

HIGHWAY SAFETY DESIGN and OPERATIONS GUIDE 1997



**AMERICAN ASSOCIATION of STATE
HIGHWAY and TRANSPORTATION OFFICIALS
444 NORTH CAPITOL STREET NW SUITE 249
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PREFACE

In 1967, the American Association of State Highway and Transportation Officials (AASHTO) published a committee report titled *Highway Design and Operational Practices Related to Highway Safety*. This report subsequently became known as the “Yellow Book.” It included discussion, comments, and recommendations concerning a wide range of issues related to highway design practices.

The Yellow Book also addressed safety on roads and streets under the control of state and local highway agencies. The Federal Highway Administration (FHWA) strongly endorsed the Yellow Book for application to highways with design speeds in excess of 50 miles per hour (mph) (80 kilometers per hour [km/h]) and to projects with lower design speeds to the extent practical.

The Yellow Book was updated, expanded, and issued in a revised form in 1974. The publication has heightened the awareness of highway planners, designers, and operators to the need for

incorporating safety into their processes and procedures.

In October 1991, the FHWA presented the AASHTO Standing Committee on Highway Traffic Safety with a draft proposed replacement to the Yellow Book. The proposed replacement focused on new information as well as emphasized current well-known safety practices that are still not being fully used. The committee agreed to take the lead in finalizing the proposed guide with technical assistance and support from the FHWA.

This resulting document, the *Highway Safety Design and Operations Guide*, presents concepts for enhancing safety in the operation and management of highways. It represents the culmination of past efforts combined with the results of research and proven engineering practices. This publication contains those state-of-the-art technologies that must be applied to achieve a safe level of traffic operations in the constantly changing environment of the nation’s highway network.



1 INTRODUCTION

Today's highway transportation professional can look at the latest safety data with satisfaction. Since the last edition of this book was published in 1974, significant gains have been made in practically all aspects of highway safety, though use of and traffic densities on the nation's highways have been steadily on the rise. Accident and fatality rates are at their lowest levels ever. (See table 1-1.) Without question, the highway design and operational elements presented in earlier editions of this book have contributed significantly to these achievements. However, the emphasis on highway safety since the 1960s also has led to important advances in vehicle safety performance, increased use of safety belts, less impaired driving, better emergency medical treatment and other improvements that also have contributed substantially to highway safety. The reduction in total crashes as shown also reflects changes in police and accident reporting practices.

But highway professionals should not let the good news about safety deceive them into thinking that the battle is won. Although accident and fatality rates continue to decline, recent data show that the rate of decrease is slowing, suggesting that improvements in highway safety may be more difficult to achieve in the future.¹

Background

Following passage of the 1966 Highway Safety Act and the rapid expansion of the Interstate Highway System, it became clear that highway safety was becoming a major public concern. Higher-speed freeways, more powerful vehicles, and increased mobility of the driving public

had led to escalating safety problems on the nation's roads and highways. Realization of these circumstances by the American Association of State Highway and Transportation Officials (AASHTO) resulted in the 1967 publication of a committee report *Highway Design and Operational Practices Related to Highway Safety*.² This report, which became known as the "Yellow Book," included discussion, references, and recommendations about the safety implications of various highway design and operational practices. The Federal Highway Administration (FHWA) strongly endorsed the new book and required that its provisions be applied to all highways with design speeds of 50 miles per hour (mph) or more and to those with lower design speeds whenever

Table 1-1. Motor vehicle accident statistics, 1972 and 1995.^{3,4}

Statistics	1972	1995	Change (Percent)
CRASHES:			
Total (rounded)	17,000,000	10,700,000	-37
Fatal crashes	48,800	39,000	-20
DEATHS:			
Total	56,600	43,900	-22
Collisions between vehicles	24,200	19,400	-20
Pedestrian crashes	10,700	6,300	-41
Collisions with trains	1,500	500	-67
Collisions with bicycles	1,100	900	-18
Other single-vehicle crashes	19,000	16,700	-12
Miscellaneous	100	100	0
MOTOR VEHICLE STATISTICS:			
Vehicles registered	119,384,000	204,146,000	+71
Motor-vehicle-kilometers (millions)	2,040,000	3,867,000	+90
RATES:			
Motor vehicle deaths per 100 million vehicle-kilometers	2.8	1.1	-59
Motor vehicle crashes per 100 million vehicle-kilometers	83	28	-67

practical. Since then, this guide to good highway design and practices has been widely accepted, with its recommendations incorporated in many other AASHTO, state, and local highway agency policies and manuals.

In 1974, a revised edition of the guide was published.⁵ The material was expanded in both substance and coverage to reflect changes in the highway system and vehicles; however, it still focused chiefly on high-speed roads. This new edition of the guide takes into account the considerable changes in technology and in user patterns and characteristics that have occurred since 1974. In addition, the authors have attempted to consider how trends in population, vehicles and emerging technology will affect highway safety in the future.

The Changing Highway Environment

At least three changes to the highway environment have been identified as actual or potential safety problems:

- Changes in vehicle size and mix
- Increases in the number of elderly drivers
- Increases in congestion and changes in highway usage

Vehicle Size and Mix

If not adequately considered, changes in the types of vehicles and their characteristics, the mixing of small, lightweight passenger vehicles with large trucks, and the increased number of pedestrians and bicyclists may have a pronounced deleterious effect on safety. The downsizing of the passenger vehicle already has had significant effects on roadside design and the selection of roadside features and safety devices. Much of the safety hardware on today's highways originally was designed for full-sized passenger vehicles, which typically weighed more than 1,800 kilograms (kg). However, a large percentage of passenger vehicles today are considerably lighter and smaller.

Lighter-weight vehicles contain less material to absorb the energy produced during rapid-deceleration collisions. A study by the National Highway Traffic Safety Administration found that fatalities were 2.5 to 3 times greater for compacts and subcompacts than for full-sized cars.¹ Collision testing of previously acceptable safety appurtenances using subcompact cars showed more damage to the cars and their occupants than collision testing of the same safety features using heavier cars. Also, efforts to meet pollution and fuel efficiency goals have led to smaller engines. Vehicles with less powerful engines accelerate more slowly, thus increasing the risk of a collision risk while passing or merging.

Trucks are evolving in the opposite direction. Larger, heavier trucks and greater numbers of multiunit trucks are entering the vehicle fleet. Because of their slower acceleration and longer braking distances, these trucks often operate at lower speeