safe operation. However, heavier trucks need more powerful engines to accelerate from a stop at intersections and to maintain speed on upgrades. Furthermore, a truck's cargo should be loaded evenly, side to side and fore to aft of the cargo area, to maintain a low center of gravity for the vehicle as a whole. The center-of-gravity height is a key determinant of a vehicle's rollover threshold, as discussed later in this chapter.

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 mi/h)]. The turning radii of representative trucks are presented in Table 4. The turning radius of a truck influences highway geometric design through consideration of offtracking and swept path width, which are discussed below.

OFFTRACKING AND SWEPT PATH WIDTH

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. This phenomenon, in which the rear wheels of a vehicle do not follow the same path as the front wheels as the vehicle makes a turn, is known as offtracking. 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 becomes more

Table 3. Longer combination vehicle weight limits by state *(3)*

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[1]	
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	

[1] 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.

Table 4. Minimum turning radius for selected heavy vehicles *(1, 2)*

Design vehicle type	Symbol	Minimum design turning radius (ft)	Centerline turning radius (ft)	Minimum inside radius (ft)
Single-unit truck	SU	42.0	38.0	28.3
Single-unit truck (three-axle)	SU25	51.5	47.5	36.4
Intercity bus	BUS-40	45.0	40.8	27.6
Intercity bus	BUS-45	45.0	40.8	25.5
City transit bus	CITY-BUS	42.0	37.8	24.5
Conventional school bus (65 pass.)	S-BUS-36	38.9	34.9	23.8
Large school bus (84 pass.)	S-BUS-40	39.4	35.4	25.4
Articulated bus	A-BUS	39.8	35.5	21.3
Intermediate semitrailer	WB-40	40.0	36.0	19.3
Intermediate semitrailer	WB-50	45.0	41.0	17.0
Interstate semitrailer[1]	WB-62	45.0	41.0	7.9
Interstate semitrailer	WB-67	45.0	41.0	4.4
Long interstate semitrailer	WB-71	21.5	17.0	13.8
"Double-bottom" semitrailer/trailer	WB-67D	45.0	41.0	19.3
Rocky mountain double semitrailer/ trailer	WB-92D	82.0	78.0	82.4
Turnpike double-semitrailer/trailer	WB-109D	60.0	56.0	14.9
Triple-semitrailer/trailer/trailer	WB-100T	45.0	41.0	9.9

[1] Revised WB-62 design vehicle proposed in Reference 2.

pronounced as the vehicle speed increases. Each type of offtracking is discussed below.

Low-Speed Offtracking

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 heavy vehicles, 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 1; the other, and more important descriptor for use in highway design is the *swept path width*, shown for a tractor-semitrailer in Figure 2 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 increasing 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 type of offtracking is discussed more fully below.

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. (*4*), for example) as:

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

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 $\ell << R$, then this may be reduced to the simpler form $-0.5(\ell^2/R)$, which is the often used Western Highway Institute formula (*5*). Eq. (1) is sufficiently accurate for most purposes, but additional effects of multiple axles (e.g., tandems, tridems, etc.), roadway superelevation, and body roll may also be included (see Glauz and Harwood (*6*)). (This formulation also assumes $\ell << R$.)

As noted above, Eq. (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

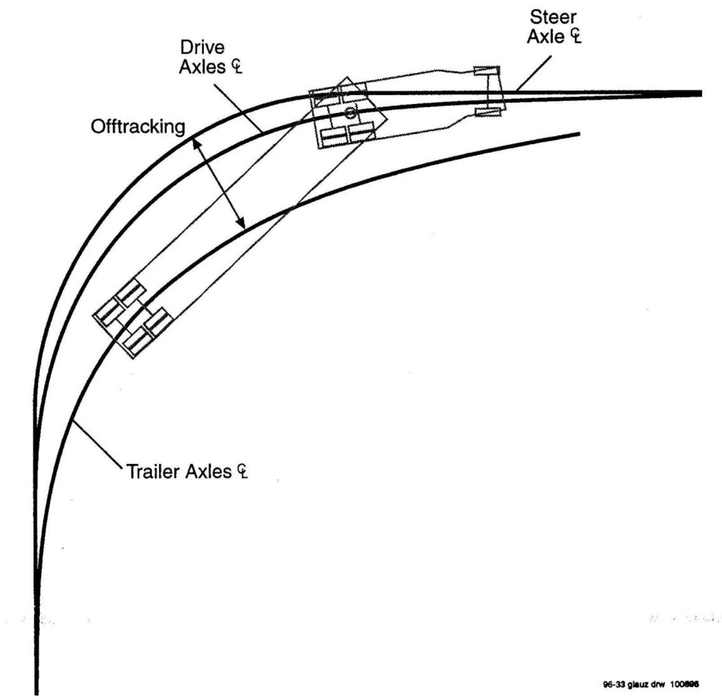


Figure 1. Illustration of truck offtracking.

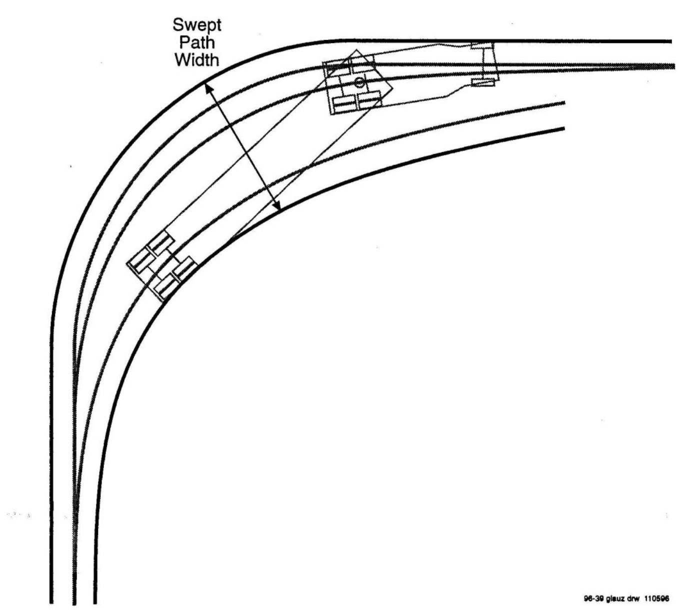


Figure 2. Illustration of swept path width.

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). The largest component of the offtracking for a long semitrailer is the distance from the kingpin to the center of the rear tandem axle, known as the KCRT distance.

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 is a key factor in the design of intersections and 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. Commercially available software packages are 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 5 presents the maximum low-speed offtracking and swept path width in 90° turns of varying radii for typical truck types.

High-Speed Offtracking

When a vehicle moves through a curve at higher speed, there is a tendency for the rear axles of the vehicle 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 *(7),* and their model was later expanded by Glauz and Harwood *(6)*. The model includes the fully developed low-speed offtracking terms, discussed above, plus a speed dependent portion that is the high-speed contribution. It is proportional to the axle spacing, ℓ, 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 mi/h), for example, on highway entrance or exit ramps. Net outward offtracking rarely exceeds 0.6 m (2.0 ft).

Net high-speed offtracking is a less important factor in highway design than low-speed offtracking, because high-speed offtracking generally offsets low-speed offtracking. At very high speeds, however, drivers of heavy vehicles need to be aware that the rear of their vehicle may track to the outside, rather than the inside, of a turn and position their vehicle accordingly.

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

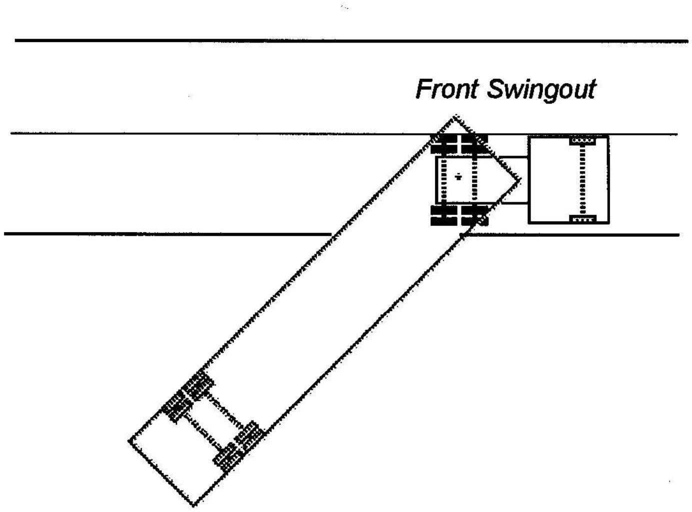
TRAILER SWINGOUT

The front of a trailer is generally ahead of the front axles that support the trailer. Likewise, 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 3.

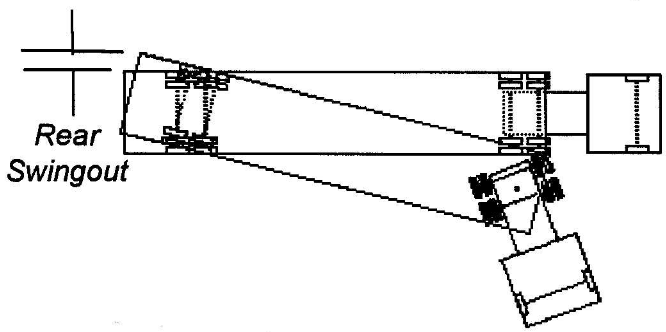
Table 5. Maximum low-speed offtracking and swept path width for selected trucks in 90° turns *(2)*

Design vehicle type	Symbol	Maximum offtracking (ft) for specified turn radius				Maximum swept path width (ft) for specified turn radius			
		50 ft	75 ft	100 ft	150 ft	50 ft	75 ft	100 ft	150 ft
Single-unit truck (two-axle)	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[1]	WB-62	17.0	13.1	10.3	7.0	25.3	21.3	18.6	15.3
Interstate semitrailer	WB-67	19.4	15.0	12.1	8.3	27.6	23.4	20.3	16.6
Long interstate semitrailer	WB-71	21.5	17.0	13.8	9.6	29.8	25.3	22.0	17.9
"Double-bottom"-semitrailer/trailer	WB-67D	11.5	8.3	6.3	4.2	19.7	16.6	14.6	12.5
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

[1] Revised WB-62 design vehicle proposed in *NCHRP Report 505* (*2*).



Front Swingout



Rear Swingout

Figure 3. Illustration of front and rear swingout for a tractor-trailer combination making a turn (8).

Swingout is a function of the trailer wheelbases and other dimensions, and the radius of the turn, and 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.

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. Table 6 shows the maximum rear swingout in 90° turns for a varying radii for selected trucks.

It is important to recognize that rear swingout, like low-speed offtracking, increases 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

Table 6. Maximum rear swingout for selected design vehicles in 90° turns *(2)*

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)[1]	WB-62	0.17	0.13	0.09	0.06
Interstate semitrailer	WB-67	0.17	0.14	0.10	0.07
Interstate semitrailer[2]	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[3]	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

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

outside front wheel of the tractor and not by the trailer wheels. This finding suggests that rear swingout is rarely a concern to other vehicles, unless they are making a parallel turn *(2)*.

BRAKING DISTANCE

Braking distance is the distance needed to stop a vehicle from the instant brake application begins *(1)*. 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. The process of bringing a heavy vehicle to a stop requires a complex interaction between the driver, the brake system, the truck tires, the dimensions, and loading characteristics of the vehicle, and the pavement surface characteristics. Heavy vehicles use both air and hydraulic brake systems. Combination trucks typically have air brake systems; buses often have hydraulic brakes.

Locked-Wheel Braking vs. Controlled Braking

Heavy vehicle 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. 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.

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 4 illustrates the dynamics of a tractor-trailer truck if its wheels are locked during emergency braking *(9)*. The behavior depends upon which axle locks first—they usually do not all lock up together. When the steering wheels (front axle) are locked, steering control is

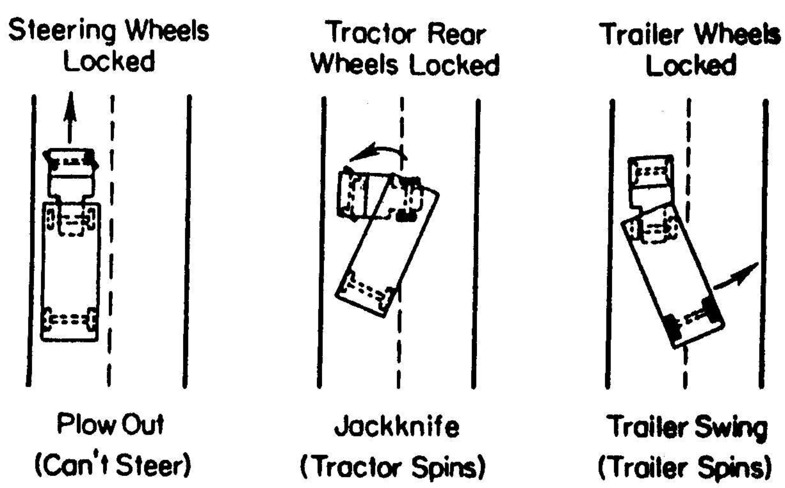


Figure 4. Tractor-trailer dynamics with locked wheels (9).

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(s) 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 are considered safe. Therefore, it is essential that combination trucks stop in a controlled braking mode and that highway geometric design criteria should recognize the distances required for trucks to make a controlled stop.

Antilock Brake Systems

Antilock brake systems have been introduced in the heavy vehicle fleet to enable vehicles to make controlled stops without locking the wheels and losing vehicle control.

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 *(10)*. Antilock brake systems have been required for air-brake-equipped tractors manufactured on or after March 1, 1997; air-brake-equipped trailers and single-unit trucks manufactured on or after March 1, 1998, and hydraulic-brake-equipped single-unit trucks and buses manufactured after March 1, 1999. Antilock brake systems were also available as an option for some of these vehicles before those dates.

Because their useful life is relatively short, nearly all truck tractors in the current fleet currently have antilock brakes or will soon be replaced by a tractor that does. A recent field study found that approximately 43 percent of trailers in combination trucks are currently equipped with antilock brake systems *(2)*. 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.

The introduction of antilock brakes has improved the braking performance of the truck fleet. FMVSS 121 specifies a performance standard for truck braking distance. The required braking distances for heavy vehicles equipped with antilock brakes are summarized in Table 7. *NCHRP Synthesis of Highway Practice 241 (11)* has observed that truck braking distances remain longer than passenger car braking distances on dry pavements. By contrast, on wet pavements, which are most critical to safety, the braking distances of trucks and passenger cars are nearly equal.

DRIVER EYE HEIGHT

The drivers of heavy vehicles generally sit higher than passenger car drivers and, thus, have greater eye heights. As a result, truck and bus drivers can see farther than passenger car drivers at vertical sight restrictions, such as hillcrests. This may permit truck and bus drivers to see traffic conditions or objects in the road sooner and, therefore, begin braking sooner. The AASHTO *Green Book (1)* 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 reported in *NCHRP Report 400 (12)*. Driver eye height is considered directly in the design of vertical curves at hillcrests. However, there is no comparable advantage for truck and bus drivers at horizontal sight restrictions.

Table 7. Truck braking distances specified as performance criteria for antilock brake systems in FMVSS 121 *(18)*

Vehicle speed (mi/h)	Truck braking distance (ft)[1] 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

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

TRUCK ACCELERATION CHARACTERISTICS

Two aspects of truck acceleration performance are important to highway/heavy vehicle interaction. 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 conflict zone such as an intersection or railroad-highway grade crossing. The primary factors that affect the clearance times of trucks are as follows:

- length of conflict zone
- length of truck
- truck weight-to-power ratio
- truck gear ratio
- roadway geometry (percent grade, curvature)

Because of their lower acceleration rates and greater lengths, heavy vehicles take longer than passenger cars to clear a specific hazard zone.

A simplified analytical model of the low-speed acceleration of trucks has been developed by Gillespie *(13)*. The Gillespie model estimates the time required for a truck to clear a conflict zone, starting from a full stop, as:

$$t_c = \frac{0.682\,(L_{HZ} + L_T)}{V_{mg}} + 3.0 \qquad \textbf{(2)}$$

where:
- t_c = time required to clear zone (s)
- L_{HZ} = length of conflict zone (ft)
- L_T = length of truck (ft)
- V_{mg} = maximum speed mi/h in the gear selected by the driver (= 60/gr on a level road)
- gr = gear ratio selected by driver

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 *(13)*. These data are shown in Figure 5. 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 Eq. (2) for a level grade is also presented in the figure.

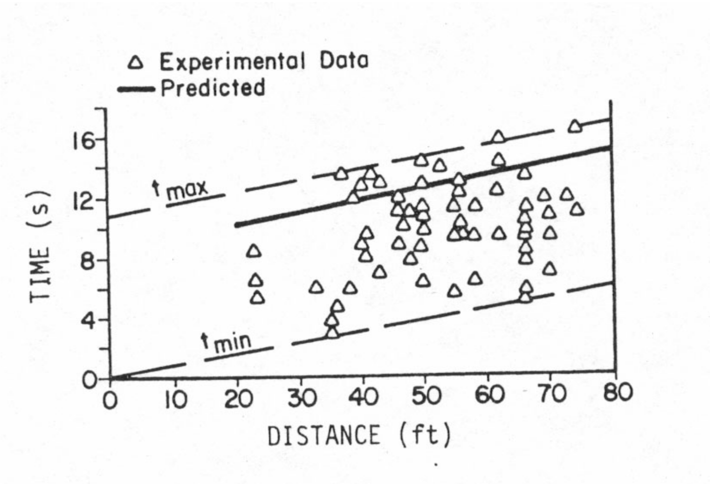


Figure 5. Field observations of times for 19.8-m (65-ft) tractor-trailer trucks to clear intersection distances after starting from a stop (13, 14).

Eq. (2) provides a relatively conservative estimate of clearance times, since the majority of the experimental points fall below the prediction. The experimental data in Figure 5 are bounded by two parallel lines representing the maximum and minimum observed clearance times.

High-Speed Acceleration

The acceleration capability of a truck at higher speeds is primarily a function of the truck weight-to-power ratio, the truck's current speed, and the local highway grade. Aerodynamic drag forces have a secondary effect, which decreases at higher elevation. The performance of diesel engines is not affected by elevation, although the performance of gasoline engines decreases with increasing elevation *(2, 15)*.

The maximum acceleration of a heavy vehicle on an upgrade can be estimated as the minimum of a_c, a_p, and a_e determined as *(2, 16)*:

$$a_c = -0.2445 - 0.0004\ V' - \frac{0.021\ C_{de}\ (V')^2}{(W/A)} - \frac{222.6\ C_{pe}}{(W/NHP)\ V'} - gG \quad (3)$$

$$a_p = \frac{\dfrac{15368\ C_{pe}}{(W/NHP)\ V'}}{1 + \dfrac{14080}{(W/NHP)\ V'^2}} \quad (4)$$

$$a_e = \frac{0.4\ V'\ a_o}{0.4\ V' + \dfrac{1.5\ a_o}{|a_o|}(a_p - a_c)},\ V \geq 10\ \text{ft/s} \quad (5)$$

$$a_e = \frac{10\ a_o}{10 + \dfrac{1.5\ a_o}{|a_o|}(a_p - a_c)},\ V < 10\ \text{ft/s} \quad (6)$$

where:

a_c	=	coasting acceleration (ft/s^2) during gearshifts
a_p	=	horsepower-limited acceleration (ft/s^2)
a_e	=	effective acceleration (ft/s^2) including an allowance of 1.5 s for gearshift delays
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)

g	=	acceleration of gravity (32.2 ft/s^2)
G	=	local grade (expressed as a decimal proportion)

Eq. (3) represents the coasting acceleration of the truck. Eq. (4) represents the acceleration as limited by engine horsepower. Eqs. (5) and (6) combine the coasting and horsepower-limited accelerations into an effective acceleration that allows the truck to use maximum horsepower except during gearshift 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 that were adapted by St. John and Kobett to incorporate gearshift delays (*15, 16*). 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. On level sections and on downgrades, driver restraints often limit heavy vehicle acceleration to levels less than the vehicle capability computed with Eqs. (3) through (6).

Eqs. (3) through (6) can be used to plot heavy vehicle speed profiles on grades and, therefore, estimate the speed-maintenance capabilities of heavy vehicles on upgrades as a function of the three key parameters: the vehicle weight-to power ratio, the vehicle speed, and the vertical profile of the highway. Recent field data have shown that the truck population using freeways has an 85th percentile weight-to-power ratio in the range from 102 to 126 kg/kW (170 to 210 lb/hp), while on two-lane highways the truck population is in the range from 108 to 168 kg/kW (180 to 280 lb/hp) *(2)*.

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 *(17)*. 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, include the following:

- number of trailing units
- shortness of trailers (longer ones experience less amplification)
- loose dolly connections
- greater loads in rearmost trailers
- increased vehicle speeds

Quantifying rearward amplification in terms of multiples of lateral acceleration is relevant to vehicle design, 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) *(17)*.

SUSPENSION CHARACTERISTICS

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
- 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
- compliance steer coefficient

A detailed discussion of the effects of these suspension characteristics on truck performance is presented by Fancher et al. *(18)*.

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:

$$\text{Load Transfer Ratio} = \text{Sum}(F_L - F_R) / \text{Sum}(F_L + F_R) \quad (7)$$

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

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.

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
- lateral weight distribution

Most research suggests that a reasonable value for a minimum rollover threshold for loaded trucks is in the range from 0.34 to 0.40 *g (17, 19, 20)*. Most trucks have rollover thresholds substantially higher than this range. In an appendix to the U.S. Comprehensive Truck Size and Weight Study *(21)*, it is stated that fatal accident data show so few cases with rollover thresholds less than 0.35 *g* that rates cannot be calculated.

Vehicle rollover thresholds are not explicitly considered in highway design because horizontal curves and other locations where vehicles turn are designed to generate lateral accelerations well below the rollover thresholds of the vehicles that use the facility. However, the rollover thresholds of vehicles can be used to judge the margin of safety before rollover would occur at any particular highway feature.

This page intentionally left blank.

CHAPTER THREE

ROLE OF ROADWAY GEOMETRIC DESIGN IN SAFELY ACCOMMODATING HEAVY VEHICLES ON THE HIGHWAY

This chapter addresses the role of roadway geometric design in safely accommodating heavy vehicles on the highway. The geometric design elements and issues addressed in this chapter include:

- design vehicles
- sight distance
- upgrades
- downgrades
- acceleration lanes
- horizontal curves
- intersection design
- interchange ramps
- roadside features

The geometric design policies of most state and local highway agencies are based on or derived from the AASHTO *Green Book*; therefore, the *Green Book* criteria for geometric design are the focus of much of the following discussion. The discussion draws extensively from the analyses of *Green Book* design criteria conducted recently in *NCHRP Report 505 (2)*.

DESIGN VEHICLES

The design vehicles presented in the AASHTO *Green Book* are a primary tool for incorporating heavy vehicle considerations in highway geometric design. The *Green Book* design vehicles are especially important in the design of intersections. The *Green Book* design vehicles and their specific dimensions are presented in Appendix A.

SIGHT DISTANCE

Sight distance plays a key role in the safe operation of the highway system. Several types of sight distance are considered in highway geometric design including stopping sight distances, passing sight distance, intersection sight distance, and railroad-highway grade crossing sight distance. The relationship of heavy vehicle to each of these types of sight distance is discussed below.

Stopping Sight Distance

Sight distance is the length of roadway ahead that is visible to the driver. The minimum sight distance available on the roadway should be sufficiently long 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. Stopping sight distance is needed at every point on the roadway. In the survey reported in Appendix B, only 23 percent of highway agencies identified stopping sight distance as related to safety problems encountered by heavy vehicles.

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 in *NCHRP Report 400 (37)*. Design values for stopping sight distance are based on the following model:

$$SSD = 1.47Vt + 1.075\frac{V^2}{a} \qquad \textbf{(8)}$$

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 Eq. (8) represents the brake reaction distance and the second term represents the braking distance. The stopping sight distance design criteria applicable for all highway types are presented in Table 8. Figure 6 illustrates the application of stopping sight distance to crest vertical curves, while Figure 7 illustrates the application of stopping sight distance to horizontal curves.

The *Green Book* design criteria for stopping sight distance are based primarily on passenger car rather than heavy vehicle considerations. The key considerations that affect design criteria for stopping sight distance, vertical curve length, and offsets to sight obstructions on horizontal curves are as follows:

- assumed speed for design
- brake reaction time
- deceleration rate (or coefficient of tire-pavement friction)
- driver eye height
- object height

Stopping sight distance design for passenger cars and heavy vehicles does not differ with respect to assumed speed, brake reaction time, and object height. In fact, the brake reaction time of professional drivers may be better than the general driving population.

At crest vertical curves, truck and bus drivers have an advantage over passenger car drivers because they sit higher above the pavement and, thus, can see objects ahead that a passenger car driver cannot. The driver eye height for trucks used in geometric design is 2,400 mm (8.0 ft), as indicated in Chapter Two. Thus, heavy vehicle drivers actually need shorter vertical curves than passenger car drivers to attain adequate stopping sight distance. There is, however, no comparable advantage for heavy vehicle drivers on horizontal curves.

The design situation for stopping sight distance involves a vehicle braking to a stop on a wet pavement with relatively poor friction characteristics. Historically, the braking distances of heavy vehicles have been longer than those for passenger cars. However, recent data show that, on wet pavements, the braking distances of trucks and passenger cars are nearly equal *(11)*. Thus, the stopping sight distance needs for passenger cars and trucks are now comparable *(2)*.

In summary, it appears that the current highway design criteria for stopping sight distance can safely accommodate heavy vehicles.

Passing Sight Distance

Greater sight distance is required for one vehicle to pass another in the lane normally reserved for opposing traffic on a two-lane highway than is required simply to bring a vehicle to a stop before reaching an object in the road. Table 9 presents the passing sight distance criteria used in geometric design and the criteria used in marking of passing and no-passing zones on two-lane highways *(1, 22)*. The geometric design criteria are more conservative than the marking criteria, but neither is based on a completely consistent set of assumptions.

The current passing distance criteria shown in Table 9 were derived on the basis of passenger car behavior and do not explicitly consider heavy vehicles. Using a new sight distance model with more consistent assumptions, Harwood et al. *(14)* derived sight distance requirements for various passing scenarios involving passenger cars and trucks, as shown in Figure 8. The figure indicates that all passing scenarios are accommodated within the current geometric design criteria. Furthermore, Harwood et al. also found that a truck can safely pass a passenger car on any crest vertical curve on which a passenger car can safely pass a truck. The current marking criteria for passing and no-passing zones do not necessarily accommodate all passing maneuvers that truck drivers might wish to make. However, there is currently no indication that the passing and no-passing zone markings lead truck

Table 8. Design criteria for stopping sight distance *(1)*

Design speed (mi/h)	Minimum stopping sight distance used in design (ft)
15	80
20	115
25	155
30	200
35	250
40	305
45	360
50	425
55	495
60	570
65	645
70	730
75	820
80	910

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

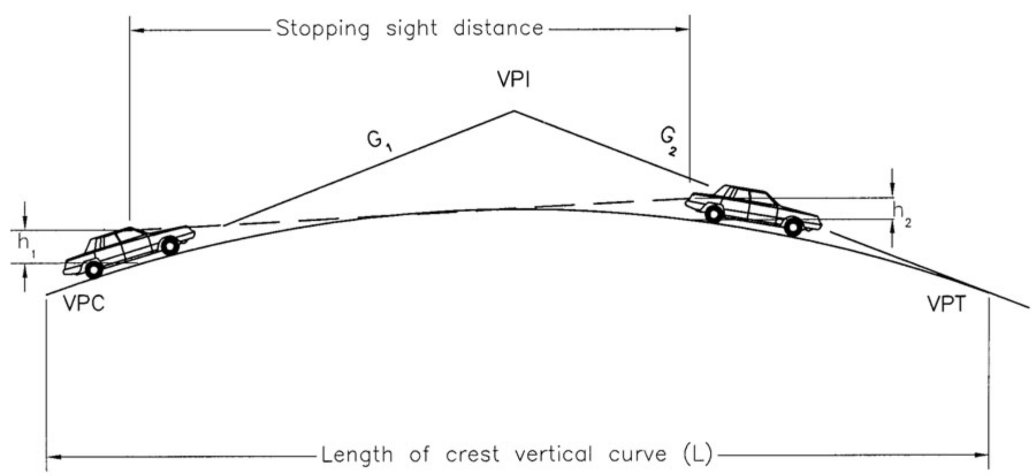


Figure 6. Application of stopping sight distance to crest vertical curves (1).

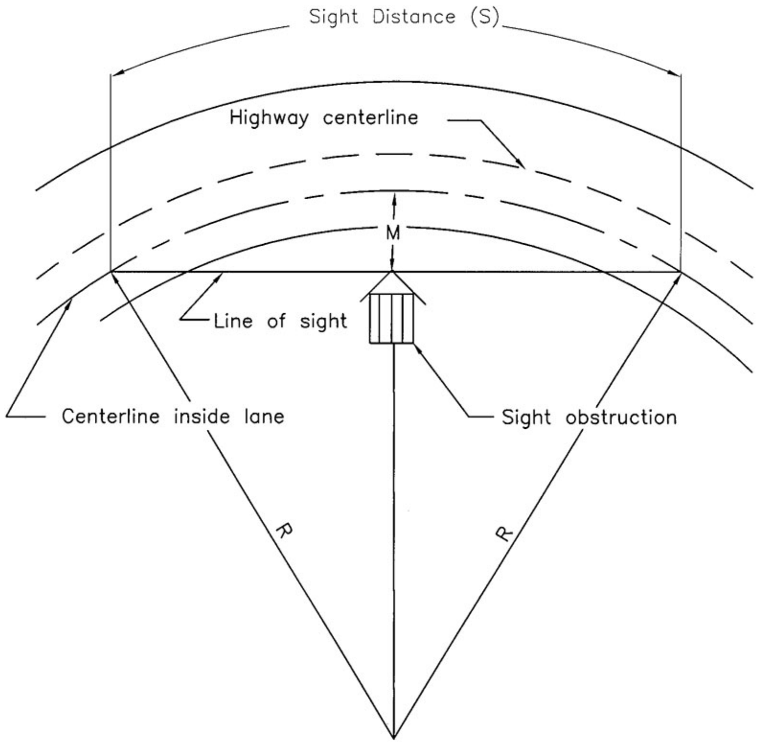


Figure 7. Application of stopping sight distance to horizontal curves (1).

Table 9. Design and marking criteria for passing sight distance *(1, 22)*

Design or prevailing speed (mi/h)	Passing sight distance (ft)	
	Highway design[a]	Marking of passing and no-passing zones[b]
25	900	450
30	1,090	500
35	1,280	550
40	1,470	600
45	1,625	700
50	1,835	800
55	1,985	900
60	1,985	900
65	2,285	1,100
70	2,480	1,200

[a] Based on AASHTO *Green Book (1)*.
[b] Based on MUTCD *(22)*.

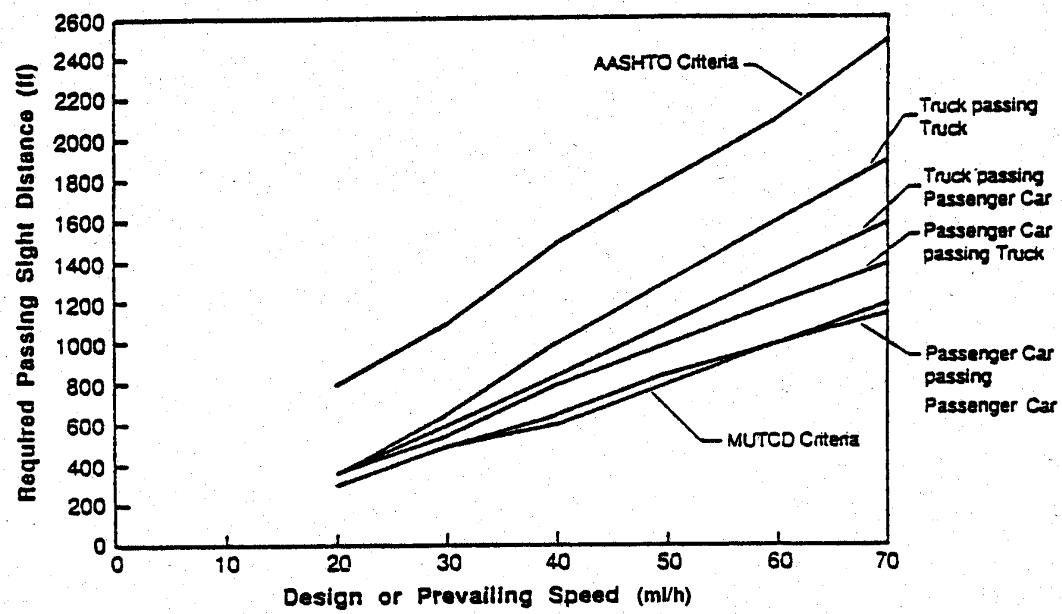


Figure 8. Required passing sight distance for passenger cars and trucks in comparison to current criteria (14).

drivers to make poor passing decisions or that trucks are overinvolved in passing-related accidents. Thus, there is no indication that a change in the marking criteria to better accommodate trucks would have safety benefits *(2)*. There is concern that such a change could eliminate some passing zones that are currently used effectively by passenger cars. Further research on this issue is needed.

Intersection Sight Distance

Sight distance is needed at intersections not only for drivers to see objects or other vehicles ahead on the roadway, but also to see potentially conflicting vehicles on other roadways. Sight distance at intersections is assured by maintaining triangular areas clear of sight obstructions in each quadrant of each intersection. Figure 9 illustrates the types of clear sight triangles that should be maintained at intersections: approach and departure sight triangles both to the left and to the right of each intersection approach.

Design criteria for intersection sight distance are established in the *Green Book* for a series of cases that apply to specific types of intersection traffic control and specific vehicle turning or crossing maneuvers. These design criteria were recently revised based on research in *NCHRP Report 383 (23)*. With one exception, the intersection sight distance criteria include explicit adjustment factors for heavy vehicles based on the research in NCHRP Report 383. The only case that does not explicitly address heavy vehicles is the design of intersections with no traffic control on any of the approaches. Such uncontrolled intersections typically have very low traffic volumes and even lower volumes of heavy vehicles.

Only 23 percent of highway agencies in the survey reported in Appendix B identified intersection sight distance as related to safety problems encountered by heavy vehicles.

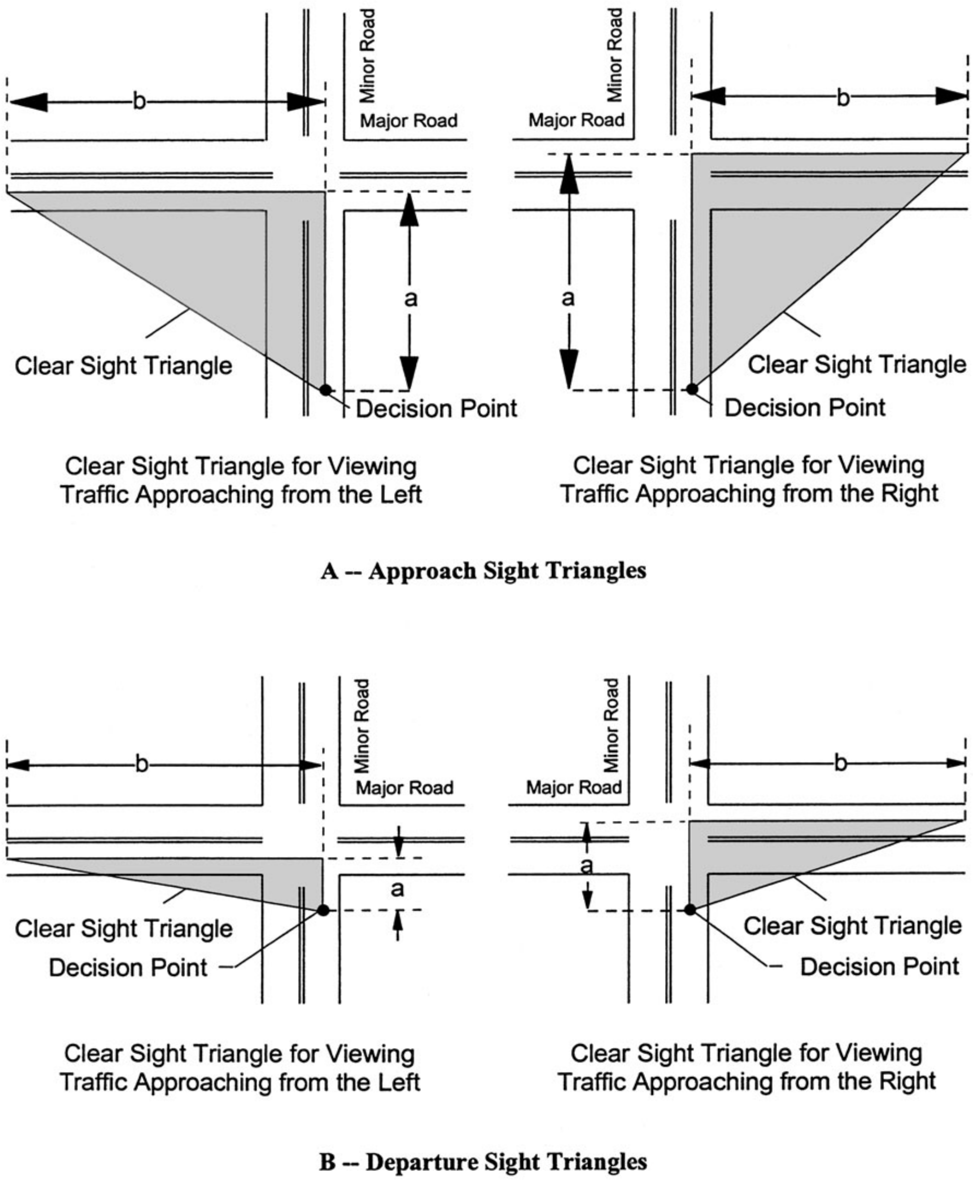


Figure 9. Clear sight triangles for intersections (1).

Railroad–Highway Grade Crossing Sight Distance

Sight distance is provided at railroad-highway grade crossings to ensure that approaching motor vehicles can see any train that is also approaching the crossing *(1)*. Sight distance is provided at railroad-highway grade crossings with clear sight triangles similar to those illustrated for intersections in Figure 9. *NCHRP Report 505 (2)* reviewed the current *Green Book* criteria for sight distance at railroad-highway grade crossings and found them adequate to accommodate heavy vehicles.

Recent experience has drawn attention to a safety issue unrelated to sight distance—the spacing between railroad-highway grade crossings and adjacent intersections—as an important factor for design and traffic control. Locations with short spacings between intersections and railroad tracks should be designed so that longer vehicles stopped at the intersection are not forced to stop in a position where the rear of the vehicle extends onto the railroad tracks.

Approximately 40 percent of highway agencies responding to the survey described in Appendix B indicated the railroad-highway grade crossings are a safety concern related to heavy vehicles.

UPGRADES

Heavy vehicles do not usually have engines sufficiently powerful to maintain normal highway speeds on long, steep upgrades. Slower vehicles have the potential to create both traffic operational and safety concerns at such sites. The speed maintenance capabilities of heavy vehicles on grades are primarily a function of the weight-to-power ratio of the vehicle, as documented in Chapter Two. As a heavy vehicle proceeds up a grade, it gradually loses speed until it reaches a crawl speed that is a function of the grade and truck characteristics. When traveling at its crawl speed, the heavy vehicle cannot accelerate but can travel at constant speed, without further speed loss.

To mitigate the potential traffic operational and safety effects of heavy vehicles, highway agencies often provide truck climbing lanes. An added lane on the upgrade allows heavy vehicles to avoid impeding passenger cars and other faster vehicles. The AASHTO *Green Book (1)* considers the provision of a climbing lane warranted when truck speeds are reduced by 16 km/h (10 mi/h) and certain minimum traffic volume or level of service criteria are met. A spreadsheet program has been developed for use by highway agencies to estimate speed profiles for specific trucks on specific upgrades *(2)*.

There are no formal safety effectiveness measures for truck climbing lanes, although Harwood and St. John *(24)* have estimated a 25 percent accident reduction effectiveness for passing lanes on two-lane highways, in general.

In response to the survey presented in Appendix B, 66 percent of highway agencies indicated that they have formal warrants for truck climbing lanes. In response to the survey presented in Appendix C, 23 percent of industry respondents indicated that they consider long, steep upgrades to be a high-priority safety concern, while 61 percent of respondents indicated that they consider long, steep upgrades to be a low-priority issue that represent a safety concern at a few locations. Approximately 66 percent of industry respondents indicated that they consider truck climbing lanes to be highly desirable improvements that should be used widely.

DOWNGRADES

Long, steep downgrades also represent a safety concern for heavy vehicles. In the industry survey reported in Appendix C, 40 percent of respondents indicated that they consider long, steep downgrades to be a major safety concern at many locations, while another 53 percent of respondents consider downgrades to be a safety concern at a few specific locations.

Heavy vehicle drivers must travel slowly down long, steep grades to minimize braking. If the vehicle service brakes are used too frequently, they may overheat and the vehicle may run out of control due to loss of braking ability. To avoid such incidents, highway agencies are signing at the top of long downgrades to advise heavy vehicle drivers of the appropriate choice of speed or gear ratio. Conventional signing has been used for this purpose (see Chapter Four), but automated systems to advise drivers on safe downgrade speeds have come into use as well (see Chapter Five). In the industry survey reported in Appendix C, 97 percent of respondents indicated that downgrade signing is desirable or highly desirable and 78 percent indicated that automated signing for downgrades is desirable or highly desirable. Criteria for such signing have been developed in research by Allen et al. *(25)*.

At particularly long or steep grades, highway agencies may provide roadside parking places at the top of the grade for heavy vehicle drivers to stop and check the temperature of their brakes and, if appropriate, to let the brakes cool. Such brake check areas may assist in reducing the frequency of out-of-control trucks on downgrades. Brake check areas are currently used by 49 percent of highway agencies and another 3 percent of agencies are considering their use (see Appendix B). Brake check areas are considered desirable or highly desirable by 90 percent of the industry survey respondents in Appendix C.

To assist heavy vehicle drivers who do lose control due to overheating of their brakes, many highway agencies provide emergency escape ramps in the middle or lower portion of long downgrades. Rather than continuing down a grade out of control, the driver can choose to enter the escape ramp where an arrester bed can bring the vehicle to a safe stop. Sixty-three percent of highway agencies have installed emergency escape ramps and such ramps are considered desirable or highly desirable by 100 percent of the respondents to the industry survey.

Allen et al. *(26)* have proposed a simulation model that could help highway agencies evaluate the need for emergency escape ramps. This issue has also been addressed by Abdelwahab and Morrall *(27)*.

ACCELERATION LANES

Acceleration lanes are provided at entrance ramps to major highways to provide a location for vehicles to increase their speed before entering the highway. Design criteria for the length of acceleration lanes, including adjustment factors for heavy vehicles, are presented in the AASHTO *Green Book (1)*. Recent research in *NCHRP Report 505 (2)* concluded that the current design criteria for acceleration lanes accommodate average trucks but may not be long enough to accommodate the lowest performance trucks. Seventy-five percent of the respondents to the industry survey in Appendix C indicated that acceleration lanes were a major safety concern at many locations. Further research on this issue is needed.

HORIZONTAL CURVES

The design criteria for horizontal curves in the AASHTO *Green Book (1)* are based on keeping the lateral acceleration of the vehicle within limits that are comfortable to the driver. A vehicle can exceed these tolerable limits without approaching the point of skidding or rolling over, but heavy vehicles have lower margins of safety against skidding or rollover than passenger cars *(2)*.

The lateral acceleration experienced by a vehicle traversing a horizontal curve is influenced by both the radius and superelevation of the curve. Skidding or rollover by a heavy vehicle on a horizontal curve designed in accordance with *Green Book* criteria is likely only if the vehicle is traveling at a speed higher than the design speed of the curve. A truck will roll over before it skids at curves with design speeds of 70 to 80 km/h (40 to 50 mi/h) and below; for curves above that design speed, a truck will skid before it rolls over *(2)*.

In the highway agency survey reported in Appendix B, 51 percent of highway agencies identified horizontal curve radius and 31 percent identified horizontal curve superelevation as a source of safety problems for heavy vehicles. In the industry survey reported in Appendix C, 67 percent of respondents identified sharp curves as a high-priority safety issue for heavy vehicles. Two respondents to the industry survey commented that inappropriate superelevation (and, particularly, the presence of reverse superelevation on some curves) creates a safety concern for heavy vehicles.

INTERSECTION DESIGN

Heavy vehicles are a key consideration in the design of at-grade intersections. Key intersection concerns for heavy vehicles include curb return radii for right turns, available storage length in left-turn lanes, median width, and visibility restrictions due to vehicles in opposing left-turn lanes.

The curb return radii for right turns are determined through a process that balances the needs of all highway transportation modes. The curb return radius should be sufficiently large to accommodate the offtracking and swept path of specific design vehicles that use the intersection without the vehicle encroaching on the curb or on an adjacent or opposing lane. At the same time, particularly in urban areas, it is desirable to keep the curb return radius small to minimize pedestrian crossing distances and avoid disturbing existing roadside development. Most designs involve some compromise between these objectives. In the survey reported in Appendix B, 51 percent of highway agencies identified curb return radii for right turns as a source of safety concerns for heavy vehicles. Tight radii for right turns were identified as a high-priority safety concern by 94 percent of the respondents to the industry survey presented in Appendix C.

Left-turn lanes are designed to include sufficient length for deceleration, storage, and a transition taper. The storage length for turn lanes is strongly influenced by the volume of heavy vehicles using the lane. In particular, if more vehicles than anticipated use the left-turn lane, the queue may overflow into the through vehicle lanes, creating safety problems. In the industry survey reported in Appendix C, 69 percent of respondents indicated that insufficient steerage length for left turns was a high-priority safety concern.

On divided highways, the median width at intersections should be selected to steer a design vehicle of appropriate length. *NCHRP Report 375 (28)* evaluated the design of divided highway intersections and recommended that medians at rural intersections should be as wide as practical and should accommodate the length of design vehicles that are present in sufficient numbers to serve as a basis for design. In urban areas, narrower medians operate more safely and the selected median width should generally be just wide enough to accommodate current, and anticipated future, left-turn treatments.

At some intersections, the view along the opposing roadway for the driver of a vehicle in a left-turn lane may be blocked by presence of a vehicle in the opposing left-turn lane. This is a particular concern when the vehicle in the opposing left-turn lane is large. Figure 10 illustrates the application of parallel and diagonal offset left-turn lanes to mitigate this problem. Both of these left-turn lane designs offset the opposing left-turn lanes by moving them out of the sight line of the left-turning driver.

INTERCHANGE RAMP DESIGN

Interchange ramps are designed to have sufficient width to allow vehicles to pass a stalled heavy vehicle. The design of horizontal curves on interchange ramps, particularly exit ramps, is challenging because vehicles leaving a major road may often exceed the design speed of the ramp. The design speeds for such ramp curves should be selected appropriately and, at some locations, conventional or automated signing may be needed to warn heavy vehicle drivers of the desired travel speed (see Chapters Four and Five).

Interchange ramps were identified as a safety concern by 51 percent of the highway agencies responding to the Appendix B survey and as a major safety concern by 68 percent of the industry representatives responding to the Appendix C survey.

ROADSIDE DESIGN

Roadside design includes the consideration of roadside slopes, roadside clear zones, and traffic barriers. These issues are addressed the AASHTO *Roadside Design Guide (29)*. Roadside slopes and clear zone widths are designed for all vehicle types and do not explicitly consider heavy vehicles. Traffic barriers, such as guardrails, bridge rails, and median barriers, are intended to contain and redirect specific vehicle types that may run off the road. At some locations, highway agencies have used traffic barriers specifically intended to contain heavy vehicles including tall concrete median barriers and super heavy-duty guardrails at the bottom of long downgrades. The level 4 and 5 testing procedures in *NCHRP Report 350 (30)* are appropriate for barriers intended to contain heavy vehicles.

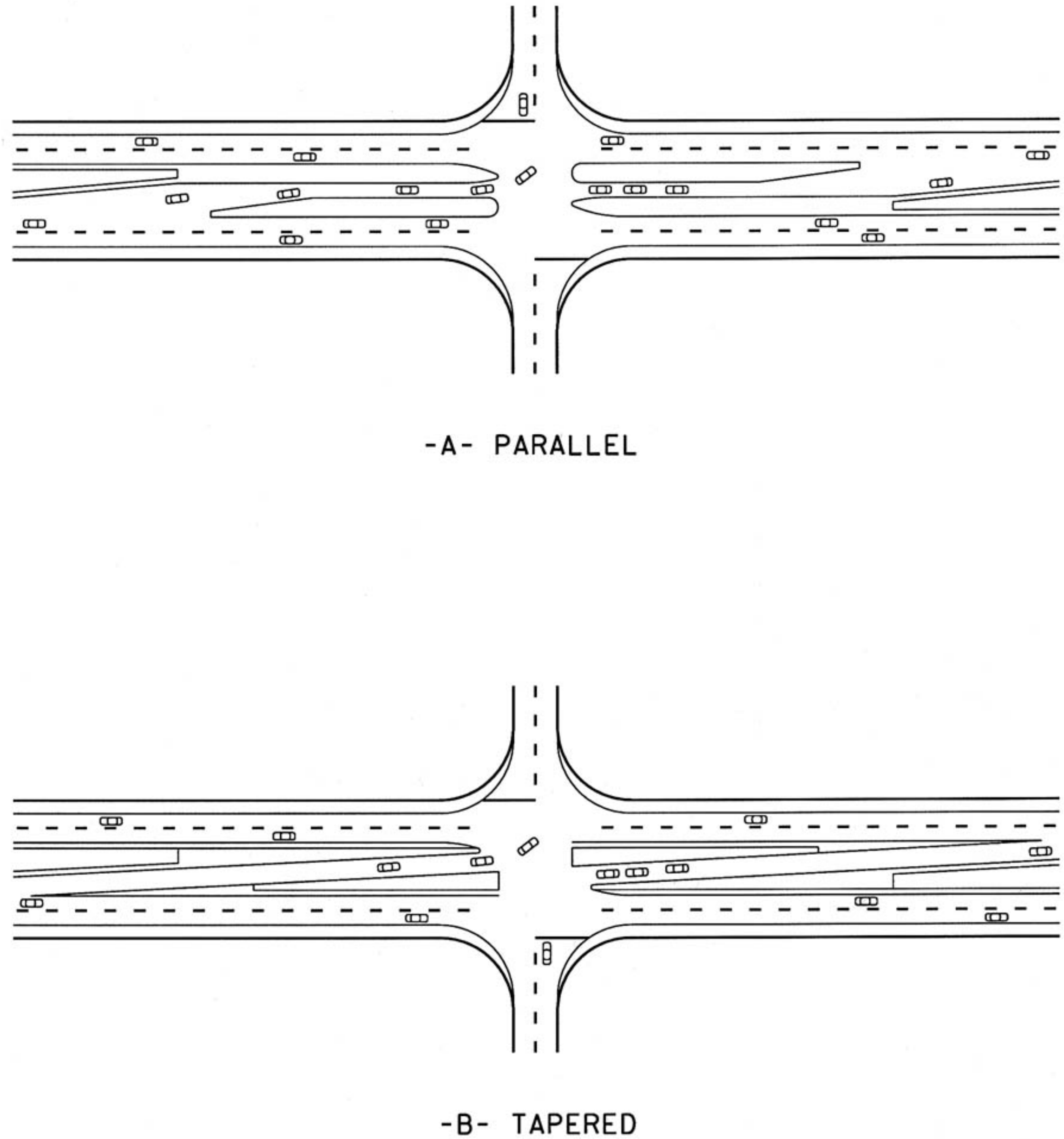


Figure 10. Parallel and tapered offset left-turn lanes (1).

CHAPTER FOUR

ROLE OF TRAFFIC CONTROL DEVICES AND TRAFFIC REGULATIONS IN SAFELY ACCOMMODATING HEAVY VEHICLES ON THE HIGHWAY

This chapter discusses the role of traffic control devices and traffic regulations in safely accommodating heavy vehicles on the highway. The applications of traffic control devices and traffic regulations addressed in this chapter include:

- differential speed limits for passenger cars and heavy vehicles
- lane use restrictions for heavy vehicles
- heavy vehicle prohibitions on particular roads
- exclusive lanes or exclusive roadways for heavy vehicles
- signing and marking of interchange ramps
- restriction of sign visibility by heavy vehicles
- signal timing to accommodate heavy vehicles

DIFFERENTIAL SPEED LIMITS FOR PASSENGER CARS AND HEAVY VEHICLES

Differential speed limits are speed limits that restrict all heavy vehicles, or at least heavy vehicles of a specific size, weight, or axle configuration, to traveling at lower speeds than the rest of the traffic stream. Proponents of differential speed limits argue that heavy vehicles have limited maneuvering and braking capabilities and should be required to travel at lower speeds in mixed traffic to help accommodate their differences from passenger cars. It has also been maintained that lower speeds for heavy vehicles should reduce their accident risk. Proponents of uniform speed limits (i.e., the same speed limit for passenger cars and heavy vehicles) argue that differential limits may increase speed variance, resulting in more traffic conflicts and, thus, more accidents between trucks and other types of vehicles. Increased speed variance has been shown to be related to increased accident frequency *(31, 32)*. It has also been maintained that the higher driver position in a heavy vehicle provides greater sight distance than for passenger car drivers, giving truck drivers more time to stop.

The highway agency survey in Appendix B found that 31 percent of state highway agencies have implemented differential speed limits for passenger cars and trucks and 9 percent of state highway agencies are considering differential speed limits. Table B-3 in Appendix B shows the specific combinations of passenger car and truck speed limits that have been used. In all cases, the differences in speed limits for passenger cars and trucks is either 8 or 16 km/h (5 or 10 mi/h).

In a recent study, Garber et al. (*33*) compared the safety effects of uniform speed limits for all vehicles with differential speed limits for passenger cars and trucks. Accident, speed, and volume data were obtained from ten states for rural highways for the period 1991 to 2000. These states were divided into four policy groups based on the type of speed limit employed during the period: maintenance of a uniform speed limit only, maintenance of a differential speed limit only, a change from a uniform to a differential speed limit, and a change from a differential to a uniform speed limit. Table 10 presents an overview of data availability from the various states included in the study.

Statistical analyses were used to evaluate speed and accident rate changes over time within the four policy groups. A before-after analysis was conducted for those states that had changed from a uniform to a differential speed limit (or vice versa) during the study period. For the states that maintained the same speed limit over the entire

Table 10. Overview of data availability on speed limits from various states *(33)*

Rural interstate speed limits (1991-2000)		Accident data	Speed data
Policy Group 1:	Maintained a uniform speed limit		
Arizona	121 km/h (75 mi/h)	Y	N
Iowa	105 km/h (65 mi/h)	N	Y
Missouri	89 km/h (55 mi/h) before 1996 113 km/h (70 mi/h) after 1996	Y	N
North Carolina	105 km/h (65 mi/h) before 1996 113 km/h (70 mi/h) after 1996	Y	N
Policy Group 2:	Maintained a differential speed limit (passenger cars/trucks)		
Illinois	113/105 km/h (70/65 mi/h)	N	Y
Indiana	105/97 km/h (65/60 mi/h)	N	Y
Washington	No speed limits	N	N
Policy Group 3:	Changed from uniform to differential speed limit(passenger cars/trucks		
Arkansas	From:105 km/h (65 mi/h) To: 113/105 km/h (70/65 mi/h) 1996	Y	N
Idaho	From:105 km/h (65 mi/h) To: 121 km/h (75 mi/h) 1996 To: 121/105 km/h (75/65 mi/h), 1998	Y	Y
Policy Group 4:	Changed from differential to uniform speed limit (passenger cars/trucks)		
Virginia	From: 105/89 km/h (65/55 mi/h) To: 105 km/h 965 mi/h), 1994	Y	Y

10-year period, the data were categorized into two subperiods, 1990 to 1995 and 1996 to 2000, in order to determine whether significant changes occurred over time even without a change in speed limit. Table 11 presents the results of the before-after accident analysis.

The Garber et al. study found no consistent safety benefits with differential speed limits. The mean speed, 85th percentile speed, median speed, and accident rate generally increased over the 10-year period, regardless of whether a differential or uniform speed limit was in place.

After the enactment of the Surface Transportation and Uniform Relocation Assistance Act in 1987, several states changed the speed limit on rural Interstate highways from 89 to 105 km/h (55 to 65 mi/h). Because of concern about the impact of the increased speed limit on accidents involving trucks, some of these states imposed a differential speed limit, restricting the maximum speed limit for trucks to 89 km/h (55 mi/h). To determine the safety effect of this strategy, Garber and Gadiraju (*34*) conducted a study of sites in California, Michigan, Maryland, Virginia, and West Virginia. At some of the study sites, a uniform speed limit of either 89 or 105 km/h (55 or 65 mi/h) was maintained. At other study sites, a differential speed limit of 105 km/h (65 mi/h) for passenger cars and 89 km/h (55 mi/h) for trucks was implemented.

Speed and accident data were used to evaluate the effects of differential speed limits on vehicle speeds and accident characteristics. Accident data were collected at each site for three years prior to and at least one year after the effective date of the change in speed limit. Results of the before-after analysis indicated the following:

- Compared with the uniform speed limit of 105 km/h (65 mi/h), the differential speed limit has no significant effect in reducing: (a) nontruck/truck accident rates or (b) two-vehicle accident rates.
- The differential speed limit increases the interaction among vehicles in a traffic stream as a result of the increase in speed variance.
- The imposition of the differential speed limit on Interstate highways with AADT less than 50,000 vehicles per day may result in higher accident rates for certain accident types, such as rear-end and side-

Table 11. Results of before-after accident analysis *(33)*

Policy group	State	Type of accident rate	All sites: Difference	All sites: Significant	ADT filtered sites: Difference	ADT filtered sites: Significant
Group 1: maintained a uniform limit	Arizona	Total	+	N	+	Y
		Fatal	+	N	+	N
		Rear end	+	N	+	Y
		Total truck involved	+	N	+	Y
		Truck-involved fatal	+	N	+	Y
		Truck-involved rear end	+	N	+	N
	Missouri	Total	+	N		
		Fatal	–	N		
		Rear end	+	N		
		Total truck involved	+	Y		
		Truck-involved fatal				
		Truck-involved rear end				
	North Carolina	Total	+	Y	+	Y
		Fatal	+	N	–	N
		Rear end	+	Y	+	Y
		Total truck involved	+	N	+	N
		Truck-involved fatal	–	N	–	N
		Truck-involved rear end	+	N	+	N
Group 3: Charged from uniform to differential limit	Arkansas	Total	–	N	+	N
		Fatal	+	N	+	N
		Rear end	+	N	+	N
		Total truck involved	+	N	+	Y
		Truck-involved fatal				
		Truck-involved rear end				
	Idaho	Total	–, +	N, N	–, +	N, N
		Fatal	–, +	N, N	–, +	N, N
		Rear end	–, +	N, N	–, +	N, N
		Total truck involved	–, +	N, N	–, +	N, N
		Truck-involved fatal	–, 0	N, N	–, 0	N, N
		Truck-involved rear end	–, +	N, N	–, +	N, N
Group 4: Changed from differential to uniform limit	Virginia	Total	+	N	+	N
		Fatal	–	N	–	N
		Rear end	+	N	+	Y
		Total truck involved	+	Y	+	Y
		Truck-involved fatal	+	N	+	N
		Truck-involved rear end				

swipe accidents, although the results were not statistically significant.

The National Highway Traffic Safety Administration (NHTSA) also conducted a study (*35*) following the passage of the 1987 Federal legislation. Accident data were analyzed from four states that raised the speed limit following the legislation. Two of the states (Georgia and Florida) had uniform 105 km/h (65 mi/h) speed limits while the other two (Ohio and Virginia) had differential speed limits of 105 km/h (65 mi/h) for passenger cars and 89 km/h (55 mi/h) for trucks.

In the states with differential speed limits, the study showed a higher percentage of accidents involving trucks that were exceeding the speed limit. This result may be expected since trucks in Ohio and Virginia were more likely to exceed the truck speed limit of 89 km/h (55 mi/h) than trucks in Georgia and Florida with a uniform speed limit of 105 km/h (65 mi/h) for both passenger cars and trucks. However, there appeared to be very little difference in the percentages of trucks involved in "high-speed" accidents [exceeding 105 km/h (65 mi/h)] between the two types of speed limits.

Just as the 1987 Federal legislation provided an opportunity to evaluate the safety effects of differential speed limits, Zaremba and Ginsburg (*36*) conducted a before-after study following the enactment of the mandatory 89 km/h (55 mi/h) speed limit in 1974. They investigated the safety effects of rear-end accidents involving passenger cars and trucks in four states. Three of the four states had differential speed limits before the law was enacted. The results suggested that with the change from a differential to a uniform speed limit, the overall reduction in rear-end accident rates was approximately 15 percent on high-speed roadways. In this analysis, rear-end accidents were then separated into two categories: car-struck-in-rear-by-truck (CSRT) and truck-struck-in-rear-by-car (TSRC) accidents. Accident rate reductions of 5 and 34 percent, respectively, were observed for these two categories. The TSRC accident rate, in particular, had a substantial reduction due to the uniform and lower speed limit.

A 1974 study by Hall and Dickinson (*37*) evaluated speed and accident data from 84 study sites located on Interstate, U.S., and state routes in Maryland. Multiple regression analysis was used to determine whether a significant relationship could be found among speed parameters, accidents, and accident rates. Figure 11 illustrates the distribution of accidents by type of vehicles involved. Trucks were involved in 15.5 percent of all accidents on roadway sections with a differential speed limit and 19.5 percent of all accidents on roadway sections without a differential speed limit. However, the accident analysis found no relationship between posted differential speed limit and truck accidents, although truck compliance with the differential limit was comparatively low.

Harkey and Mera (*38*) conducted a study to determine whether differential or uniform speed limits were more beneficial to safety and traffic operations on Interstate highways. Speed and accident data were collected from 12 states employing both types of limits. Sites included rural and urban Interstate locations and represented the following speed limits for cars/trucks: 89/89 km/h (55/55 mi/h), 105/89 km/h (65/55 mi/h), 105/97 km/h (65/60 mi/h), and 105/105 km/h (65/65 mi/h). Accident type, accident severity, and vehicle type involvement (e.g., car-into-truck vs. truck-into-car) were examined. The results of the accident analysis indicated the following:

- The states with differential speed limits experienced higher proportions of car-into-truck accidents for rear-end collisions; however, this difference was not statistically significant.
- The states with uniform speed limits experienced higher proportions of truck-into-car accidents for all collision types, including rear-end and sideswipe accidents.
- There were no differences in fatal accident proportions between the differential and uniform speed limit states, but the states with uniform speed limits did experience a higher proportion of injury accidents.

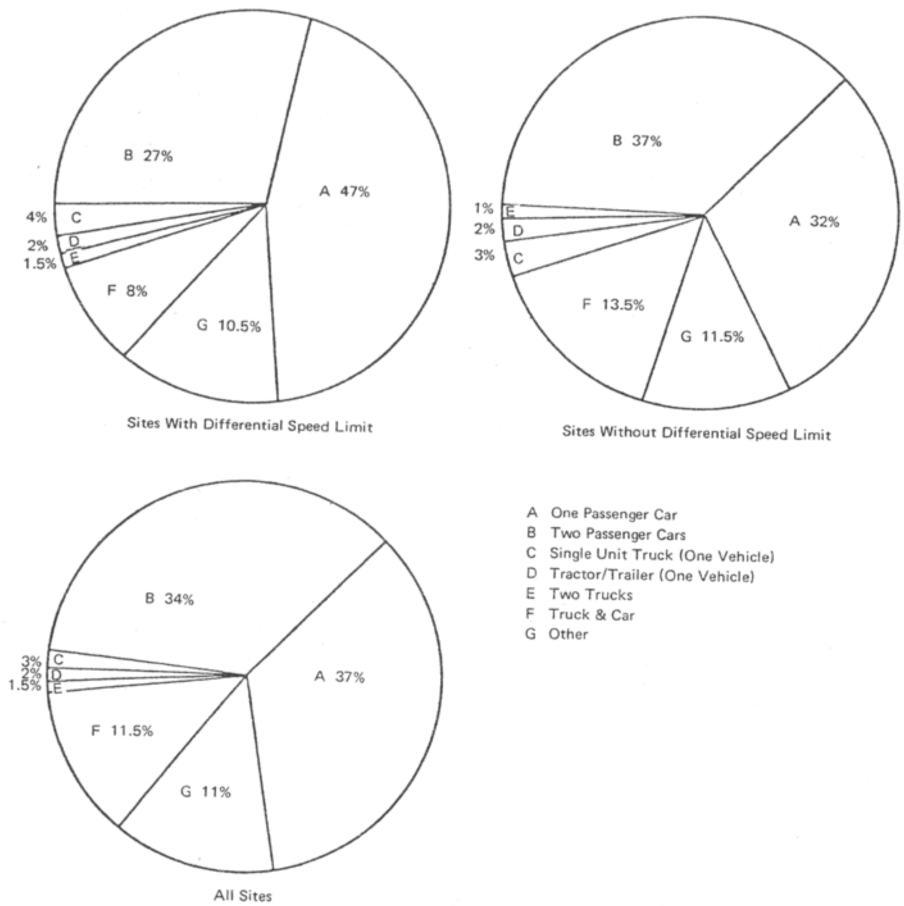


Figure 11. Distribution of accidents by type of vehicle involved (37).

Overall, the accident analysis showed very little difference in overall accidents or accident severity between the states with respect to the type of speed limit. However, the findings do suggest that the types of collisions and the roles of the vehicles involved may be impacted by the type of speed limit. In the states with differential speed limits, the car-truck rear-end collisions were more likely to involve cars striking trucks. In the states with uniform speed limits, the car-truck accidents were more likely to involve trucks striking cars. Following the passage of the 1987 Federal legislation, Baum et al. *(39)* conducted a study that compared vehicle speeds on rural Interstates in California and Illinois, which have a differential speed limit, with those in Arizona and Iowa, which have a uniform speed limit. The results of the study were as follows:

- A posted differential speed limit on rural Interstates was found to reduce high truck speeds on the faster roads.
- Trucks represent a smaller percentage of the high-speed traffic in states with differential speed limits than in states with uniform speed limits when average car speeds exceed 102.0 km/h (63.4 mi/h). Specifically, for each 1.6-km/h (1-mi/h) increase in mean car speed over 102.0 km/h (63.4 mi/h) on rural Interstates, the odds relative to cars of a truck traveling about 113 km/h (70 mi/h) decreases by 20 percent in the states with differential speed limits compared with states having uniform speed limits.
- Trucks travel 2.3 km/h (1.4 mi/h) slower in states with differential speed limits than in those without. This difference increases to

4.8 km/h (3.0 mi/h) for the fastest 5 percent of trucks.

In summary, differential speed limits have been shown to reduce the speeds of trucks relative to passenger cars, but no accident reduction effect of differential speed limits has been demonstrated. Indeed, there is concern that by increasing speed variance, differential speed limits may increase overall accident rates. The Appendix C survey showed concerns on the part of the trucking industry that differential speed limits may be adverse to safety.

LANE USE RESTRICTIONS FOR HEAVY VEHICLES

Lane restrictions are restrictions whereby all trucks, or at least trucks of a specific size, weight, or axle configuration, are restricted from traveling in specified lanes on a roadway. There are several variations in truck lane restriction strategies. One type of lane restriction restricts trucks from using the left lane(s) of a highway, typically a freeway with three or more lanes in each direction of travel; another type restricts trucks to using only the right lane of a highway. Figure 12 illustrates a truck lane restriction in the left lane.

Lane restrictions can be implemented on a mandatory or a voluntary basis; however, in many states, no attempts are made to enforce the restrictions. Lane restrictions may be implemented on either a site-specific or statewide basis, depending on the motivation behind the restriction and justification of its use. Most site-specific restrictions exist in areas with grades, where trucks have difficulty maintaining speed, or where there are unusual safety concerns. Most lane restrictions operate 24 hours a day to ease enforcement efforts and motorist confusion.

Truck lane restrictions are usually implemented for one of the following purposes:

- to improve traffic operation and efficiency
- to improve safety
- to extend pavement life

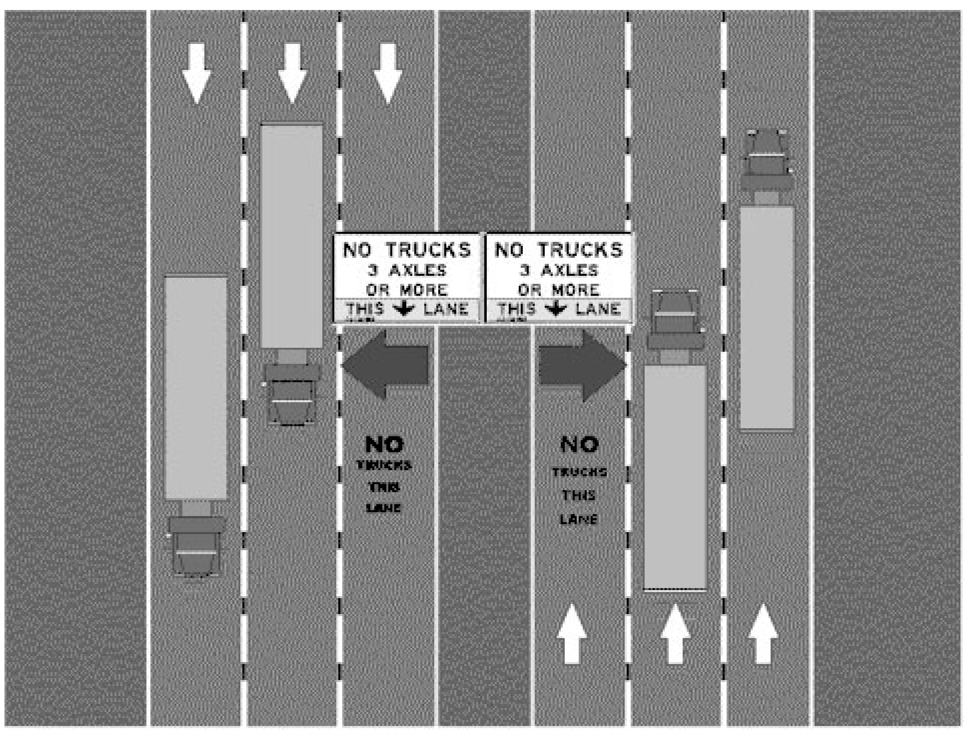


Figure 12. Truck lane restriction in left lane (40).

From a traffic operational standpoint, the presence of large trucks in the traffic stream is perceived to restrict the free flow of traffic, resulting in low speeds, large headways, and ultimately, an underutilization of the facility. To improve traffic operation and efficiency, trucks are most often restricted from traveling in the extreme left lanes, thus reserving these faster lanes for passenger cars. From a safety standpoint, large trucks are thought to present a safety hazard because of their decreased stopping capabilities, lack of maneuverability, and large size, which occupies more lane space and blocks motorists' visibility.

The survey results reported in Appendix B indicate that 37 percent of highway agencies have used and 9 percent are considering restrictions on truck and bus use of the left lane. Six percent of highway agencies have used and 11 percent are considering restricting all trucks and buses to the right lane. The majority of respondents to the trucking industry survey consider such restrictions undesirable or unnecessary; approximately 36 of the industry survey respondents indicated that such restrictions of trucks from the left lane were highly desirable or desirable at some locations.

Garber and Gadiraju (*41*) conducted a study to determine the effect of truck lane restrictions and differential speed limits on traffic flow, speeds, headways, and accident patterns. Nine test sites, with relatively high truck percentages, were selected from sections of Interstate and arterial highways in Virginia. Speed, traffic volume, and accident data were obtained in order to determine the speed-flow relationships for different traffic lanes at different locations and the relationship between congestion and accident rates on multilane highways. Traffic flow models and models relating accident rates to congestion were developed. Simulation was then used to study the effects of truck lane restrictions and differential speed limits on traffic volumes, speeds, headways, and accident rates. Using the model relating congestion and accident rates, and the hourly counts and truck volumes from the simulation results, the expected changes in accident rates were determined.

The results did not indicate any safety benefits from the implementation of lane restrictions and differential speed limits, but suggested a potential for an increase in accident rates if the strategies were imposed on highways with high volumes and a high percentage of trucks. A slight increase in truck-related and all-vehicle accidents were observed in the right lane, although these increases were not statistically significant.

To improve safety on the Capital Beltway, the Virginia Department of Highways and Transportation implemented a lane restriction that banned trucks and tractor-trailers from the farthest left (median) lane (*42*). For analysis purposes, vehicles were classified as either tractor-trailers (any combination, with a three-axle minimum), single-unit trucks larger than a panel truck, and other vehicles. An evaluation of the lane restriction indicated the following:

- A slight reduction in the total number of accidents for both trucks and passenger cars was observed.
- The number of injury accidents decreased by approximately 20 percent.
- Tractor-trailer trucks experienced the highest accident rate of all vehicle types.
- The number of tractor-trailer accidents occurring in the median lane was less than the number of accidents occurring outside the median lane after the tractor trailer had, just prior to the accident, been traveling in the median lane. In other words, the weaving action of trucks moving out of the median lane because of the restriction appeared to have resulted in an increase in tractor-trailer accidents.

Secondary results of this study were as follows:

- Truck and truck/trailer volumes were lowest in the median lane and highest in the far right lanes, prior to the implementation of the lane restriction.
- No changes in speed were detected for any vehicle type.
- Motorists supported the program because they felt less intimidated by the trucks.

The Nevada Department of Transportation (DOT) conducted a study (*43*) to determine the impact on pavement deterioration of a voluntary truck lane restriction. On an Interstate test site in Nevada, trucks were requested to travel in the left-hand lane to ease the pavement deterioration rate in the well-traveled right lane. While the focus of this study was pavement deterioration, the researchers noted that the redistribution of trucks had no significant impact on traffic accidents.

In 1988, Florida conducted a six-month study (*44, 45*) to determine the effect of prohibiting large trucks from using the left lane on I-95 between the hours of 7:00 a.m. and 7:00 p.m. With signs posted about every mile—and with good media coverage and strict police enforcement—98 percent compliance was achieved. The accident rate for all vehicles decreased 2.5 percent for a 24-hour period but increased 6.3 percent during the hours of restriction. The proportion of accidents involving trucks with three or more axles decreased 3.3 percent during the hours of the restriction.

To reduce the number of crashes involving combination trucks on Houston freeways, officials from the City of Houston and the Houston District of the Texas Department of Transportation (TxDOT) decided to conduct a 36-week lane restriction demonstration project (*46*) on a freeway in Houston. During the demonstration period, trucks were prohibited from using the left lane of the freeway. It was decided that a 13-km (8-mi) section of the I-10 East Freeway was most appropriate for the demonstration project. Traffic volume data were reviewed to determine compliance with the truck lane restriction by measuring the percentage of trucks in the left lane compared to other lanes. Accident data were compiled during the demonstration project and compared to data taken on the same stretch of road prior to the restriction. The study results indicated a 68 percent reduction in accidents. Average compliance rates were generally in the 70 to 80 percent range. Furthermore, passenger car drivers overwhelmingly supported the project. The success of the demonstration project has resulted in TxDOT considering implementation of the restriction on additional freeways in Houston.

The evidence on the safety effectiveness of truck lane restrictions is mixed. Prior to the Houston study discussed above, no previous study had shown an overall decrease in accident experience. The Houston study showed a positive result in one freeway corridor over an eight-month period. This result is promising but further data are needed before a safety benefit from lane restrictions could be considered documented.

HEAVY VEHICLE PROHIBITIONS

In a review of countermeasures for truck accidents on urban freeways, Fitzpatrick et al. (*44*) identified several locations where trucks are prohibited from using certain facilities. In each case, the prohibition had been made for reasons other than safety (e.g., reduce congestion, reduce pavement wear, etc.). Thus, no safety evaluations were conducted. Obviously, if trucks are prohibited from using a facility, the facility will no longer experience truck-related accidents. However, the safety effect of diverting trucks to other facilities is not known. A summary of the truck restriction locations is presented below:

- In an effort to reduce congestion, San Diego has restricted trucks from Route 163 through scenic Balboa Park. The merging of traffic from five to two lanes, a 6 percent grade, and a lack of acceleration and deceleration lanes for interchanges all contribute to heavy congestion on the freeway. Public opinion prohibits construction of additional lanes because of the extensive landscaping and scenic location of the freeway.
- A truck ban currently exists on the Pasadena Freeway in Los Angeles (now restored to its original name, Arroyo Seco Parkway) primarily because the pavement of the facility, which opened in 1940, is too weak to support trucks. The California Department of Transportation (Caltrans) reports that with no trucks, this 178-mm (7-inch) pavement is still in good condition. The only large vehicles allowed on the freeway are transit buses and trucks making local pickups and deliveries.
- There is also a truck avoidance policy currently in effect for the Harbor Freeway (I-710) in Los Angeles during major reconstruction. It is only a voluntary ban,

and Caltrans reports that the reduction in truck volume is negligible.

- Beginning in December 1978, a new truck restriction required that trucks traveling through Atlanta use the I-285 bypass instead of freeways that run through the center of the city. In evaluating compliance with this ban, a survey conducted by the Georgia Department of Transportation showed a violation rate of 5.4 percent.

EXCLUSIVE LANES OR ROADWAYS FOR HEAVY VEHICLES

As a result of the increasing volumes of heavy vehicles on major highways, highway agencies are becoming interested in the provision of exclusive lanes or exclusive roadways for heavy vehicles. The survey reported in Appendix B found that exclusive lanes for trucks and buses only have been used or considered by 17 percent of highway agencies, exclusive lanes for buses only by 20 percent of highway agencies, and exclusive roadways for heavy vehicles only by 3 percent of highway agencies.

In a review of countermeasures for truck accidents on urban freeways, Fitzpatrick et al. (*44*) identified several locations where separate truck facilities were either in use or were being considered. No evaluations of the effect of this countermeasure on truck accidents were available. Obviously, if trucks are removed from a facility, the facility will no longer experience truck-related accidents. However, the safety of the separate truck facility is not known. A summary of the locations is presented below:

- A 53-km (33-mi) segment of the New Jersey Turnpike consists of interior lanes for passenger cars only and exterior lanes for trucks, buses, and passenger cars. Located within the same right-of-way, the interior and exterior roadways each have three lanes in each direction, with the exception of a 16-km (10-mi) section that has only two lanes in each direction on the exterior roadway. Each roadway has 3.6-m (12-ft) lanes and 3.6-m (12-ft) shoulders. Opposing directions of travel are separated by a concrete median barrier, and the passenger-car-only lanes are separated from the truck/bus/car lanes by a metal beam guardrail.
- In California, the reconstruction of a section of I-5 north of Los Angeles resulted in two parallel roadways. After completion of the new interstate roadway, the old roadway was maintained to carry truck traffic.
- Truck facilities have been considered for the corridor connecting the San Pedro ports and downtown Los Angeles. Proposals include using the paved Los Angeles River channel as an exclusive truck facility, and using the Alameda Street corridor to carry trucks and trains within a right-of-way also shared by passenger cars.
- Truck facilities have also been considered for the I-10 Houston-Beaumont (Texas) corridor and the Houston North Freeway (I-45). Studies of these potential sites concluded that construction of an exclusive truck facility was not warranted because of limited truck volumes along certain sections of the corridor and the estimated cost of the facilities.

An earlier study in Texas examined various approaches to handling increases in truck volumes. One approach included a study *(47)* to investigate the feasibility of an exclusive truck roadway in the median of the I-35 corridor between Dallas-Ft. Worth and San Antonio. The objectives of this study included:

- establish critical geometric design elements for exclusive truck facilities
- identify typical cross sections to accommodate truck lanes within an existing median area
- prepare alternative access control configurations to serve exclusive truck facilities
- develop a moving-analysis computer program to evaluate geometric constraints and operational performance along a specific corridor

The researchers determined that modifications to highway design policy should be considered in the following areas in development of criteria for the design of exclusive truck facilities:

- Vehicle characteristics
- Sight distance
- Horizontal alignment
- Vertical alignment
- Cross-section elements

Several of the design recommendations made in this study have since been incorporated in the AASHTO *Green Book (1)*.

A key issue in designing exclusive truck facilities is to decide how trucks enter and leave the facility. Several alternatives for allowing access to and from an exclusive truck facility were considered including:

- *Existing Ramps*—Trucks enter the freeway on ramps designated for both cars and trucks and then move to the appropriate lanes designated for trucks only. Adequate advance signing and decision sight distance are necessary for successful operation.
- *Frontage Roads*—Trucks still interact with other traffic on the cross-street intersections near the trunk ramp terminals. A disadvantage to this alternative is the potential for adverse effects on intersection capacity.
- *Exclusive Truck Routes*—Large vehicles must enter or exist at an interchange or intersection specifically designed for trucks or other large vehicles. This is advantageous in providing direct access to specific truck traffic generators, such as large industrial complexes, and in avoiding congested areas.

No estimates of the safety performance of such facilities have been developed.

SIGNING AND MARKING OF INTERCHANGE RAMPS

Sharp horizontal curves, particularly on interchange ramps, have been found by a number of highway agencies to require warning signs to advise heavy vehicles of safe operating speeds. Typically, such installations have used a warning sign showing a truck tipping over with an advisory speed (see example in Figure 13). The highway agency survey reported in Appendix B found that 31 percent of highway agencies had used advisory speed limits for all trucks on specific ramps and 60 percent had used advisory speed limits for all vehicles on specific ramps. Regulatory speed limits on ramps were used much less often (by 6 percent of highway agencies or less). Special warning signs for trucks (e.g., the truck rollover sign) were used by 57 percent of highway agencies. Twenty-six percent of highway agencies have used special warning signs for trucks accompanied by a permanent flasher. Thirty-seven percent of highway agencies had found a need to reconstruct particular ramp curves to change their radius or superelevation.

Figure 13. Truck rollover warning sign typically used at curves on interchange ramps.

Research by Knoblauch and Nitzburg *(48)* addressed ramp signing for trucks and methods for treating interchange ramps that are prone to cause high center of gravity vehicles to lose control and overturn. The research involved several studies including:

- A state-of-the-practice review was conducted in 12 states to determine the nature and extent of the truck rollover accident problem, determine procedures for identifying problem ramps, and identify active and passive treatments currently being used at problem ramps.
- A "design-a-sign" study using 61 professional truck drivers was conducted to

attempt to identify critical ramp characteristics and to develop innovative procedures for effectively communicating this information to approaching drivers.

- A series of laboratory studies were conducted to identify specific sign elements and formats that most effectively warn truck drivers about potentially dangerous ramps.
- Field tests were conducted at interchange ramps in Virginia and Maryland that had experienced problems with truck rollover accidents. A truck tipping sign with activated flashing beacons was installed at the ramp and an advance warning sign was installed prior to the ramp.

The results of the research are summarized below:

- The sign formats that were best understood by truck drivers consisted of the rear silhouette of a tipping truck, a diagrammatic arrow, and an advisory speed indication.
- Truck drivers prefer the use of advance warning signs located well in advance of a ramp and the use of flashing lights or beacons to identify particularly hazardous locations.
- Truck drivers understood from the sign that they had to be more careful when they were hauling a top-heavy load than when they were hauling a regular load.
- In the first field test, the sign with the tipping truck produced a slight short-term reduction in truck ramp speeds at one of the two experimental sites. However, the effect dissipated within 3 months of the sign installation.
- In the second field study, the sign with the tipping truck and the flashing beacons (that were activated when the truck approached the ramp) combined with an advance warning sign approximately 457 m (1,500 ft) upstream from the ramp produced no statistically significant change in truck speeds. There was, however, a 6.4-km/h (4-mi/h) reduction in the 90th and 95th percentile speeds of top-heavy trucks, suggesting that the truck tipping sign with flashers may have an effect on the most targeted group-high-speed, top-heavy trucks.
- In the third field test, the addition of flashing beacons to an existing tipping truck sign and an advance warning sign had no effect on the approach or ramp speeds of trucks.

Maryland and Virginia (*44*) reevaluated ramp speeds on the Capital Beltway to determine whether the posted speeds were appropriate for trucks. Virginia reduced speeds on 44 ramps and Maryland also reduced speeds on several ramps. California is evaluating turning roadways to determine the adequacy of speed signing for trucks.

An ITS application for improving safety on ramp curves is presented in Chapter Five. Retting et al. *(49)* evaluated the effect on traffic speeds of experimental pavement markings on freeway exit ramps. A special pavement marking pattern was employed that narrowed the lane width of both the ramp curve and a portion of the tangent section leading into the curve by use of a gradual inward taper of existing edgeline or exit gore pavement markings or both. Traffic speeds were analyzed before and after installation of the pavement markings at four experimental ramps in New York and Virginia. Results indicated that the markings were generally effective in reducing speeds of passenger vehicles and large trucks. The markings were associated with significant reductions in the percentages of passenger vehicles and large trucks exceeding posted exit-ramp advisory speeds.

The literature shows that truck rollover signs and other similar measures are potentially effective in reducing truck speeds, particularly those considered most likely to roll over. However, the safety effectiveness of such signing has not been demonstrated.

RESTRICTION OF SIGN VISIBILITY BY HEAVY VEHICLES

Heavy vehicles are generally large in size and may block the ability of other drivers to see highway signs. In the survey reported in Appendix B, 20 percent of highway agencies indicated that they had encountered safety problems related to the obstruction of sign visibility by trucks and buses.

A paper by Schorr *(50)* examined both the blockage of roadside signs when a passenger car is passing a truck and the blockage of overhead signs when a passenger car is following a truck. When a passenger car is passing a truck on the left, the passenger car driver's view of signs on the right side of the roadway is blocked for some distance. The most critical position for the passenger car driver is when the front of his car is even with the rear of the truck. In this position, the passenger car driver's view of roadside signs is blocked for 46 m (150 ft). Since roadside signs may be legible for more than 46 m (150 ft) and since the passing driver may have had an opportunity to see the same sign while following the truck before he began the passing maneuver, this situation is not critical *(50)*.

Sign blockage for passenger car drivers does become critical, however, when two or more trucks are traveling together in the right lane. For example, if a second truck is traveling within 19 m (63 ft) in front of the first truck, the passing driver's view is blocked for 139 m (455 ft) from the rear of the first truck. If three trucks are traveling together in the right lane, roadside signs may be blocked for as much as 320 m (1,050 ft) *(50)*.

The potential for obstruction of the view of passing drivers to roadside signs cannot be remedied through changes in the criteria for horizontal and vertical placement of signs, but may require that critical signs be supplemented with overhead signs or with signs placed on the left side of the roadway.

The passenger car driver's view of overhead signs may also be blocked when closely following a truck. When following a truck by five car lengths [29 m (95 ft)], a passenger car driver does not have a full view of an overhead sign mounted with 4.9 m (16 ft) of vertical clearance until the car is within 43 m (140 ft) of the sign. At a speed of 80 km/h (50 mi/h), an overhead sign would be visible to the passenger car driver for only 1.9 s. This situation can be remedied by mounting overhead signs higher or by providing supplementary roadside signs *(50)*.

The Appendix B survey indicated that highway agencies had taken the following actions to improve sign visibility:

- Placing regulatory signs on both sides of the roadway on freeways
- Using double stop signs or placing stop signs on both sides of the road
- Using overhead signs
- Placing an additional traffic signal head over the opposing through lane
- Additional use of advance warning signs

Ullman and Dudek (*51*) recently developed mathematical models to evaluate the effect of roadway geometrics and large trucks on variable message sign readability.

Al-Kaisy and Bhatt (*52*) developed a simulation approach to study the occlusion of ground-mounted traffic signs by heavy vehicles on multilane highways. This study is part of a more extensive research effort to examine the different factors that determine the effect of heavy vehicles on the visibility of traffic signs. The model simulates roadway geometry and traffic signs as well as the movement and location of passenger cars and trucks on the facility upstream of the subject traffic sign. The model also accounts for other traffic conditions such as traffic volumes, percentage of trucks, lane utilization, and average speeds of passenger cars and trucks. The occlusion of ground-mounted traffic signs by heavy vehicles was estimated by two measures:

- the probability of a traffic sign being occluded by heavy vehicles under certain traffic and geometric conditions
- the likelihood of a passenger car driver missing the sign based on the minimum time required for the driver to detect, recognize, and read the message.

There are no available studies that quantify the extent to which sign blockage by heavy vehicles creates safety problems for other vehicles.

SIGNAL TIMING TO ACCOMMODATE HEAVY VEHICLES

The *Manual on Uniform Traffic Control Devices* (MUTCD) *(22)* specifies an interval 3 to 6 s for the yellow vehicle change interval at traffic signals. The yellow signal display may be followed with an all-red clearance interval and such clearance intervals are frequently used at intersections with substantial truck volumes.

Since implementation of the North American Free Trade Agreement (NAFTA), some highways in the border areas of Texas have experienced an increase in truck traffic. The higher truck volumes have resulted in increased pavement damage and traffic delay at rural, high-speed signalized intersections. A decrease in safety has also been observed at these intersections due to truck braking limitations. Research by Sunkari et al. (*53*) developed a system to reduce the number of stops made by trucks at high-speed signalized intersections. The system incorporated truck priority logic and used loop detectors and a classifier to identify trucks approaching the intersection. The system was implemented at an intersection in Sullivan City, Texas, and was effective in reducing the number of stopping maneuvers made by trucks at the intersection. However, no evaluation was conducted to determine the effect of this system on safety.

SAFETY IMPROVEMENTS FOR NIGHT DRIVING

Two respondents to the trucking industry survey reported in Appendix C noted the need to provide lane lines that are more visible at night and in adverse weather. FHWA is currently considering guidelines for increasing the retroreflectivity of lane lines and other pavement markings. Other respondents to the industry survey noted the need for more rest areas and pulloffs, the need to improve lighting and enforcement at rest areas, and the need for more enforcement of failure to dim headlight beams at night.

The highway agency survey reported in Appendix B noted only one potential safety issue related to truck and bus travel at night. This issue is the need to improve low visibility of border stations at night; only a limited number of states operate agricultural inspection stations of this type on high-speed highways near state borders.

This page intentionally left blank.

CHAPTER FIVE

ITS INITIATIVES FOR IMPROVING SAFETY IN HIGHWAY/HEAVY VEHICLE INTERACTIONS

This chapter addresses ITS programs intended to improve the safety of heavy trucks and buses. The largest ITS program directly related to commercial trucks is the Commercial Vehicle Operations (CVO) program. However, because this program is intended primarily to improve the operational efficiency of commercial vehicle operators and agencies, only a brief overview of the program is presented first. The types of ITS programs that are discussed in greatest detail in this chapter concern speed management technologies. Several ITS systems have been deployed at locations of steep downgrades and/or sharp horizontal curves to reduce the speeds of trucks. Other types of programs that are addressed include advanced technologies to improve the traffic flow along the mainline facility near inspection (weigh) stations and collision avoidance systems designed to improve bus safety.

ITS COMMERCIAL VEHICLE OPERATIONS (CVO) PROGRAM

The purpose of the ITS/CVO program is to define, pilot test, and deploy technologies, information systems, and networks to enhance roadway safety, credentialing, and operations *(54)*. ITS/CVO applications fall into four areas:

Safety Information Exchange: Improve targeting of high-risk operators by providing inspectors better access to current safety information; automate safety inspection activities; and support deployment of in-vehicle technologies designed to improve safety.

Electronic Credentialing: Automate administration functions and enhance data communications capabilities of state and administrative agencies to enable paperless transactions between motor carriers and regulatory agencies.

Electronic Screening: Screen commercial vehicles at fixed weigh stations, ports of entry, and mobile inspection sites for safety, size/weight, and credential compliance at mainline speeds.

Motor Carrier Operations: Improve motor carrier safety and efficiency by providing timely, accurate information to fleet managers and accelerate development and deployment of emerging technologies.

The ITS/CVO services focus on enabling seamless information exchange between motor carriers, regulators, and safety enforcement agencies. Thus, the ITS/CVO program allows enforcement agencies to focus their resources on unsafe motor carriers and provides motor carriers access to current information that can be used to improve fleet operations and safety.

In 1998, the FMCSA conducted research to examine information and technology use by motor carriers and help guide the development of effective ITS/CVO services. The study found:

- 53 percent of surveyed carriers used computer-aided routing and dispatching systems (CAD)
- 41 percent of surveyed carriers used electronic data interchange (EDI) technology
- 72 percent of surveyed carriers used mobile communication technologies
- 10 percent of surveyed carriers used on-board computers (OBC)

In addition, the study concluded that the characteristics of individual motor carriers (size of fleet, type of haul, routing variability, etc.) and their primary operational objectives (on-time performance, safety assurance, cost avoidance, etc.) directly impact a carrier's choice of technologies and perceived value of ITS/CVO services.

WARNING SYSTEMS FOR LONG DOWNGRADES

The primary objective of warning systems for long downgrades is to warn specific truck drivers that their speed is above a recommended safe descent speed for the geometric conditions and that they should reduce their speed in order to lower their potential for losing control of the vehicle on the downgrade. For many years, highway agencies have used fixed signing to advise truckers on the appropriate speed or gear for descending particular grades. The highway agency survey reported in Appendix B found that 74 percent of highway agencies have used downgrade signing to promote proper speed and gear selection. Several ITS systems have now been installed across the country to provide real-time information to heavy vehicle drivers about to descend a grade. Over 78 percent of respondents to the industry survey reported in Appendix C indicated that such systems are desirable or highly desirable.

Colorado

In 1997, the Colorado DOT installed a Downhill Truck Speed Warning System (DTSWS) inside the Eisenhower Tunnel in the westbound lanes of I-70 to reduce the number of truck-related crashes that occur on the long downgrade that follows this tunnel *(55)*. The downgrade is about 16 km (10 mi) in length with grades between 5 and 7 percent. This stretch of highway carries a significant volume of truck traffic. In 1998 and 1999, average monthly counts of heavy trucks were approximately 30,000, or 1,000 trucks per day. From 1990 to 1996, 106 truck-related crashes occurred along this 16-km (10-mi) downgrade. Two runaway truck ramps are located on the downgrade within 3.2 km (2 mi) of the tunnel, and over a 5-year period from 1995 to 1999 the truck escape ramps were used 106 times, approximately twice per month.

The DTSWS consists of loop detectors, weigh-in-motion (WIM) devices, and a variable message sign (VMS). The DTSWS calculates a safe descent speed, based upon the truck's axle configuration and gross vehicle weight and the grade profile of the highway, and displays the advisory speed for each passing truck of greater than 18,200 kg (40,000 lb). The VMS that displays the advised descent speed is located approximately 76 m (250 ft) beyond the loop detectors and WIM strips. The system is located inside the Eisenhower tunnel so that drivers receive the message before reaching the downgrade.

In 1999 an evaluation of the DTSWS was conducted to determine the effectiveness of the system. Because the DTSWS had not been operating for a long enough time to assess whether it had significantly reduced truck-related crashes, the primary objective of the evaluation was to compare speeds of trucks descending the grade after exiting the tunnel with the DTSWS either on or off. Data for the evaluation were collected over a 4-day period, 2 days with the DTSWS display on and 2 days with the DTSWS display off. Data were collected for 2 hours on each day so a total of 8 hours of data were collected. In addition, a survey was distributed to truck drivers at a weigh station located near the downgrade to assess their awareness of the speed warning system and rate its potential effectiveness.

Overall, the DTSWS appeared to significantly reduce truck descent speeds for most weight ranges above 18,200 kg (40,000 lb). A recommendation was made to revise the advised speeds and their corresponding weight ranges, indicating that the advised speeds should be within ranges that many drivers are willing to accept as good advice. Thus, reducing the risk of providing advisor speeds that are too low and which many drivers will simply ignore as being unrealistic. The truck drivers surveyed also responded positively to the DTSWS and its potential to improve safety along the downgrade.

Oregon

Due to a high number of truck-related crashes on Interstate 84 at Emigrant Pass, the Oregon DOT installed a Downhill Speed Information System

(DSIS) warning system at the location as part of its ITS/CVO "Green Light" Project *(56)*. Emigrant Pass has a 6 percent downgrade for 10 km (6.2 mi) with sharp curves. Between 1993 and 1996, a total of 40 truck-related crashes occurred Emigrant Hill, resulting in 3 fatalities and 28 injuries. The DSIS hardware and software was installed in 2000, but the system did not become operational until 2002. Prior to considering installation of the DSIS, Oregon DOT implemented runaway truck ramps and static truck advisory signs at the pass location.

The DSIS consists of high-speed, WIM scales in the roadway and automatic vehicle identification (AVI) devices that recognize in-truck "Green Light" transponder signals. The "Green Light" project is primarily a truck weigh station "preclearance" system. In less than 1 second, a computer measures the weight of a truck, reads the "Green Light" transponder signal (if the truck is equipped), and sends a customized message to a roadside VMS advising the driver of a safe range of speed for that truck to descend the hill. Properly weighed, transponder-equipped trucks receive a personalized advisory message on the VMS addressed to the driver by name (e.g., "Tate" in the following example) such as:

TRUCK ADVISORY
TATE
18 MPH DOWNHILL

Improperly weighed, transponder-equipped trucks receive a general message, such as:

TRUCK ADVISORY
TATE
STEEP DOWNGRADE

Trucks that are not equipped with a "Green Light" transponder do not receive a message. Figure 14 shows the roadside VMS at Emigrant Pass displaying an advisory message.

Oregon DOT is planning to conduct an evaluation of the system, including an analysis of crash data, escape ramp incidents, and speed data.

West Virginia

In 1998 West Virginia Division of Highways installed a downhill truck warning system at the top of a long, steep downgrade on Interstate 64 at Sandstone Mountain *(56)*. Prior to the installation of the system, a large number of runaway truck incidents occurred on the downgrade, resulting in

Figure 14. Oregon's downhill speed information system (57).

incidents occurred on the downgrade, resulting in runaway ramp uses or serious crashes. Incidents were occurring several times a month.

The system, deployed at the top of the mountain, consists of two VMSs, driven by a computer that obtains weight and classification data from loops and piezo sensors in each lane. Every vehicle is weighed and classified. The system utilizes a table, based upon the Grade Severity Rating System, to determine a recommended speed choice, and the advisory speed message is displayed on the VMS. The message is updated for every vehicle passage.

DYNAMIC CURVE WARNING SYSTEMS

Truck rollover crashes occur frequently along the U.S. highway system and often result in serious injuries. In 1998, 207 trucks were involved in fatal rollover crashes, and approximately 10,580 commercial trucks were involved in nonfatal rollover crashes *(58)*. Truck rollover crashes typically occur at freeway exit ramps with tight curves that require a reduced speed compared to the normal travel speed on the freeway and on sharp curves following steep downgrades.

To help mitigate the occurrence of rollover crashes, intelligent rollover warning systems have been installed at several problem locations. The effectiveness *(48)* and feasibility of deploying such systems was examined by FHWA in the early 1990s *(59)*. Intelligent rollover warning systems are designed to calculate the rollover potential of vehicles and direct warning messages to specific drivers if necessary. Directed messages are conveyed to drivers via VMSs or flashing lights only when potential rollovers are detected. In this manner, dynamic curve warning systems alert only those drivers with a high probability of entering into a rollover situation. The most basic systems typically incorporate one vehicle parameter such as speed or vehicle height, while the more sophisticated systems can incorporate several vehicle parameters such as speed, weight, live load, nonlive load, vehicle height, and vehicle configuration for calculating the rollover potential of a vehicle.

California

The California DOT (Caltrans) installed five speed-based curve warning systems along I-5 near the Sacramento River Canyon in Shasta County *(60)*. The five sites include:

1. Sidehill Viaduct—Postmile 30.00 (SB)
2. O'Brien—Postmile 32.30 (SB)
3. Salt Creek—Postmile 37.53 (SB)
4. La Moine—Postmile 49.23 (SB)
5. Sims Road—Postmile 57.90 (NB)

The components of the systems at each site include: a VMS, a radar speed-measuring device, and control/communication equipment. Specific messages and graphics can be displayed on each VMS every 3 to 4 seconds. Some of the standard messages displayed on the VMSs are shown in Figure 15.

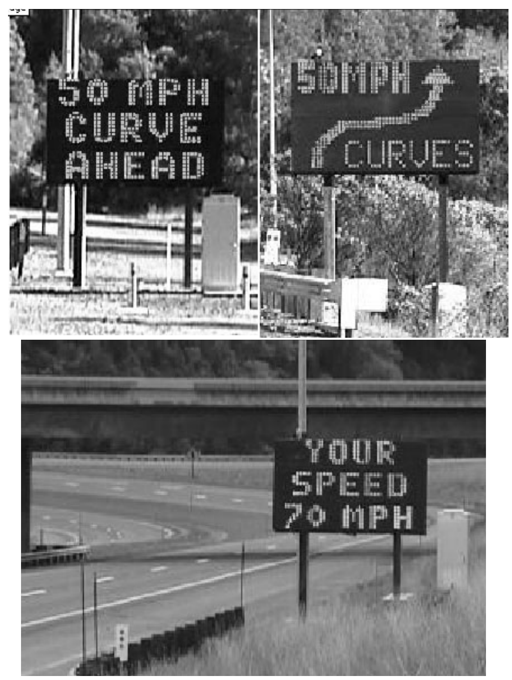


Figure 15. Several standard messages for dynamic curve warning systems in California (60).

An evaluation of the effectiveness of this speed-based curve warning system was conducted. The evaluation consisted primarily of a comparison of speed data gathered before and after installation of the warning system. Speed data were collected 9 months prior to the system's installation and again 2 months, 5 months, and 10 months after operation began. Crash data were also gathered, and surveys were distributed to truck drivers and passenger car drivers approximately 2 months and 10 months after installation.

Preliminary results indicate reductions in both operating speeds and crashes. At three of the five installation sites, reductions in truck operating speeds were observed during at least one of the three data collection periods after the warning system began operation. At two sites, each with downgrades greater than 5 percent, significant reductions in truck speeds were observed during all three periods after installation. It was also noted that speed reductions were smaller for the later time periods, possibly indicating that drivers were becoming less sensitive to the system. Due to a lack of crash data, a meaningful before-after crash analysis was not performed, but preliminary analysis showed a reduction in truck-related crashes. Survey results indicated approximately 72 percent of truck drivers thought the system was useful, and approximately 81 percent of passenger car drivers thought the system was useful.

Prior to installing and evaluating the curve warning system in the Sacramento River Valley, Caltrans installed a speed-based warning system on a freeway-to-freeway connector ramp located at postmile 14.74 (SB) on I-5 in San Joaquin County *(61)*. The ramp is on a downgrade leading to a short radius curve. The components of the system included:

- Inductive loop, piezoelectric sensor, and inductive loop combination (detector system)
- Control/communication equipment
- Static warning sign with two flashing yellow beacons

A before and after crash analysis revealed that in the 6.3 years prior to installation of the system, six truck rollover crashes occurred on the ramp. During the first 2 years after installation of the system, zero truck rollover crashes occurred. Installation of the system did produce a reduction in truck rollover crashes, but the number of crashes was too few for the difference to be statistically significant. Since no truck rollover crashes occurred in the after period, it was concluded that some of the safety improvement at the site could be attributed to the curve warning system.

Texas

The Texas DOT evaluated the effectiveness of a speed-based truck warning system installed on a freeway-to-freeway loop ramp located in Houston, Texas *(62)*. The system used three infrared light-beam sensors with a special microcontroller-based signal processor to determine a vehicle's speed, height, and length. When a vehicle exceeded it maximum safe speed, a static warning sign with flashing yellow beacons was activated.

A before and after speed-change study was conducted to measure the effectiveness of the system in effecting a speed reduction of trucks thought to be potential danger on the loop ramp. The study revealed that violating trucks in the higher initial speed range, 100 to 113 km/h (62 to 20 mi/h), reduced speed more than those in the lower speed range, 90 to 100 km/h (56 to 62 mi/h), under both the "before" and "after" operating conditions. In addition, the additional average speed reduction for all violating trucks attributed to the effect of the flashers being activated was 3 km/h (2 mi/h).

Missouri

The Missouri DOT installed a curve warning system at a location with a sharp curve after a history of rollover accidents at the site *(56)*. Traffic studies indicated that the problem was due to excessive speeds of trucks, which caused loads to shift. Static signs in the area were not effective in solving the problem.

Components of the system include: two signs, two flashers, and one narrow band microwave height detector. The system activates wigwag flashers mounted above truck rollover warning signs only when tall vehicles encroach the microwave beam from a single direction. The system has performed satisfactorily, but no formal evaluation on its effectiveness has been conducted. A photograph of the system is shown in Figure 16.

Virginia and Maryland

A curve warning system, which incorporates multiple vehicle parameters to assess the potential for vehicle rollover, was designed and installed at three ramps on the Capital Beltway (I-495) in Virginia and Maryland *(63)*. The installations are located at:

1. I-495W/I-95S in Springfield, Virginia
2. I-495W/Route 123N in McLean, Virginia
3. I-495E/I-95N in Beltsville, Maryland

This system calculates a vehicle rollover threshold speed based upon a truck's weight, rollover threshold factor, and the geometrics of the ramp (radius and superelevation of curve). The components of the system include:

- Weigh-in-motion (WIM) detectors
- Loop magnetic detectors (speed detectors)
- Radar sensing height detectors
- Warning signs
- Controller/communication equipment

Figure 17 shows the typical placement of the components for both one-lane and two-lane ramps.

An evaluation of the system was performed looking at both speed and crash data. In analyzing the speed data, the average speed at WIM Station 2 was compared to the average speed reduction from WIM Station 2 to WIM Station 3. This analysis revealed all three installations caused truck drivers to reduce their speeds exceeding the maximum safe speed for the ramp. On average there was a 25 percent speed reduction from WIM Station 2 to WIM Station 3 when the VMS was activated at all three sites. The before and after crash evaluation showed 10 reported truck rollover-type crashes in the before period across all sites and 0 truck rollover-type crashes in the 3-year after period.

Figure 16. Missouri curve warning system (56).

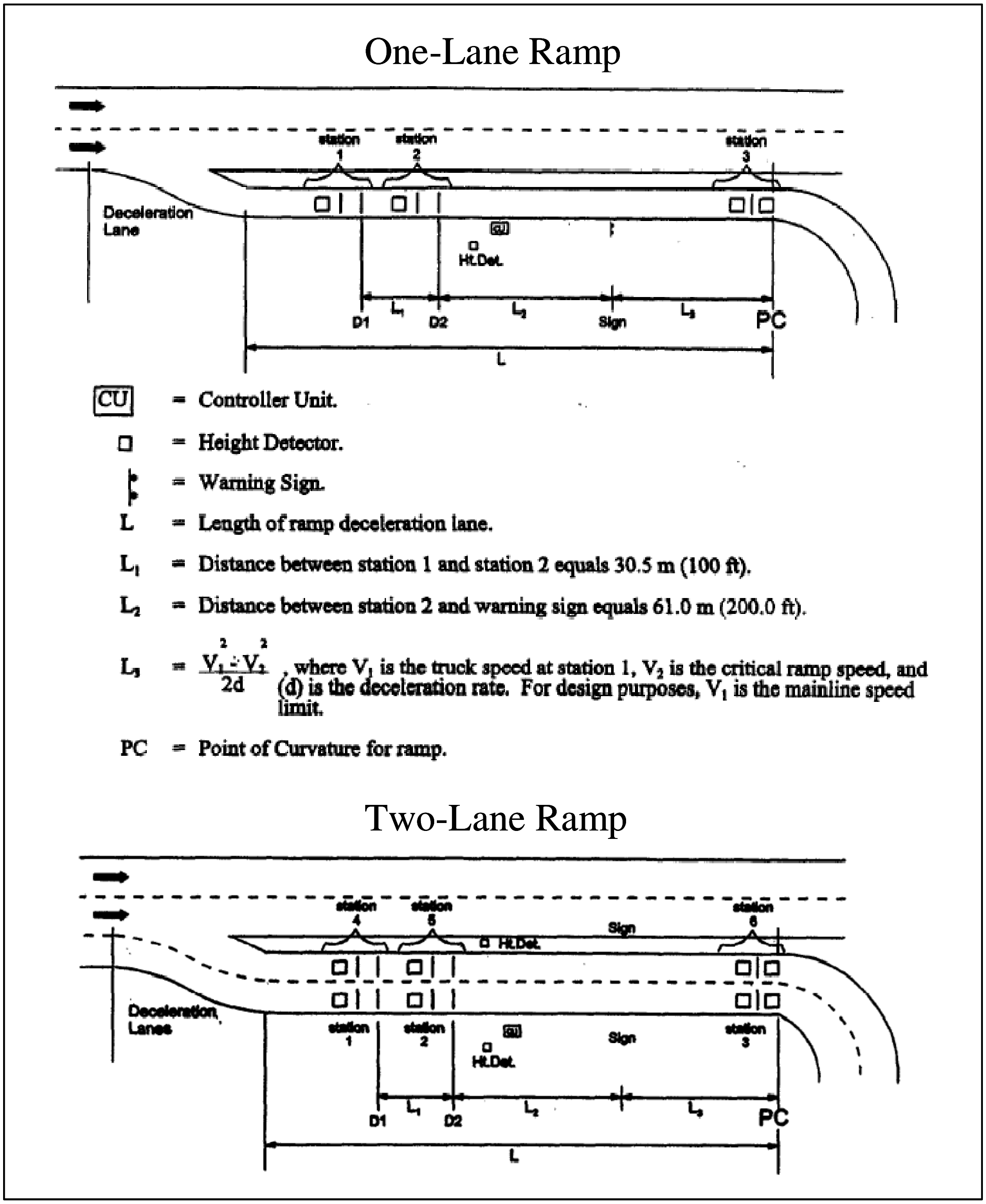


Figure 17. Typical placement of system components (63).

Pennsylvania

The Pennsylvania DOT has installed a system similar to that on the Capital Beltway at two ramp locations and has observed positive short-term results *(58)*.

Comparison of Systems

Baker et al. *(58)* investigated the different types of dynamic curve warning systems that have been deployed by highway agencies across the U.S. In particular, Baker et al. compared the number of false messages generated by speed-based curve warning systems to the number of false readings generated by speed/weight-based warning systems. The rationale for comparing false readings was to maximize the effectiveness of curve warning systems, the warning must be targeted to specific drivers. If the system is activated repeatedly when there is no actual danger, this type of system might become increasingly ignored by drivers over the long term. This could pose a problem for vehicles that are truly at risk and need to be warned of their situation.

Figure 18 conceptually compares the rollover warning thresholds obtained from both speed-based and speed/weight-based rollover warning systems. Case studies revealed that there is an added advantage of incorporating weight in addition to speed and classification when warning trucks of potential rollover. It was that speed-based rollover warning systems generated approximately 44 to 49 percent more false warnings compared to systems that incorporate vehicle weight into the rollover decision criteria. In the long run, accurate system performance will ensure truck drivers will continually respond to the messages displayed by dynamic curve warning systems.

WEIGH STATIONS

Inspections of commercial vehicles at weigh stations are conducted to verify motor carrier compliance with safety, size and weight, and credential regulations. These regulations are in place to protect public investment in roadway infrastructure and to improve traffic safety *(64)*. However, the diverging and merging of trucks as they enter and exit weigh stations can interrupt the flow of traffic on mainline facilities, particularly when weigh stations become congested and queues

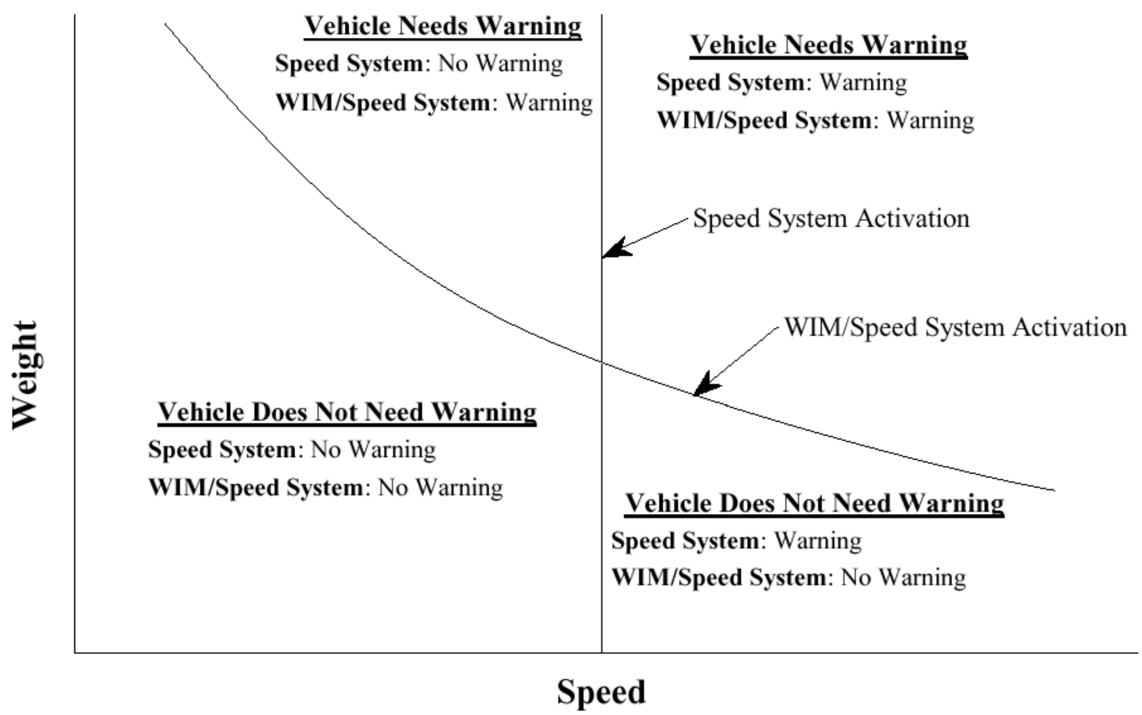


Figure 18. Comparison between speed-based and speed/weight-based rollover systems (58).

of trucks overflow from the inspection facilities onto the freeways. Electronic screening of vehicles approaching a weigh station is increasingly being used to focus inspection activities on those vehicles most likely to be in violation of applicable regulations.

One of the potential benefits of electronic screening of commercial vehicles is improved traffic flow near weigh stations. Two studies have been conducted to evaluate the impact that electronic screening technologies have on safety near weigh stations. Utilizing microscopic simulation, Saka and Glassco *(65)* modeled various traffic patterns for baseline (pre-electronic screening) and post-ITS situations (with electronic screening technology). Saka and Glassco analyzed the safety effectiveness of electronic screening technology based upon percent reductions in sudden deceleration of vehicles from shockwave phenomena and percent reduction in duration of truck-queue overflow resulting from a high traffic intensity. Simulation results supported the hypothesis that the use of electronic screening technologies at weigh station facilities significantly reduces the frequency of high-risk traffic phenomena (e.g., hard braking and truck-queue overflow), translating into a reduction in the likelihood of incidents in the vicinity of weigh station facilities. The stochastic nature of crashes made it difficult to quantify the percent reduction in the expected crash frequency from the use of electronic screening technologies.

Benekohal et al. *(64)* evaluated the effectiveness of electronic screening for interstate application by collecting speed, volume, and conflict data at several sites at a weigh station in Illinois. Benekohal et al. developed the following model to predict the number of merging conflicts near a weigh station:

$$\text{No. of Merge Conflicts} = 0.001776 \times [T_{en} \times (C_r + C_c) + 0.00000169 \times T_{en} \times C_r \times C_c] \quad \textbf{(9)}$$

where: T_{en} = truck volume on the entrance ramp
C_r = car volume on the outside (right) lane
C_c = car volume on the center lane.

The model shows that a significant number of conflicts will occur during low volume conditions, but it also shows that electronic screening, by reducing the truck volume on the entrance ramp, will reduce traffic conflicts and improve safety near weigh stations.

COLLISION AVOIDANCE WARNING SYSTEMS

The Port Authority of Allegheny County is conducting a major field test of collision avoidance warning systems in Pittsburgh, Pennsylvania *(66)*. The testing involves a side collision avoidance system that has been installed on 100 buses. Each bus is fitted with a dozen sensors that are spaced about 1.8 m (6 ft) apart and mounted between 0.8 and 1.3 m (2.5 and 4.2 ft) above the road surface. The sensors emit sonar signals that reflect off objects near the bus. An on-board computer measures the time it takes an emitted sound wave to return after bouncing off a hard object. The system can detect stationary roadside objects at least 0.3 m (1 ft) in diameter when the bus is moving and can detect a passenger car while both the bus and car are in motion. The system alerts the operator through visual indicators when an object is detected.

In a similar project, the San Mateo County Transit District in San Carlos, California is testing a frontal collision warning system (FCWS). Two buses were equipped with FCWS sensors that included radar systems, ultrasonic sensors, and laser range finders. These systems are designed to enhance transit operations through accident reductions.

This page intentionally left blank.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

The conclusions of this synthesis are as follows:

1. A wide variety of heavy vehicle types—including single-unit trucks, combination trucks with one, two, or three trailers, and buses—operate on U.S. highways. These heavy vehicle types each have unique characteristics that interact with highway features. The understanding of these interactions is important to the safe operation of the highway transportation system.
2. The dimensions of heavy vehicles, particularly the spacing between axles and hitch points and the front and rear overhang distances, are primary determinants of the vehicle turning radius, offtracking, and swept path width. These vehicle performance measures are, in turn, key factors in the design of intersections, horizontal curves, and other highway features to accommodate heavy vehicles.
3. Antilock brakes, which permit vehicles to stop in a controlled fashion without jackknifing or losing control, are now required by Federal regulation for all newly manufactured heavy vehicles. The antilock brakes used on heavy vehicles must meet a performance standard established in FMVSS 121. Braking capabilities of trucks have improved to the point that the braking distances of passenger cars and trucks on wet pavements, where braking distance is most critical to safety, are now nearly equal. Trucks have longer braking distances than passenger cars on dry pavements, however.
4. The drivers of heavy vehicles sit higher than passenger car drivers and, thus, have greater eye heights. As a result, truck and bus drivers can see farther than passenger car drivers when approaching vertical sight restrictions, such as hillcrests. This may permit truck and bus drivers to see traffic conditions or objects in the road sooner and, therefore, begin braking sooner. However, there is no comparable advantage for truck and bus drivers at horizontal sight restrictions.
5. Because of their lower acceleration rates and greater length, heavy vehicles take longer than passenger cars to accelerate and clear specific conflict zones, such as intersections and railroad-highway grade crossings. Heavy vehicle speed maintenance capabilities on upgrades are a function of the vehicle's weight-to-power ratio and the length and steepness of the grade.
6. In combination trucks with more than one trailer, the second or third trailer may experience higher lateral acceleration than the first trailer in lane change or avoidance maneuvers. The maximum desirable lateral displacement of a trailer due to this rearward amplification is 0.8 m (2.7 ft).
7. Vehicle characteristics related to the dynamic stability of trucks, as represented by load-transfer ratio and rollover threshold, include dynamic inter-axle load transfer, height of roll center, roll stiffness, roll steer coefficient, compliance steer coefficient, center-of-gravity height, overall weight, and longitudinal and lateral weight distribution.
8. The current sight distance criteria used in highway geometric design, as presented in the AASHTO *Green Book*—including stopping sight distance, passing sight distance, intersection sight distance, and railroad-highway grade crossing sight distance—can reasonably accommodate the current heavy vehicle fleet. The

MUTCD sight distance criteria used to mark passing and no-passing zones on two-lane highways are suitable for a passenger car passing a passenger car. While the marking criteria do not explicitly accommodate trucks, there is no indication that passing maneuvers involving trucks are made, with any frequency, in passing zones where sufficient sight distance is not available.

9. The geometrics and traffic control systems for railroad-highway grade crossings located close to highway intersections should be designed such that heavy vehicles are not forced to stop in a position where the rear of the vehicle extends onto the railroad tracks.

10. Where long, steep upgrades reduce truck speeds by 16 km/h (10 mi/h) or more, the provision of truck climbing lanes may be considered. The AASHTO *Green Book* presents criteria for determining where truck climbing lanes are warranted and economically justified.

11. Long, steep downgrades present a safety concern for heavy vehicles because, if the vehicle service brakes are used too often in descending the grade, they may overheat and loose their ability to decelerate the vehicle. Because of these risks, highway agencies provide warning signs and roadside brake check areas at the top of some downgrades and provide emergency escape ramps for out-of-control vehicles in the middle or lower portion of some downgrades.

12. Acceleration lanes are provided at entrance ramps to major highways to provide a location for vehicles to increase their speed before entering the highway. The AASHTO *Green Book* criteria for the length of acceleration lanes appear adequate to accommodate average trucks but may not accommodate the lowest performance trucks.

13. Horizontal curves designed in accordance with AASHTO *Green Book* criteria allow heavy vehicles to operate at the design speed of the curve with a substantial margin of safety against skidding or rolling over. Skidding or rollover should occur only when a heavy vehicle substantially exceed the design speed of the curve; the greatest risk from exceeding the design speed of a curve occurs on curves with lower design speeds.

14. Heavy vehicles are a key consideration in the design of intersections. Intersection features that must consider the presence, frequency, and characteristics of heavy vehicles include curb return radii for right turns, storage lengths for left-turn lanes, median widths on divided highways, and the offset between opposing left-turn lanes.

15. Interchange ramps are designed to provide sufficient width for other vehicles to pass a stalled heavy vehicle. The design and signing of horizontal curves on ramps is important to their safe operation because safety problems may result, as noted above, when heavy vehicles exceed the design speed of a curve. A special truck rollover warning sign for use at such locations has been used by highway agencies.

16. About 40 percent of highway agencies have used or are considering the use of differential speed limits for passenger cars and heavy vehicles. No safety benefits from differential speed limits have been demonstrated and there is concern that differential speed limits could have an adverse effect on safety due to increases in the speed variance of traffic.

17. Highway agencies have tried to improve traffic operations and safety by restricting heavy vehicle use of the left lane or restricting heavy vehicles to use only the right lane on major highways. Most evaluations of such lane restrictions have shown no effect on safety, positive or negative. A recent test in Houston for an eight-month period in one freeway corridor did find a safety benefit from left-lane restrictions for heavy vehicles.

18. Highway agencies have prohibited truck travel on selected highways for a variety of reasons unrelated to safety. Naturally, this eliminates truck-related accidents on the facility in question, but no studies for these sites have examined the safety impact of truck diversion to other routes.

19. Some highway agencies have implemented, and others are considering, exclusive truck lanes or exclusive truck roadways on selected facilities. No measures of the safety performance of such facilities are available.

20. Heavy vehicles, because of their size, can block the view of highway signs by other motorists. Highway agencies have developed specific methods for dealing with this problem where it occurs, including the use of additional advance warning signs, placement of signs on both sides of the road, and placement of overhead signs.

21. Heavy vehicles are often a consideration in selecting the length of a yellow signal phase and assessing the need for an all-red clearance interval at signalized intersections.

22. Highway agencies have used ITS technologies to improve safety for heavy vehicles at several types of sites including long, steep downgrades, sharp horizontal curves, and weigh stations. On-board collision avoidance warning systems for buses are also being tested.

The following recommendations have been developed as a result of the synthesis preparation:

1. The marking of passing and no-passing zones on two-lane highways should be evaluated to ensure that heavy vehicles use them properly. The sight distance criteria in the MUTCD used for marking passing and no-passing zones are appropriate for passenger cars, but do not explicitly consider heavy vehicles. Research to confirm that this does not lead to poor safety performance in passing zones would be desirable.

2. The current AASHTO *Green Book* criteria for acceleration lane lengths at entrance ramps to major highways appear appropriate to accommodate average trucks, but do not appear to accommodate the lowest performance trucks. Research is needed to determine whether this leads to poor safety performance and whether the design criteria for acceleration lane length can be changed in a cost-effective manner.

3. Offset left-turn lanes have been found to be effective in reducing the potential for opposing left-turn vehicles to restrict their drivers' view of potentially conflicting traffic. Such sight restrictions are of greatest concern when one or more of the opposing left-turn vehicles is a large truck or bus. However, the frequency of accidents related to such sight restrictions and the benefits of providing offset left-turn lanes to remove such sight restrictions has not been documented. Research on this topic would be desirable.

4. More research on the issue of differential speed limits is needed. The belief that lower heavy vehicle speeds will reduce accident rates is widespread but unproven. By contrast, fundamental traffic engineering principles suggest that accident rates increase as the variance of vehicle speeds on a facility increases. Highway agencies needed better information on the safety effects of differential speed limits.

5. A recent limited test of left-lane truck restrictions in Houston showed positive results for safety. However, all previous research on truck lane restriction has found no effect on safety. Further research based on field trials would be desirable to establish whether lane restrictions have safety benefits.

6. Many highway agencies are facing decisions about whether to reduce traffic congestion by building exclusive truck lanes or exclusive truck roadways. Research is needed to provide safety performance measures to assist highway agencies in such decisions.

7. The ongoing evaluation of ITS systems that use new technology to improve heavy vehicle safety should continue. New and innovative systems should be developed and the safety effectiveness of both existing and new systems should be evaluated and documented.

REFERENCES

1. *A Policy on Geometric Design of Highways and Streets*, American Association of State Highway and Transportation Officials, Washington, DC, 2001.
2. Harwood, D.W., D.J. Torbic, K.R. Richard, W.D. Glauz, and L. Elefteriadou, *NCHRP Report 505: Truck Characteristics as Factors in Roadway Desig*n, Transportation Research Board of the National Academies, 2003.
3. *Comprehensive Truck Size and Weight Study*, Report No. FHWA-PL-00-029, Federal Highway Administration, August 2000.
4. Woodroofe, J.H.F., C.A.M. Smith, and L.E. Morisset, "A Generalized Solution of Non-Steady-State Vehicle Offtracking in Constant Radius Curves," Society of Automotive Engineers, Paper No. 852333, presented at the Truck and Bus Meeting and Exposition, Chicago, Illinois, December 1985.
5. *Offtracking Characteristics of Trucks and Truck Combinations*, Research Committee Report No. 3, Western Highway Institute, San Francisco: February 1970.
6. Glauz, W.D., and D.W. Harwood, "Superelevation and Body Roll Effects on Offtracking of Large Trucks," *Transportation Research Record 1303*, Transportation Research Board of the National Academies, 1991.
7. Bernard, J.E., and M. Vanderploeg, "Static and Dynamic Offtracking of Articulated Vehicles," Paper No. 800151, Society of Automotive Engineers, 1981.
8. *Highway Safety Performance Criteria in Support of Vehicle Weight and Dimension Regulations: Candidate Criteria and Recommended Thresholds, Working Group 2—Vehicle Weights and Dimensions*, Report of the LTSS 2 Project Group, Discussion Paper, North American Free Trade Agreement Land Transportation Standards Committee, October 1999.
9. Clarke, R.M., W.A. Leasure, R.W. Radlinski, and M. Smith, *Heavy Truck Safety Study*, Report No. DOT-HS-807-109, National Highway Traffic Safety Administration, March 1987.
10. Code of Federal Regulations, *Federal Motor Vehicle Safety Standard No. 121, Air Brake Systems*, 49 *CFR* 571.121, revised as of October 1, 2002.
11. Fancher, P.S., and T.D. Gillespie, *NCHRP Synthesis of Highway Practice 241: Truck Operating Characteristics*, Transportation Research Board of the National Academies, 1997.
12. Fambro, D.B., R. Koppa, and K. Fitzpatrick, *NCHRP Report 400: Determination of Stopping Sight Distances*, Transportation Research Board of the National Academies, 1997.
13. Gillespie, T.D., "Start-Up Accelerations of Heavy Trucks on Grades," *Transportation Research Record 1052*, Transportation Research Board of the National Academies, 1986.
14. Harwood, D.W., J.M. Mason, W.D. Glauz, B.T. Kulakowski, and K. Fitzpatrick, *Truck Characteristics for Use in Highway Design and Operation*, Volume I, Research Report, Report No. FHWA-RD-89-226, Federal Highway Administration, August 1990.
15. *Horsepower Consideration for Trucks and Truck Combinations*, Western Highway Institute, San Francisco, 1978.
16. St. John, A.D. and D.R. Kobett, *Grade NCHRP Report 185: Effects on Traffic Flow Stability and Capacity*, Transportation Research Board of the National Academies, 1978.
17. Ervin, R.D., R.L. Nisonger, C.C. MacAdam, and P.S. Fancher, *Influence of Size and Weight Variables on the Stability and Control Properties of Heavy Trucks*, Report

No. FHWA/RD-83/029, Federal Highway Administration, July 1986.

18. Fancher, P.S., R.D. Ervin, C.B. Winkler, and T.D. Gillespie, *A Factbook of the Mechanical Properties of the Components for Single-Unit and Articulated Heavy Trucks*, Report No. DOT-HS-807-125, National Highway Traffic Safety Administration, December 1986.

19. Lozia, Z., "Rollover Thresholds of the Biaxial Truck During Motion on an Even Road," *The Dynamics of Vehicles on Roads and on Tracks, Supplement to Vehicle System Dynamics 28*, 1998.

20. Garcia, L.O., F.R. Wilson, and J.D. Innes, *Heavy Truck Dynamic Rollover: Effect of Load Distribution, Cargo Type, and Road Design Characteristics* presented at the 82nd annual meeting of the Transportation Research Board, January 2003.

21. *Comprehensive Truck Size and Weight Study: Summary Report for Phase I—Synthesis of Truck Size and Weight (TS&W) Studies and Issues*, Federal Highway Administration, March 1995.

22. *Manual on Uniform Traffic Control Devices for Streets and Highways*, Federal Highway Administration, 2000.

23. Harwood, D.W., J.M. Mason, R.E. Brydia, M.T. Pietrucha, and G.L. Gittings, *NCHRP Report 383: Intersection Sight Distance*, Transportation Research Board of the National Academies, 1996.

24. Harwood, D.W., and A.D. St. John, *Passing Lanes and Other Operational Improvements on Two-Lane Highways*, Report No. FHWA-RD-85-028, Federal Highway Administration, December 1985.

25. Johnson, W.A., R.J. DiMarco, and R.W. Allen, *Development and Evaluation of a Prototype Grade Severity Rating System*, Report No. FHWA-RD-81-185, Federal Highway Administration, March 1982.

26. Allen, R.W., D.W. Harwood, J.P. Christos, and W.D. Glauz, *The Capability and Enhancement of VDANL and TWOPAS for Analyzing Vehicle Performance on Upgrades and Downgrades Within IHSDM*, Report No. FHWA-RD-00-078, Federal Highway Administration, 2000.

27. Abdelwahab, W., and J.F. Morrall, "Determining Need for and Location of Truck Escape Ramps," *Journal of Transportation Engineering*, American Society of Civil Engineers, September/October 1997.

28. Harwood, D.W., M.T. Pietrucha, M.D. Wooldridge, R.E. Brydia, and K. Fitzpatrick, *NCHRP Report 375: Median Intersection Design*, Transportation Research Board of the National Academies, 1995.

29. *Roadside Design Guide*, American Association of State Highway and Transportation Officials, Washington, DC, 2002.

30. Ross, H.E., D.L. Sicking, R.A. Zimmer, and J.D. Michie, *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features*, Transportation Research Board of the National Academies, 1993.

31. Garber, N.J., and R. Gadiraju, Speed Variance and Its Influence on Accidents, University of Virginia, Charlottesville, 1988.

32. *Special Report 254: Managing Speed: Review of Current Practice and Enforcing Speed Limits*, Transportation Research Board of the National Academies, 1998.

33. Garber, N.J., J.S. Miller, B. Yuan, and X. Sun, *The Safety Impacts of Differential Speed Limits on Rural Interstate Highways*, presented at 82nd annual meeting of the Transportation Research Board, January 2003.

34. Garber, N. J. and R. Gadiraju, "Impact of Differential Speed Limits on the Speed of Traffic and the Rate of Accidents," *Transportation Research Record* 1375, Transportation Research Board of the National Academies, 1992.

35. *Commercial Motor Vehicle Speed Control Devices*, National Highway Traffic Safety Administration, Washington, DC, May 1991.

36. Zaremba, L.A., and M.J. Ginsburg, "The 55 mi/h Limits and Front-to-Rear Collisions Involving Autos and Large Trucks," *Accident Analysis and Prevention*, 1977.

37. Hall, J.W., and L. V. Dickinson, "Truck Speeds and Accidents on Interstate Highways," *Transportation Research Record 486*, Transportation Research Board of the National Academies, 1974.

38. Harkey, D.L., and R. Mera, *Safety Impacts of Different Speed Limits on Cars and Trucks: Final Report*, Report No. FHWA-RD-93-161, Federal Highway Administration, 1994.

39. Baum, H.M., J.R. Esterlitz, P. Zador, and M. Penny, "Different Speed Limits for Cars and Trucks: Do They Affect Vehicle Speeds?" *Transportation Research Record 1318*, Transportation Research Board of the National Academies, 1991.

40. http://www.doh.dot.state.nc.us/preconstruct/traffic/safety/trucksafety/trucklane/

41. Garber, N.J. and R. Gadiraju, "Effect of Truck Strategies on Traffic Flow and Safety on Multilane Highways (Abridgment)," *Transportation Research Record 1256*, Transportation Research Board of the National Academies, Washington, DC, 1990.

42. *Capital Beltway Truck/Tractor Trailer Restriction Study,* Final Report, Virginia Department of Highways and Transportation, Highway and Traffic Safety Division, Richmond, 1985.

43. *Truck Lane Redistribution Test on an Interstate Highway: Follow Up Study*, Nevada Department of Transportation, Research and Development Division, 1983.

44. Fitzpatrick, K., D. Middleton, and D. Jasek, "Countermeasures for Truck Accidents on Urban Freeways: A Review of Experiences (Abridgment)," *Transportation Research Record 1376*, Transportation Research Board of the National Academies, 1992.

45. *Effects of Lane Restrictions for Trucks*, FHWA, U.S. Department of Transportation, June 1986.

46. "TTI Evaluates Lane Restrictions for Houston Demonstration Project," *Texas Transportation Researcher, Vol. 38, No. 1*, Texas Transportation Institute, College Station, TX, 2002.

47. Mason, J.M., Jr. and R.C. Briggs, "Geometric Design of Exclusive Truck Facilities," *Transportation Research Record 1026*, Transportation Research Board of the National Academies, 1985.

48. Knoblauch, R.L., and M. Nitzburg, *Ramp Signing for Trucks*, Report No. FHWA-RD-91-042, Federal Highway Administration, 1993.

49. Retting, R.A., H.W. McGee, and C.M. Farmer, "Influence of Experimental Pavement Markings on Urban Freeway Exit-ramp Traffic Speeds," *Transportation Research Record 1705*, Transportation Research Board of the National Academies, 2000.

50. Schorr, D.J., "Traffic Control Device Problems Associated with Large Trucks," *Transportation Research Record 1052*, Transportation Research Board of the National Academies, 1985.

51. Ullman, G.L., and C.L. Dudek, "Effect of Roadway Geometrics and Large Trucks on Variable Message Sign Readability," presented at 80th annual meeting of the Transportation Research Board, January 2001.

52. Al-Kaisy, A. and J. Bhatt, "A Simulation Approach to Investigate the Effect of Heavy Vehicles on Sign Visibility," presented at the 16th Biennial Symposium on Visibility and Simulation, University of Iowa, Iowa City, 2002.

53. Sunkari, S.R., H. Charara, and T. Urbanik II, "Minimizing Truck Stops at High-Speed Rural Signalized Intersections," presented at the annual meeting of the Institute of Transportation Engineers, Chicago, IL, 2001.

54. *Motor Carrier Technologies—Fleet Operational Impacts and Implications for ITS/CVO, Tech Brief*, Report FMCSA-MCRT-00-008, Federal Motor Carrier Safety Administration, March 2000. http://www.fmcsa.dot.gov/pdfs/tb00-008.pdf.

55. Janson, B.N., *Evaluation of Downhill Truck Speed Warning System on I-70 West of Eisenhower Tunnel*, Colorado Department of Transportation, December 15, 1999. (http://www.itsdocs.fhwa.dot.gov/jpodocs/repts_te/98B01!.pdf).

56. Robinson, M., P. McGowen, A. Habets, and C. Strong, *Safety Applications of ITS in Rural Areas*, ITS Joint Program Office, U.S. Department of Transportation, September 2002. http://www.itsdocs.fhwa.dot.gov//JPODOCS/REPTS_TE/tech.htm.

57. http://www.odot.state.or.us/trucking/its/green/whatsnew.htm.

58. Baker, D., R. Bushman, and C. Berthelot, "The Effectiveness of Truck Rollover Warning Systems," *Transportation Research Record 1779*, Transportation Research Board of the National Academies, 2001.

59. McGee, H., S. Joshua, W. Hughes, R. Strickland, Z. Bareket, and P. Fancher, *Feasibility of an Automated Truck Warning System*, Report FHWA-RD-93-039, Federal Highway Administration, September 1993.

60. Tribbett, L., P. McGowen, and J. Mounce, *An Evaluation of Dynamic Curve Warning Systems in the Sacramento River Canyon*, Final Report, Western Transportation Institute, prepared for California Department of Transportation, April 2000. http://www.coe.montana.edu/wti/wti/pdf/Curve_Warning_Final.pdf.

61. Bola, R.S., *Evaluation of a Truck-Activated Rollover Warning System*, Report No. 51-366-623263, California Department of Transportation, June 1999.

62. Lee, C.E., D.W. Borchardt, and Q. Fei, *Truck Monitoring and Warning Systems for Freeway-To-Freeway Connections*, Report TX-00/7-2915-1, Texas Department of Transportation, October 1999.

63. Strickland, R., and H. McGee, *Evaluation of Prototype Automatic Truck Rollover Warning Systems*, Report FHWA-RD-97-124, Federal Highway Administration, January 1998. http://ntl.bts.gov/data/124.pdf.

64. Benekohal, R.F., Y.M. El-Zohairy, E. Forrler, and M.F. Aycin, "Truck Delay and Traffic Conflicts around Weigh Stations: A Case Study in Illinois," *Transportation Research Record 1653*, Transportation Research Board of the National Academies, 1999.

65. Saka, A.A., and R.A. Glassco, "Modeling Traffic Safety Benefits of Intelligent Transportation System Technologies at Truck Inspection Facilities," *Transportation Research Record 1779*, Transportation Research Board of the National Academies, 2001.

66. Siuru, B., "Major Field Tests of Collision Avoidance Systems Underway In Pittsburgh," *Mass Transit*, Vol. 27, No. 5, July 2001, pp. 42-43. http://www.masstransitmag.com/articles/2001/mt_07-01/mt_07-01_06.htm.

APPENDIX A

DESIGN VEHICLES

Many elements of highway geometric design are based on the consideration of specific design vehicles. These design vehicles are used to assure that highway geometric features are designed to accommodate specific classes of heavy vehicles. The truck and bus design vehicles used in the current AASHTO *Green Book (1)* are illustrated in this appendix, along with some additional design vehicles *(2)* that have been recommended in research for possible future incorporation in the *Green Book*, but are not currently included. The design vehicles are presented here to illustrate the various heavy vehicle types discussed in this synthesis. For comparative purposes, school buses and city transit buses have been included in this appendix even though these bus types are not within the scope of the synthesis. The dimensions of the design vehicles shown in this appendix typically represent the larger vehicles within a specific design vehicle classification, but not necessarily the largest possible vehicle.

The design vehicles presented in this appendix are:

- Single-unit truck (two axles)—Figure A-1
- Single-unit truck (three axles)—Figure A-2
- Intercity bus (BUS-12 [BUS-40])—Figure A-3
- Intercity bus (BUS-14 [BUS-45])—Figure A-4
- City transit bus—Figure A-5
- Conventional school bus—Figure A-6
- Large school bus—Figure A-7
- Articulated city transit bus—Figure A-8
- Intermediate semitrailer (WB-12 [WB-40])—Figure A-9
- Intermediate semitrailer (WB-15 [WB-50])—Figure A-10
- Interstate semitrailer (WB-19 [WB-62])—Figure A-11
- Interstate semitrailer (WB-20 [WB-67])—Figure A-12
- Double-trailer combination—Figure A-13
- Rocky Mountain double combination—Figure A-14
- Turnpike-double combination—Figure A-15
- Triple-trailer combination—Figure A-16

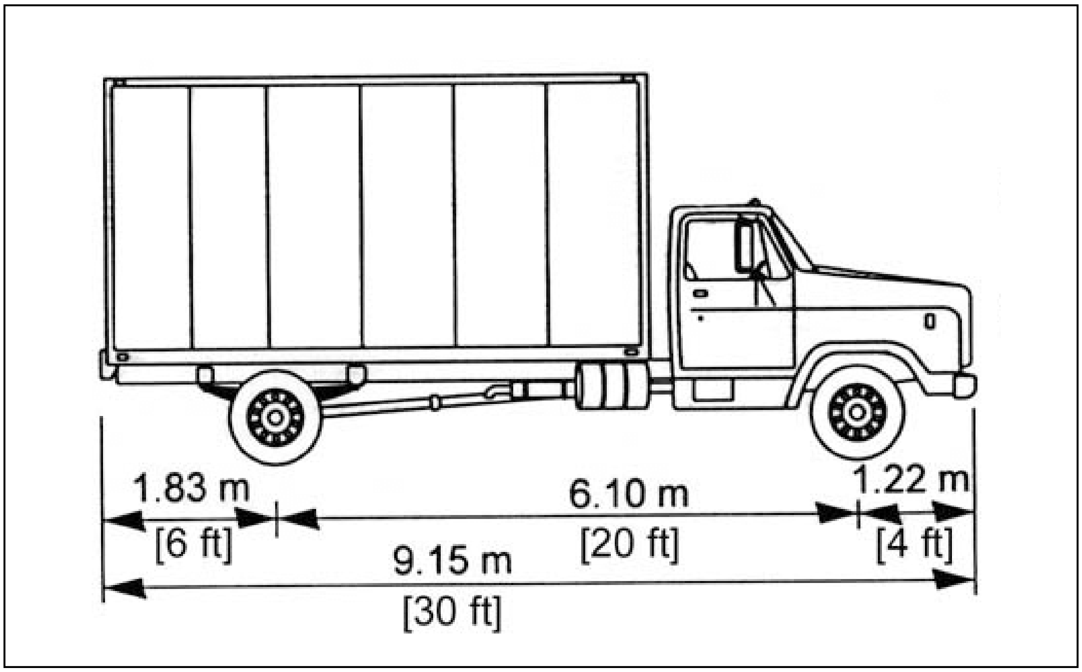


Figure A-1. Dimensions of single-unit (SU) truck design vehicle in current Green Book (1).

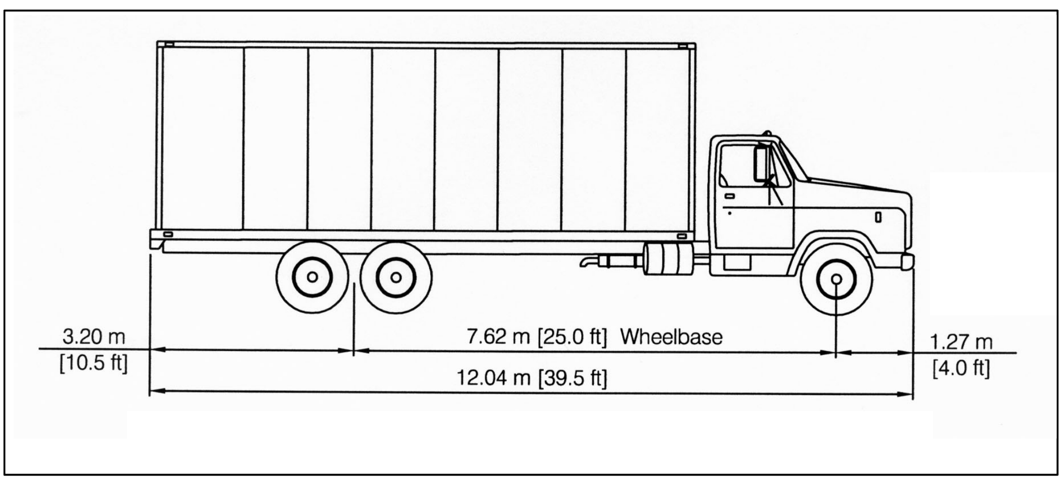


Figure A-2. Dimensions of recommended three-axle single-unit (SU-8 [SU-25]) design vehicle.

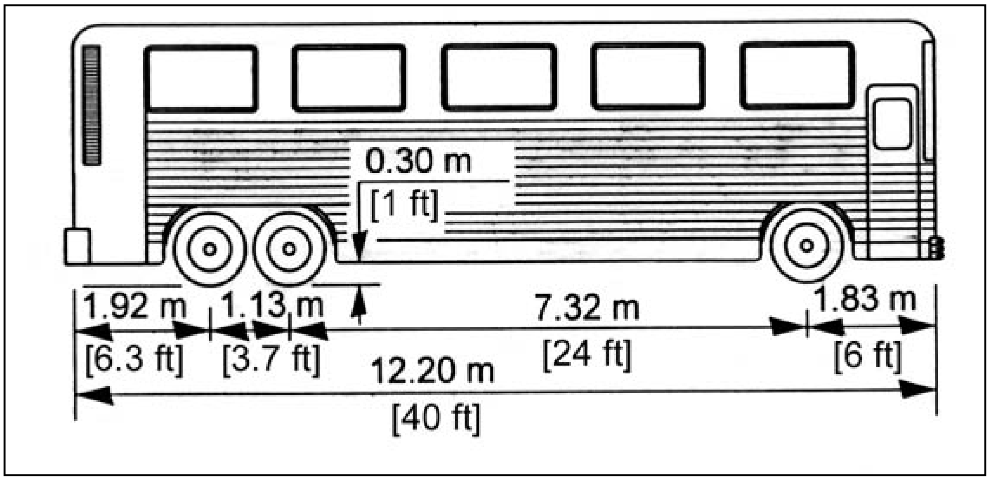


Figure A-3. Dimensions of intercity transit bus (BUS-12 [BUS-40]) design vehicle in current Green Book (1).

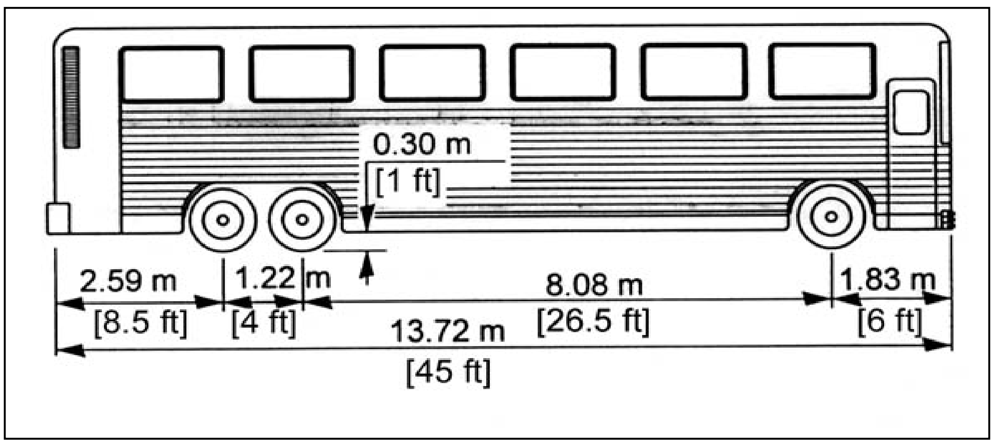


Figure A-4. Dimensions of intercity transit bus (BUS-14 [BUS-45]) design vehicle in current Green Book (1).

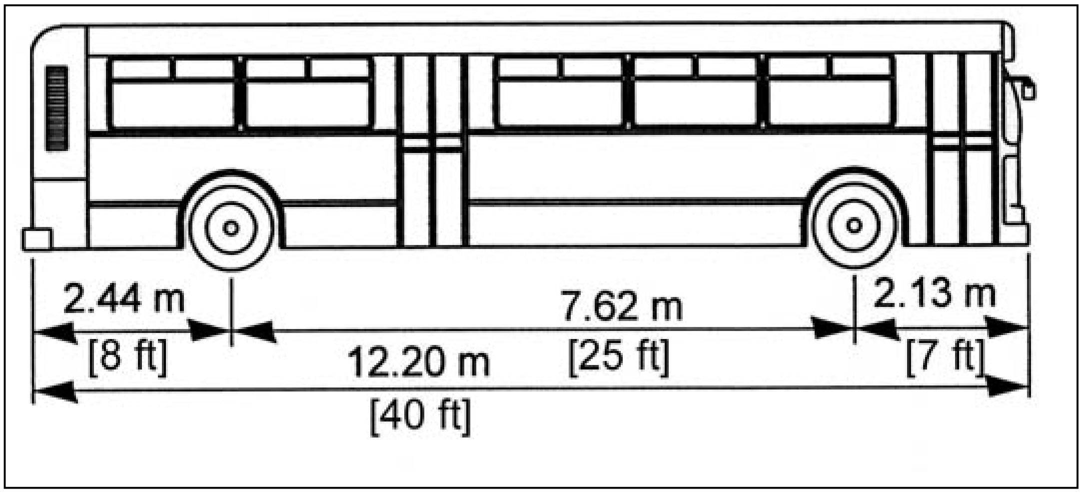


Figure A-5. Dimensions of city transit bus design vehicle in current Green Book (1).

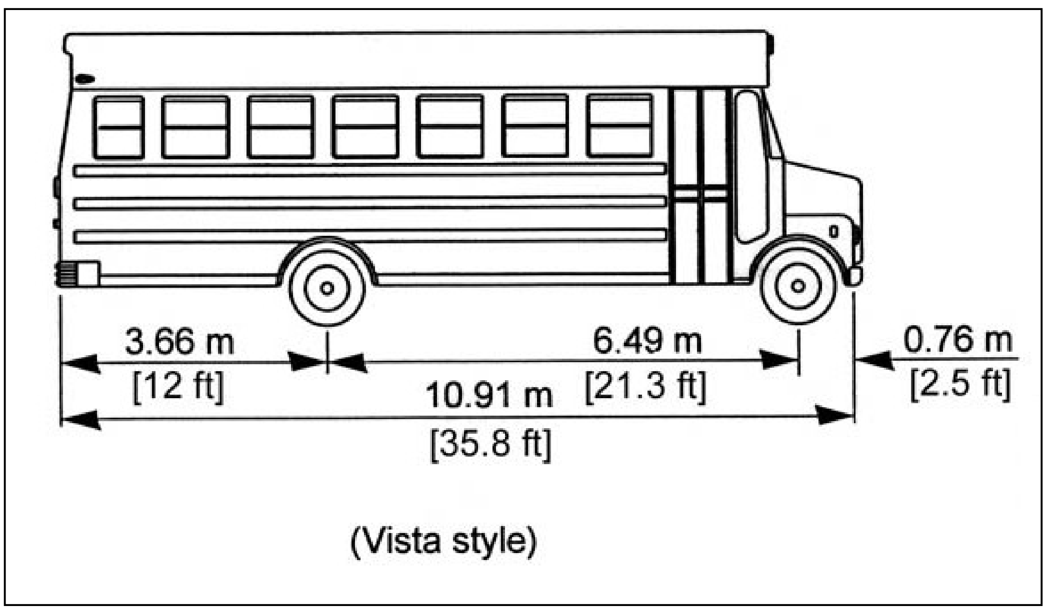


Figure A-6. Dimensions of conventional school bus design vehicle in current Green Book (1).

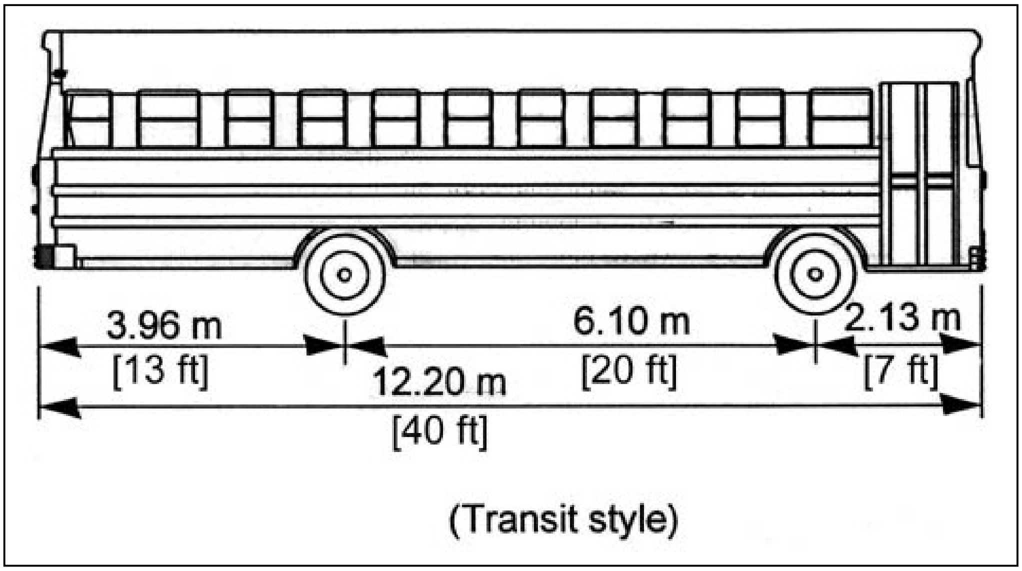


Figure A-7. Dimensions of large school bus design vehicle in current Green Book (1).

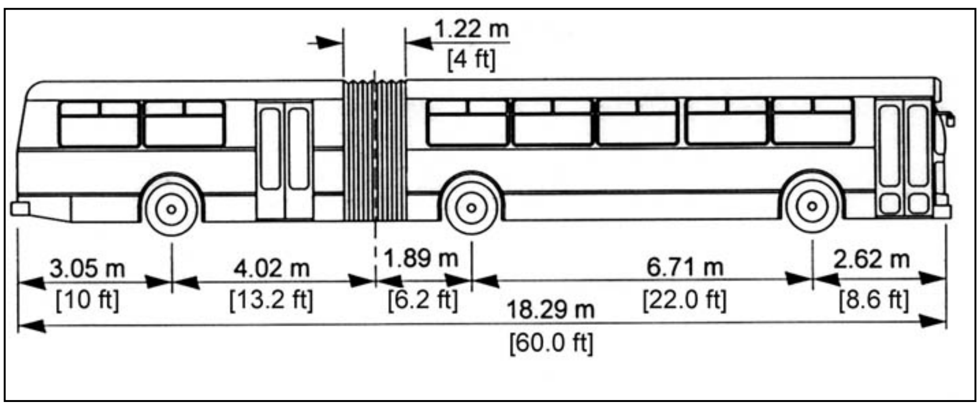


Figure A-8. Dimensions of articulated city transit bus design vehicle in current Green Book (1).

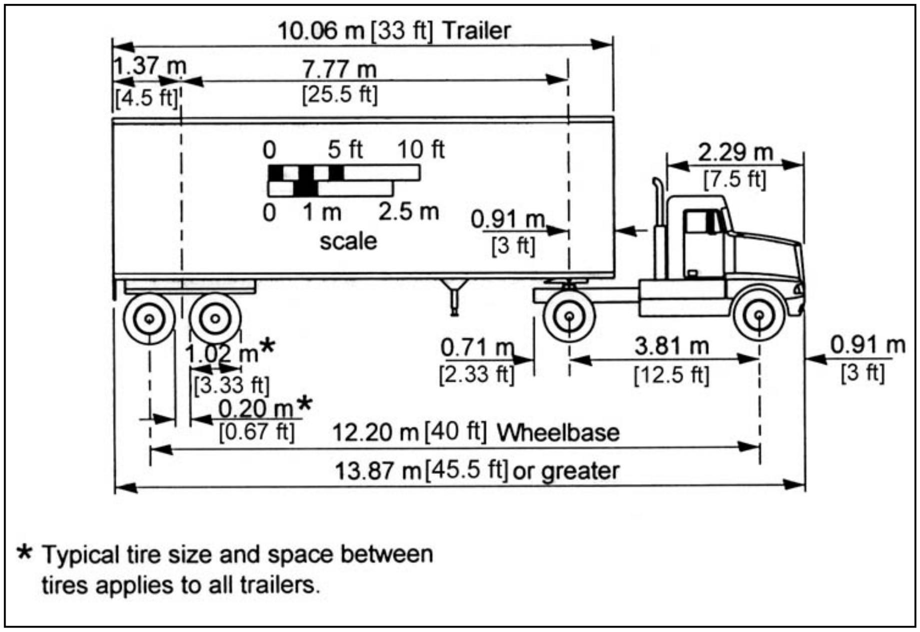


Figure A-9. Dimensions of intermediate semitrailer (WB-12 [WB-40]) design vehicle in current Green Book (1).

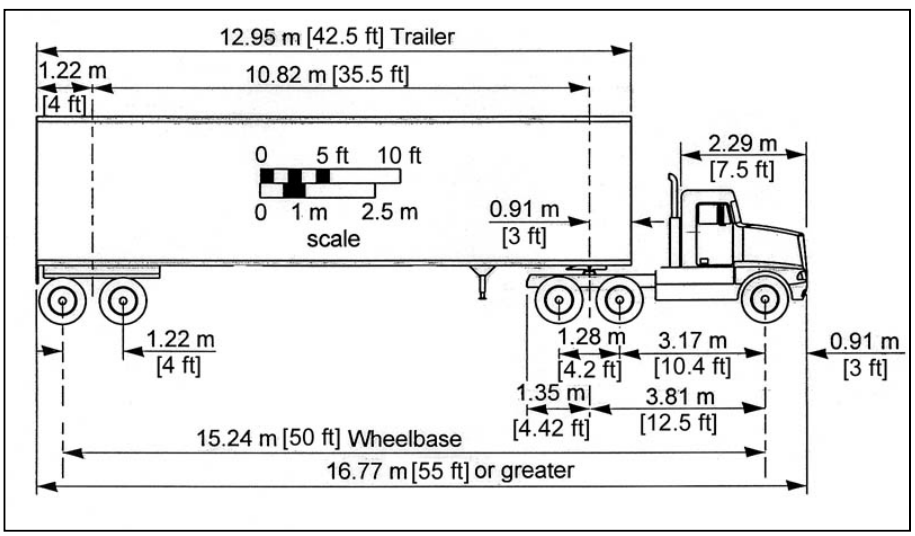


Figure A-10. Dimensions of intermediate semitrailer (WB-15 [WB-50]) design vehicle in current Green Book (1).

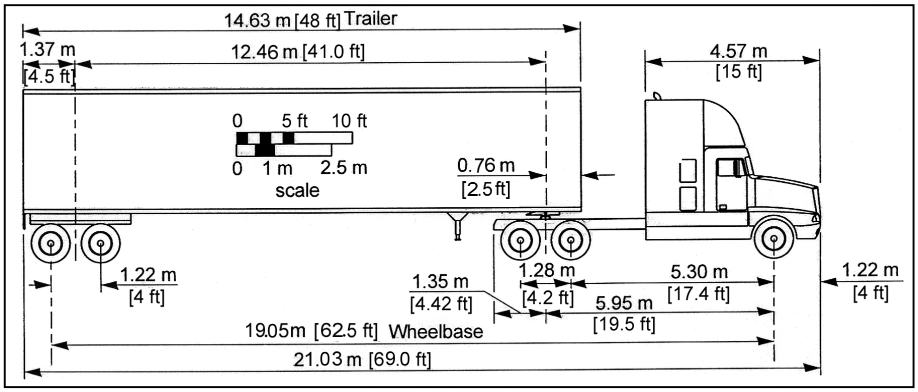


Figure A-11. Recommended revision in the dimensions of interstate semitrailer (WB-19 [WB-62]) design vehicle (2).

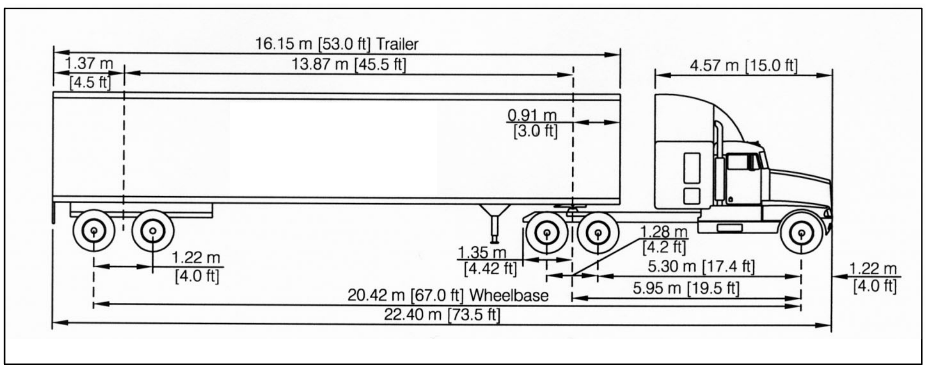


Figure A-12. Recommended dimensions of interstate semitrailer (WB-20 [WB-67]) design vehicle (2).

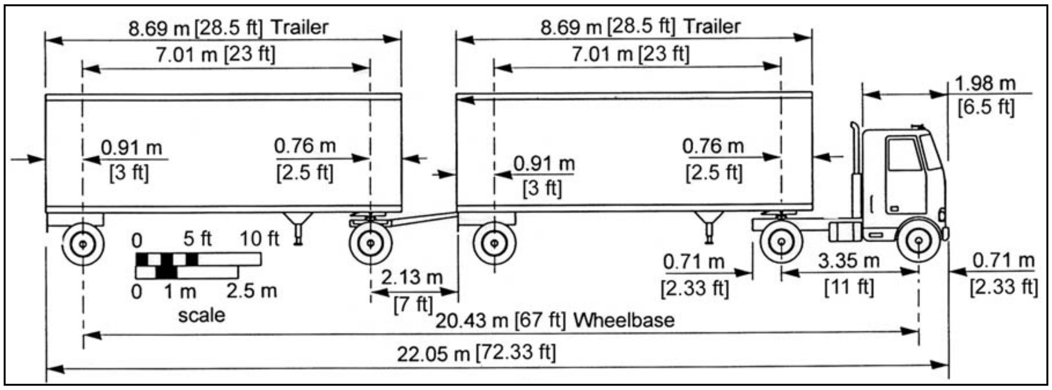


Figure A-13. Dimensions of double-trailer combination (WB-20D [WB-67D]) design vehicle in current Green Book (1).

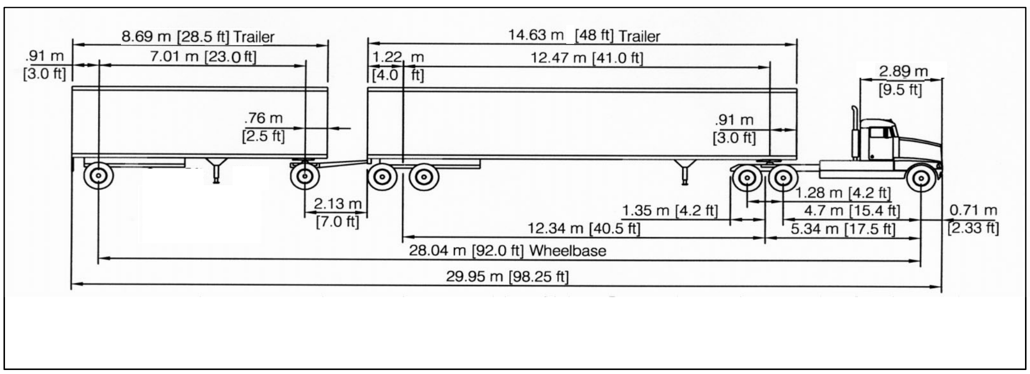


Figure A-14. Recommended dimensions of Rocky Mountain Double combination (WB-28D [WB-92D]) design vehicle.

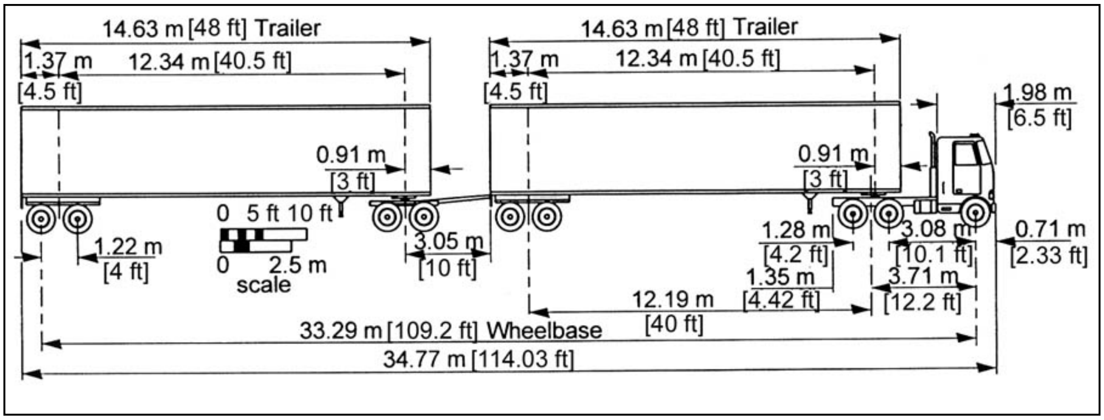


Figure A-15. Dimensions of turnpike-double combination (WB-33D [WB-109D]) design vehicle in current Green Book (1).

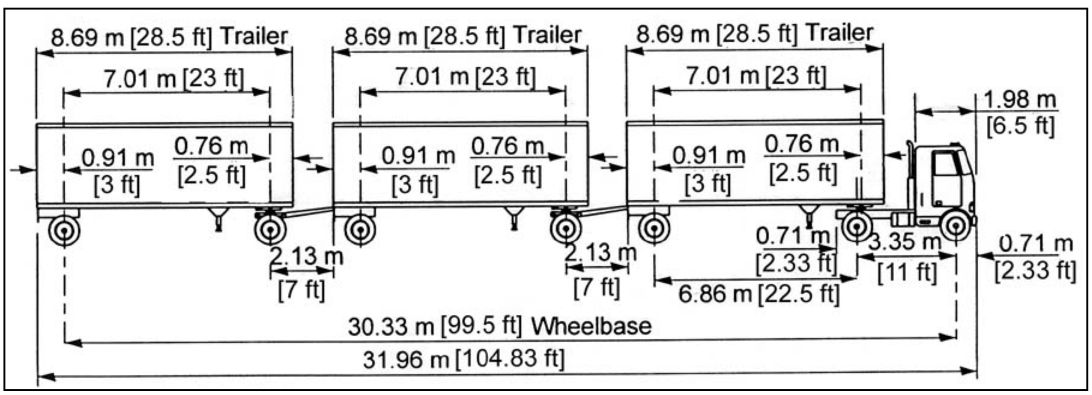


Figure A-16. Dimensions of triple-trailer combination (WB-30T [WB-100T]) design vehicle in current Green Book (1).

This page intentionally left blank.

APPENDIX B

HIGHWAY AGENCY SURVEY

A survey of state highway agencies was conducted to determine any safety problems they have encountered related to highway/heavy vehicle interactions and mitigation measures that may have taken to address such problems.

SURVEY QUESTIONNAIRE

A copy of the survey questionnaire is presented in Figure B-1. The questionnaire includes 15 questions related to highway agency experience with highway/heavy vehicle interactions. The questionnaire included both objective questions that could be answered by placing checkmarks or completing blank spaces and descriptive questions that required a written response.

SURVEY DISTRIBUTION AND RESPONSE

The survey was sent to the chief highway design or traffic engineer of each of the 50 state highway agencies. Responses were received from 35 of the 50 agencies, for an overall response rate of 70 percent. The responses included highway agencies from all geographic areas of the United States. The responses have been tabulated and analyzed and are presented below.

Question 1—Safety Problems Related to Highway/Heavy Vehicle Interactions

Question 1 asked highway agencies whether they had encountered safety problems related to interaction of heavy trucks and buses with specific types of highway features. The responses are presented in Table B-1. Overall, 29 of the 35 highway agencies (83 percent) reported that they had experienced at least one type of heavy vehicle safety problem related to highway geometric design. Four geometric design features were reported as being encountered most frequently; problems related to horizontal curve radius, vertical grade, intersection curb return radii for right turns, and interchange ramps had each been encountered by 51 percent of highway agencies. Other problems reported with some frequency were related to: railroad-highway grade crossings (40 percent of highway agencies); acceleration lanes (37 percent); intersection turning paths for left turns (34 percent); horizontal curve superelevation (31 percent); intersection turn lanes (29 percent); and deceleration lanes (29 percent).

States that had encountered any of the problems identified in Table B-1 were asked in Question 1b whether they consider those problems to be potentially correctable through geometric design or traffic control improvements. A total of 24 of the 29 highway agencies (83 percent) that had experienced safety problems related to highway/heavy vehicle interactions thought that those problems were potentially correctable through geometric design or traffic control improvements. The overall assessment of most highway agencies is that the problems they have encountered can be addressed with existing geometric design and traffic control criteria. Thus, addressing the problems that exist is primarily an issue of needing sufficient funding rather then needing revised geometric design or traffic control policies. In response to Question 1c, only five highway agencies indicated that they thought changes in geometric design or traffic control criteria for trucks were needed. Three of those five states explicitly cited the need to update design vehicles to match the truck fleet.

Question 2—Are Changes Needed to the Design Vehicles in the 2001 AASHTO *Green Book?*

In response to Question 2, three state highway agencies responded that changes to design vehicles were needed. The specific design vehicle changes

Commercial Truck and Bus Safety Synthesis Program
Synthesis 3—Highway/Heavy Vehicle Safety Interaction

STATE HIGHWAY AGENCY SURVEY

The Commercial Truck and Bus Safety Synthesis Program is sponsored by the Federal Motor Carrier Safety Administration and is managed by the Transportation Research Board. This survey is intended to identify what types of safety problems related to interactions between heavy trucks and buses and roadway features have been encountered by state highway agencies and what types of policy changes or roadway engineering improvements have been made to address those problems. The survey should be completed by a geometric design or traffic safety engineer.

1. Has your agency encountered any safety problems related to the interaction of heavy trucks or buses with the following roadway geometric design features? (check all that apply)

Stopping sight distance	_______
Intersection sight distance	_______
Horizontal curve radius	_______
Horizontal curve superelevation	_______
Vertical grade	_______
Intersection curb return radii (turning paths for right-turns)	_______
Intersection turning paths for left-turns	_______
Intersection turn lanes	_______
Interchange ramps	_______
Acceleration lanes	_______
Deceleration lanes	_______
Railroad-highway grade crossings	_______
Other (please specify)	_______

If you answered YES to ***any*** of the preceding questions, do you consider those problems potentially correctable through geometric design or traffic control improvements?

Is there a need for improvement in existing geometric design and traffic control criteria related to heavy trucks or buses?

Figure B-1. Questionnaire used for highway agency survey.

2. Based on the current heavy truck and bus population using the roads under your agency's jurisdiction, do you see a need for changes in, or additions to, the design vehicles presented in the 2001 edition of the AASHTO *Policy on Geometric Design of Highways and Streets* (commonly known as the Green Book)? ___ YES ____ NO

   If YES, what changes or additions would you recommend:

3. Does your agency have warrants for added truck climbing lanes on steep grades? _____ YES ____ NO

   If YES, do these warrants differ from those presented in the AASHTO Green Book? ___ YES ____ NO

   If your warrants differ from those in the AASHTO Green Book, would you please send us a copy of those warrants?

4. Has your agency installed emergency escape ramps for trucks on long, steep downgrades? ____ YES ____ NO

   If YES, do you have any design criteria or warrants for emergency escape ramps that differ from those presented in the AASHTO Green Book?
   ___ YES ____ NO

   If your criteria or warrants differ from those in the AASHTO Green Book, would you please send us a copy of those criteria or warrants?

Figure B-1. Questionnaire used for highway agency survey. (Continued)

5. Does your agency use, or are you considering, any of the following approaches to safely accommodating large trucks and buses on the highway (check all that apply)?

	Currently used	Considering for future use
Different speed limits for cars and trucks	_____	_____
Restriction of truck and bus use of left lane	_____	_____
Restriction of all trucks and buses to right lane	_____	_____
Provision of brake check areas in advance of steep downgrades	_____	_____
Downgrade signing to promote proper	_____	_____
speed and gear selection	_____	_____
Exclusive lanes for use by heavy trucks and buses only (no passenger cars permitted)	_____	_____
Exclusive lanes for use by buses only (no passenger cars or trucks permitted)	_____	_____
Exclusive roadways for use by heavy vehicles only (no passenger cars permitted)	_____	_____
Modified traffic signal timing or longer clearance intervals for heavy vehicles	_____	_____

6. Has your agency evaluated or estimated the safety effectiveness of any of the improvement types listed in Question 5? ____ YES ____ NO

If YES, what did the evaluation find? If possible, may we have a copy of the evaluation?

7. If your agency has used different speed limits for passenger cars and heavy vehicles on the same facility (see Question 5):

What is the speed limit for passenger cars? ____ for heavy vehicles? _____

On what types of facilities are these speed limits used?

Figure B-1. Questionnaire used for highway agency survey. (Continued)

8. Has your agency encountered safety problems related to truck or buses on interchange ramps (see Question 1)? ___ YES ____NO

If YES, what types of countermeasures have you used for such problems? (check all that apply):

Advisory speed limits for trucks on specific ramps	_____
Advisory speed limits for all vehicles on specific ramps	_____
Regulatory speed limits for trucks on specific ramps	_____
Regulatory speed limits for all vehicles on specific ramps	_____
Special warning signs for trucks (e.g., truck rollover sign)	_____
Special warning signs for trucks accompanied by permanent flasher	_____
Special warning signs for trucks with flashers activated when a high-speed truck is detected	_____
Reconstruction of ramp to change horizontal curve radius or superelevation	_____
Other (please specify)	_____

9. Does your agency have any formal criteria for deciding whether to prohibit heavy trucks and buses from using particular roadways? ___ YES ____ NO

If YES, may we have a copy of those criteria?

10. Has your agency encountered any problems related to truck or bus travel at night that are related to, or potentially correctable by, geometric design or traffic control?
___ YES ___ NO

If YES, what is the nature of those problems:

Figure B-1. Questionnaire used for highway agency survey. (Continued)

11. Does your agency use roadside safety hardware (bridge rail, guardrail, etc.) that is designed specifically to accommodate large trucks and buses?
___ YES ___ NO

If YES, what types of hardware are used? Under what situations is such hardware used?

Has such hardware been successfully crash tested with large trucks or buses?

12. Does your agency use any signing intended specifically for drivers of heavy trucks and buses? ___ YES ____ NO

If YES, what types of signing are used:

13. Has your agency experienced safety problems related to obstruction of the visibility of signs or other traffic control devices by heavy trucks or buses?
_____ YES ______ NO

If YES, has your agency implemented any specific traffic control device placement criteria or countermeasures for mitigating the effect of such obstructions to visibility? _____ YES _____ NO

If YES, please describe:

14. Has your agency implemented any ITS initiatives intended specifically to improve safety for heavy trucks and buses? ___ YES ____ NO

If YES, please describe those ITS initiatives:

Figure B-1. Questionnaire used for highway agency survey. (Continued)

15. Has your agency encountered any other specific safety problems related to the interaction between heavy trucks or buses and roadway features that have not been mentioned previously in your response to this questionnaire?
___ YES ___ NO

If YES, what is the nature of these problems?

16. May we have the name of an individual in your agency that we may contact for further information should that be necessary?

Name ______________________________
Agency_____________________________
Address ____________________________
____
____
Phone: ____________________________
Fax: ____________________________
e-mail: ____________________________

Your response to this survey prior to August 20, 2002, would be appreciated. Please mail your response to:

Mr. Douglas W. Harwood
Principal Traffic Engineer
Midwest Research Institute
425 Volker Boulevard
Kansas City, MO 64110

Figure B-1. Questionnaire used for highway agency survey. (Continued)

Table B-1. Highway agency responses concerning safety problems encountered by heavy vehicles related to specific geometric design features

	Number of responses	Percentage of responses
Stopping sight distance	8	23%
Intersection sight distance	8	23%
Horizontal curve radius	18	51%
Horizontal curve superelevation	11	31%
Vertical grade	18	51%
Intersection curb return radii (turning paths for right-turns)	18	51%
Intersection turning paths for left-turns	12	34%
Intersection turn lanes	10	29%
Interchange ramps	18	51%
Acceleration lanes	13	37%
Deceleration lanes	10	29%
Railroad-highway grade crossings	14	40%
Other (please specify)	4	11%

requested were inclusion of trucks with 17.4-m (57-ft) trailers and 4.9-m (16-ft) wide mobile homes as design vehicles.

Question 3—Warrants for Added Climbing Lanes on Steep Grades

In response to Question 3, 23 highway agencies (66 percent) indicated that they have explicit warrants for adding climbing lanes on steep grades. In all but four states, the climbing lane warrants are identical to those presented in the AASHTO *Green Book.*

Question 4—Use of Emergency Escape Ramps on Long, Steep Downgrades

The responses to Question 4 indicated that 22 out of 35 highway agencies (63 percent) have installed emergency escape ramps on long, steep downgrades. Only one highway agency indicated that they have criteria for emergency escape ramps that differ from the AASHTO *Green Book*. That state uses a combination of accident experience and a model for predicting truck brake temperature to evaluate the need for escape ramps at particular locations.

Question 5—Highway Agency Use of Specific Methods for Safely Accommodating Heavy Vehicles

Highway agencies were asked in Question 5 whether they use specific techniques for safely accommodating large trucks and buses on the highway. The responses are presented in Table B-2. The most widely used specific methods for accommodating heavy vehicles are:

- downgrade signing to promote proper speed and gear selection (used by 74 percent of highway agencies)
- provision of brake check areas in advance of steep downgrades (49 percent)
- restriction of truck and bus use of the left lane (37 percent)
- different speed limits for cars and trucks (31 percent)

The specific methods most commonly being considered for future use are:

- restriction of all trucks and buses to the right lane (11 percent)
- different speed limits for cars and trucks (9 percent)

Table B-2. Highway agency used for specific methods for safety accommodating heavy vehicles on the highway

	Currently used		Considering for future used		Combined	
	Number of responses	Percentage of responses	Number of responses	Percentage of responses	Number of responses	Percentage of responses
Different speed limits for cars and trucks	11	31%	3	9%	14	40%
Restriction of truck and bus use of left lane	13	37%	3	9%	16	46%
Restriction of all trucks and buses to right lane	2	6%	4	11%	6	17%
Provision of brake check areas in advance of steep downgrades	17	49%	1	3%	18	51%
Downgrade signing to promote proper speed and gear selection	26	74%	0	0%	26	74%
Exclusive lanes for use by heavy trucks and buses only (no passenger cars)	3	9%	3	9%	6	17%
Exclusive lanes for use by buses only (no passenger cars or trucks)	4	11%	3	9%	7	20%
Exclusive roadways for use by heavy vehicles only (no passenger cars)	0	0%	1	3%	1	3%
Modified traffic signal timing or longer clearance intervals for heavy vehicles	3	9%	1	3%	4	11%

- restriction of truck and bus use of the left lane (9 percent)
- exclusive lanes for use by heavy trucks and buses only (9 percent)
- exclusive lanes for use by trucks only (9 percent)

Question 6—Evaluation of Improvement Types Identified in Question 5

Only 3 of the 35 highway agencies (9 percent) indicated in response to Question 6 that they had conducted any formal evaluation of the improvement types identified in Question 5. Two states indicated that they had evaluated restriction of trucks to particular lanes, but in both cases the results were inconclusive. One state indicated that an evaluation was under way at the present time.

Question 7—Different Speed Limits for Passenger Cars and Heavy Vehicles

Table B-2 showed that 11 states have used different speed limits for passenger cars and heavy vehicles on the same facility. Table B-3 shows the speed limits that have been used in different states. In some states, the use of differential speed limits is a statewide practice; in others, differential speed limits are used at particular sites. The maximum difference in speed limit that has been used is 16 km/h (10 mi/h). Two highway agencies stated explicitly in response to this question that they consider the use of differential speed limits to be undesirable. Another agency stated that they previously used differential speed limits, but no longer do so.

Question 8—Safety Problems Encountered by Heavy Vehicles at Interchange Ramps

In response to Question 8, 26 of the 35 states (74 percent) indicated that they had encountered safety problems related to heavy vehicles on interchange ramps. Table B-4 summarizes the specific types of countermeasures that have been used by highway agencies to address such problems. The most frequently used countermeasures are:

- advisory speed limits for all vehicles on specific ramps (60 percent of all responding highway agencies)
- special warning signs for trucks (e.g., truck rollover sign) (57 percent)
- reconstruction of ramp to change horizontal curve radius or superelevation (37 percent)
- advisory speed limits for trucks on specific ramps (11 percent)

Question 9—Criteria for Prohibiting Heavy Vehicles From a Roadway

Nine highway agencies (26 percent) indicated in response to Question 9 that they have formal criteria for deciding whether to prohibit heavy vehicles for using particular roadways. One state indicated that they have prohibited trucks on one particular 10 km (6 mi) section of Interstate highway. Another state indicated that they have had emergency regulations on truck prohibition that are currently being reevaluated and amended. A third state indicated that roadway geometric design problems are one factor in deciding whether to permit trucks. However, neither of these states cited specific criteria used in deciding these heavy vehicle prohibitions. One state indicated that they impose weather-related weight restrictions on trucks. In the remaining states, heavy vehicle prohibitions were related to bridge or pavement structural capacities.

Question 10—Problems Related to Heavy Vehicle Travel at Night

In response to Question 10, only 1 agency out of 35 (3 percent) indicated that they had encountered problems related to truck or bus travel at night that are related to, or potentially correctable by, geometric design or traffic control. That one agency cited a problem related to low visibility of border stations at night.

Question 11—Roadside Safety Hardware to Accommodate Heavy Vehicles

A total of 10 of the 35 responding highway agencies (29 percent) indicate that they use roadside safety hardware (bridge rail, guardrail, etc.) that is designed specifically to accommodate large trucks and buses. The types of roadside safety hardware used:

- concrete median barriers, including tall barriers
- bridge rail
- super heavy-duty guardrail at the bottom of a long downgrade

Respondents indicated that they have used NCHRP Report 350 *(30)* test levels 4 and 5 for testing of such barriers, but not all hardware currently used to accommodate trucks has been tested with trucks. Factors included in deciding where to use such hardware include high truck percentages and high truck accident experience. Tall median barriers are used for glare control, as well as to accommodate trucks.

Table B-3. Highway agency usage of different speed limits on the same facility for passenger cars and heavy vehicles

State	Speed limits (mi/h) Passenger cars	Speed limits (mi/h) Heavy vehicles	Facility type
Arkansas	70	65	Rural freeways
Idaho	75	65	Freeways
Illinois	65	55	Freeways
Maine	45	35	Arterials
Michigan	70	55	Freeways
Montana	75	65	Interstate highways
North Carolina	65	55 or 60	Selected freeway sections
Ohio	65	55	Rural freeways
Texas	75/70/65	70/65/60/55	Selected freeways and other state highways
Virginia	55	45	Selected secondary roads
Washington	70	60	Rural freeways

Table B-4. Highway agency responses concerning safety problems related to trucks or buses on interchange ramps

	Number of responses	Percentage of responses
Advisory speed limits for trucks on specific ramps	11	31%
Advisory speed limits for all vehicles on specific ramps	21	60%
Regulatory speed limits for trucks on specific ramps	1	3%
Regulatory speed limits for all vehicles on specific ramps	2	6%
Special warning signs for trucks (e.g., truck rollover sign)	20	57%
Special warning signs for trucks accompanied by permanent flasher	9	26%
Special warning signs for trucks with flashers activated when a high-speed truck is detected	7	20%
Reconstruction of ramp to change horizontal curve radius or superelevation	13	37%
Other	2	6%

Question 12—Signing Specifically for Drivers of Heavy Vehicles

In response to Question 12, 24 of the 35 respondents (69 percent), indicated that they have used signing intended specifically for drivers of heavy trucks and buses. This question was primarily intended to elicit comments on new or innovative types of signing, but the list of types of signing presented below obviously includes types of signing that are used by all highway agencies. The specific types of signing used are:

- steep downgrade/brake check signing
- emergency escape ramp signing
- truck rollover signing
- curve warning signs
- truck advisory speed signs
- truck speed limits
- weight restrictions
- height restrictions/vertical clearance

- other truck restrictions
- lane use signing
- truck route signing
- slow vehicles keep right
- restricted use of engine brakes
- high wind warning signs
- low ground clearance warning signs

Question 13—Obstruction of Sign Visibility by Heavy Vehicles

Seven out of the 35 highway agencies that responded to the survey (20 percent) indicated in response to Question 13 that they had experienced safety problems related to the obstruction of sign visibility by heavy trucks and buses. In one case, the state indicated that the problem was not documented, but was based on limited cases involving overweight/oversize vehicles operating under permit. The other six highway agencies indicated that they had taken actions at specific sites to alleviate the problems. These actions included:

- Placing regulatory signs on both sides of the roadway on freeways
- Using double stop signs or placing stop signs on both sides of the road
- Using overhead signs
- Placing an additional traffic signal head over the opposing through lane
- Additional use of advance warning signs

Question 14—ITS Initiatives to Improve Heavy Vehicle Safety

In response to Question 14, 13 of the 35 highway agencies (37 percent) indicated that they have implemented ITS initiatives intended specifically to improve safety for heavy truck and buses. The ITS initiatives cited include:

- Changeable message signs
- Allowing pre-approved trucks to bypass weigh scales
- Truck rollover alert system
- Downhill truck warning system
- Wind advisory warning system

Question 15—Other Safety Problems Related to Highway/Heavy Vehicle Interaction

The responding highway agencies were asked in Question 15 whether they had encountered any other safety problems, not mention in the preceding questions, that were related to the interaction between heavy trucks or buses and roadway features. The six highway agencies that responded mentioned a total of seven specific problems not addressed earlier in this appendix. These are:

- Geometric design of work zones (specifically, median crossovers)
- Failure of trucks to stop as they approach slow moving or stopped traffic from the rear
- Deer hits by heavy vehicles
- Trucks parking on interchange ramps
- Visibility problems due to dust storms
- Operation of double-trailer trucks in snow conditions
- Superelevation rates for horizontal curves on steep downgrades

APPENDIX C

INDUSTRY SURVEY

A survey of heavy vehicle operators and the national organizations that represent them was conducted to determine any safety problems they have encountered related to highway features at which they have encountered safety concerns related to highway/heavy vehicle interactions and mitigation measures that have taken or are planned to address such concerns.

SURVEY QUESTIONNAIRE

A copy of the survey questionnaire is presented in Figure C-1. The questionnaire includes eight questions related to the respondents' experience with highway/heavy vehicle interactions. The questionnaire included both objective questions that could be answered by placing checkmarks or completing blank spaces and descriptive questions that required a written response.

SURVEY DISTRIBUTION AND RESPONSE

The survey was sent to national organizations that represent the trucking industry and through those national organizations to individual trucking companies and owner/operators. This approach was adopted so that the individual respondents would have confidence that the survey was for a worthwhile purpose and that the results would, in fact, be used to improve highway safety.

Responses were received from 33 organizations in the trucking industry. Because there is no formal industry data base from which to choose respondents systematically or randomly, the survey results should not be considered as a representative sample of the trucking industry. Nevertheless, the survey results provide valuable information on trucking industry viewpoints.

The responses represent national industry organizations and firms in all geographic areas of the United States. Responses were received from organizations and firms in 20 of the 50 states.

Question 1—Type of Commercial Trucking or Bus Operation

Question 1 asked respondents the type of commercial trucking or bus operation they represent. The responses to this questions are presented in Table C-1, which shows 12 percent of the responses were from trucking industry organizations, 46 percent were from trucking companies or fleet owners, and 42 percent were received from truck owner/operators. No responses have been received from the bus industry.

Questions 2 and 3—Industry Segment

Questions 2 and 3 asked respondent which segments of the trucking and bus industry, respectively, they represent or operate in. Table C-2 summarizes the responses from the trucking industry to Question 2. The largest number of responses represent the private truckload carriers, for-hire truckload carriers, and less-than-truckload carriers, with some responses from specialized carrier types. The tabulated responses total more than 100 percent because multiple responses to this question were permitted.

Question 4—Highway Features Considered to Be Safety Concerns

Question 4 asked about highway features considered to be safety concerns. Table C-3 summarizes the industry responses to this question. The greatest concern related to highway features identified by respondents is tight radii for right turns at intersections; this was cited as a high-priority concern by 94 percent of the survey

Commercial Truck and Bus Safety Synthesis Program
Synthesis 3—Highway/Heavy Vehicle Safety Interaction

TRUCK AND BUS SAFETY SURVEY

The Commercial Truck and Bus Safety Synthesis Program (CTBSSP) is sponsored by the Federal Motor Carrier Safety Administration and is managed by the Transportation Research Board. This survey is intended to identify the types of safety concerns related to interactions between heavy trucks and buses and roadway features that have been encountered by owners and drivers of heavy trucks and buses and the types of safety improvements might be effective in mitigating those concerns. This survey will help highway agencies to understand your views in planning future safety improvement programs. The results will be published in a CTBSSP synthesis report. All published information on this survey will be aggregated so that the responses of individual persons or organizations are not released. Your assistance in responding to the survey would be appreciated.

1. What is your connection to commercial trucking and bus operation (check one):

   Trucking industry organization _____
   Bus industry organization _____
   Trucking company/fleet owner _____
   Bus company/fleet owner _____
   Truck owner/operator _____
   Individual truck driver _____
   Individual bus driver _____

2. If you are associated with the trucking industry, what segment of that industry do you represent or operate in (check all that apply)?

   Less-than-truckload hauling _____
   Truckload hauling (for hire) _____
   Truckload hauling (private) _____
   Bulk materials hauling _____
   Hazardous materials trucking _____
   Automobile carrier _____
   Movers/household goods _____
   Other (specify):

3. If you are associated with the bus industry, what segment of that industry do you represent or operate in (check all that apply)?

   Intercity scheduled bus _____
   Charter bus _____
   Local transit bus _____
   School bus _____
   Other (specify):

Figure C-1. Questionnaire used for industry survey.

4. Which of the following highway features do you consider to be safety concerns for truck and bus operation that are most in need of improved highway design or traffic control (check one response for each item)?

	High priority/major safety concerns at many locations	Low priority/ safety concerns at a few locations	Not a concern/no major safety problems encountered	No opinion/don't know
Sharp curves	____	____	____	____
Long, steep upgrades	____	____	____	____
Long, steep downgrades	____	____	____	____
Interchange ramps	____	____	____	____
Acceleration lanes for merging onto highway	____	____	____	____
Deceleration lanes for leaving a highway	____	____	____	____
Intersections—tight radii for right turns	____	____	____	____
Intersections—insufficient storage length for turn lanes	____	____	____	____
Highway-railroad grade crossings	____	____	____	____
Construction or maintenance work zones	____	____	____	____

5. Are there any other safety concerns related to highway design or traffic control that, in your opinion, are generally in need of improvement? Please describe.

6. Please rate the desirability of the following types of safety improvements, which are currently being made or being considered by highway agencies (check one response for each item):

	Highly desirable/should be widely used	Desirable at a few locations where truly needed	Undesirable/ not needed	No opinion/ don't know
Different speed limits for passenger cars and trucks/buses on the same roadway	____	____	____	____
Restriction of trucks and buses from using the left lane	____	____	____	____
Restriction of trucks and buses to the right lane only	____	____	____	____

Figure C-1. Questionnaire used for industry survey. (Continued)

	Highly desirable/should be widely used	Desirable at a few locations where truly needed	Undesirable/ not needed	No opinion/ don't know
Lanes reserved for exclusive use by trucks	____	____	____	____
Lanes reserved for exclusive use by buses	____	____	____	____
Separate roadways for use by trucks and buses only	____	____	____	____
Truck climbing lanes on long, steep upgrades	____	____	____	____
Brake check areas at top of long, steep downgrades	____	____	____	____
Advisory signing for speed or gear selection on long, steep downgrades	____	____	____	____
Automated systems to detect high truck and bus speeds on downgrades and warn drivers	____	____	____	____
Emergency escape ramps for trucks and buses on long, steep downgrades	____	____	____	____
Advisory signing for safe speeds for trucks and buses to avoid rollover on sharp curves	____	____	____	____
Automated systems to detect high truck and bus speeds on sharp curves and warn drivers	____	____	____	____

7. Do you have any information or opinions about the potential effectiveness in improving safety of the improvements listed above? Please describe.

8. Are there any other types of improvements related to highway design or traffic control that you believe should be used to improve the safety of the roadway system? Please describe.

Figure C-1. Questionnaire used for industry survey. (Continued)

9. (Optional) May we have the your name as a point of contact for further information should that be necessary?

Name ______________________________________

Agency ______________________________________

Address ______________________________________

____

____

Phone: ____________________________

Fax: ____________________________

e-mail: ____________________________

Please return this survey within two weeks to:

Mr. Douglas W. Harwood
Principal Traffic Engineer
Midwest Research Institute
425 Volker Boulevard
Kansas City, MO 64110

If you received the survey electronically, you are welcome to e-mail your response to dharwood@mriresearch.org.

Thank you for your cooperation.

Figure C-1. Questionnaire used for industry survey. (Continued)

Table C-1. Type of operation represented by respondents to the industry survey

Type of operation	Number of responses	Percentage of responses
Trucking industry organization	4	12.1
Trucking company/fleet owner	15	45.5
Truck owner/operator	14	42.4
Bus industry organization	0	0.0
Bus company/fleet owner	0	0.0
	33	

Table C-2. Trucking industry segment represented by respondents to the industry survey

Industry segment	Number of responses[a]	Percentage of responses[a]
Less-than-truckload hauling	9	27.3
Truckload hauling (for hire)	16	48.5
Truckload hauling (private)	13	39.4
Bulk materials hauling	7	21.2
Hazardous materials trucking	7	21.2
Automobile carriers	1	3.0
Movers/household goods	4	12.1
Other	4	12.1

[a] Because of multiple responses, the columns total to more than 100%.

respondents. Other concerns identified as high priorities by a majority of survey respondents include acceleration lanes for merging onto a highway, insufficient storage length for left turns at intersections, interchange ramps, sharp curves, construction or maintenance work zones, and highway-railroad grade crossings.

Question 5—Other Safety Concerns Related to Highway Design or Traffic Control

Question 5 asked respondents to comment on other safety concerns related to highway design or traffic control. The responses received were as follows:

- Post uniform speed limits for all vehicle types (5 responses)
- Provide sufficient maneuvering room for large trucks that use facilities including ramps, surface streets, and intersections (4 responses)
- Use advance or overhead flashers to warn drivers that the green phase of a signal is about to end (4 responses)
- Eliminate truck lane restrictions (3 responses)
- Provide more rest areas and pull offs (2 responses)
- Need wider and stronger shoulders to accommodate disabled vehicles (2 responses)
- Need lane lines that are more visible at night and in adverse weather (2 responses)
- Provide more median barriers on freeways (1 response)

Table C-3. Assessment of highway features as safety concerns by respondents to industry survey

Highway features	High priority/ major safety concerns at many locations		Low priority/ safety concerns at a few locations		Not a concern/ no major safety problems encountered		No opinion/ don't know
	Number of responses	Percentage of responses	Number of responses	Percentage of responses	Number of responses	Percentage of responses	Number of responses
Sharp curves	20	66.6	9	30.0	1	3.3	3
Long, steep upgrades	7	22.6	19	61.2	5	16.1	2
Long, steep downgrades	12	40.0	16	53.3	2	6.7	3
Interchange ramps	21	67.7	9	29.0	1	3.2	2
Acceleration lanes for merging onto highway	24	75.0	6	18.8	2	6.3	1
Deceleration lanes for leaving a highway	14	45.2	13	41.9	4	12.9	2
Intersections—tight radii for right turns	30	93.8	2	6.3	0	0.0	1
Intersections—insufficient steerage length for left turns	22	68.8	7	21.9	3	9.4	1
Highway-railroad grade crossings	16	50.0	13	40.6	3	9.4	1
Construction or maintenance zones	19	61.3	10	32.3	2	6.5	2

- Provide flatter roadside slopes on ramps (1 response)
- Improve poorly designed islands at intersections (1 response)
- Provide more shoulder rumble strips (1 response)
- Redesign interchanges to eliminate weaving areas (1 response)
- Provide wider lanes—3.6 to 4.3 m (12 to 14 ft) preferred (1 response)
- Provide appropriate superelevation on horizontal curves (1 response)
- Reduce congestion at entry to weigh scales (1 response)
- Eliminate situations where trucks must turn left into weigh scales where no left-turn lane is provided (1 response)
- Find some effective way to improve work zone safety (1 response)
- Reduce the brightness of flashing arrow panels in work zones (1 response)
- Improve pavement surfaces/fill potholes (1 response)
- Use longer yellow signal-change intervals (1 response)
- Provide more guide signs in advance of interchanges (three signs per interchange) (1 response)
- Need more uniformity in signage (1 response)

Question 6—Assessment of Specific Improvement Types

Question 6 asked respondents for their assessment of potential mitigation measures for heavy vehicle safety concerns. The primary focus of this question was to obtain an industry assessment of traffic control and regulatory strategies that have been used or are being considered by highway agencies to improve safety for heavy vehicles. The responses to Question 6 are presented in Table C-4. The mitigation measures that were most frequently rated by the survey respondents as highly desirable and appropriate for widespread use included truck climbing lanes on long, steep upgrades (66 percent); advisory signing for safe speeds for truck and buses to avoid rollover on sharp curves (61 percent); advisory signing for speed or gear selection on long, steep downgrades (59 percent), emergency escape ramps for trucks and buses on long, steep downgrades (58 percent); brake check areas at the top of long, steep downgrades (47 percent); and automated systems to detect high truck and bus speeds on sharp curves and warn drivers (46 percent). An additional mitigation measure that was rated by many survey respondents as desirable at a few locations where truly needed was the use of lanes reserved for exclusive use by trucks (50 percent). Mitigation measures considered as undesirable or not needed included different speed limits for passenger cars and heavy vehicles on the same roadway (81 percent); restriction of trucks and buses to the right lane only (79 percent); restriction of trucks and buses from using the left lane (64 percent); and separate roadways for use by trucks and buses only (58 percent).

Question 7—Potential Effectiveness of Measures for Improving Safety

Question 7 asked drivers for information or opinions about the effectiveness of potential mitigation measures like those shown in Table C-4. The following comments were received:

- Differential speed limits have an adverse effect on safety (10 responses)
- Lane restrictions cause congestion and disrupt smooth traffic flow (8 responses)
- Separate truck/bus lanes will work only if passenger cars are not allowed to use them; stiff fines are needed (1 response)
- Automated signing may not work because too few drivers pay attention to signs (1 response)

Question 8—Other Safety Improvements

Question 8 asked respondents to suggest other types of safety improvements, not mentioned in previous questions, that should be considered to

Table C-4. Assessment of mitigation measures for heavy vehicle safety concerns by respondents to industry survey

Mitigating measures	Highly desirable/ should be used widely		Desirable at a few locations where truly needed		Undesirable/ not needed		No opinion/ don't know
	Number of responses	Percentage of responses	Number of responses	Percentage of responses	Number of responses	Percentage of responses	Number of responses
Different speed limits for passenger cars and truck/buses on the same roadway	2	6.3	4	12.5	26	81.3	1
Restriction of trucks and buses from using the left lane	5	15.2	7	21.2	21	63.6	0
Restriction of trucks and buses to the right lane only	0	0.0	7	21.2	26	78.8	0
Lanes reserved for exclusive use by trucks	3	9.4	16	50.0	13	40.6	1
Lanes reserved for exclusive use by buses	4	15.4	7	26.9	15	57.7	7
Separate roadways for use by trucks and buses only	6	19.4	7	22.6	18	58.1	2
Truck climbing lanes on long, steep upgrades	21	65.6	10	31.3	1	3.1	1
Brake check areas at the top of long, steep downgrades	15	46.9	14	43.8	3	9.4	1
Advisory signing for speed or gear selection on long, steep downgrades	19	59.4	12	37.5	1	3.1	1
Automated systems to detect high truck and bus speeds on downgrades and warn drivers	12	37.5	13	40.6	7	21.9	1
Emergency escape ramps for trucks and buses on long, steep downgrades	19	57.6	14	42.4	0	0.0	0
Advisory signing for safe speeds for trucks and buses to avoid rollover on sharp curves	20	60.6	13	39.4	0	0.0	0
Automated systems to detect high truck and bus speeds on sharp curves and warn drivers	15	45.5	14	42.4	4	12.1	0

improve the safety of the highway system. The responses included:

- Need improved driver training for both heavy vehicle and passenger car drivers (4 responses; one respondent mentioned the need to teach good road manners and one stated that driver training should use the "share the road" concept)
- Increase aggressive driving enforcement (lane changing, tailgating, etc.) (2 responses)
- Reduce state-to-state variation in traffic laws and fines (2 responses)
- Provide more rest area parking spaces; improve lighting and enforcement at rest areas (2 responses)
- Need better curve design (2 responses)
- Provide appropriate superelevation on horizontal curves; eliminate curves with reverse superelevation (2 responses)
- Provide longer acceleration lanes (1 response)
- Use yield signs rather than merging signs at entrance ramps (1 response)
- Eliminate cloverleaf designs (1 response)
- Eliminate entrance ramps on curves (1 response)
- Redesign sites where several roadways merge into a single lane (1 response)
- Reduce need for work zones by building better roads in the first place (1 response)
- Provide detours around work zones (1 response)
- Make sure road construction keeps up with increases in traffic (1 response)
- Improve pavement friction for wet pavements (1 response)
- Provide more automated warning systems for sharp curves (1 response)
- Provide automated warning signs for speeding vehicles (1 response)
- Flashing lights at highway-railroad grade crossings should begin soon enough that vehicles are not trapped by the gates (1 response)
- Clear brush in front of road signs (1 response)
- Provide advance street names signs; use larger letters on street name signs (1 response)
- Require all through traffic (heavy vehicles and passenger cars) to use the left lane in urban areas (1 response)
- Make truck and bus routes truck friendly (1 response)
- Encourage graduated licensing for heavy vehicle drivers as well as for passenger car drivers (1 response)
- Need more enforcement of failure to dim high-beam headlights (1 response)
- Provide better fog lights for vehicles (1 response)

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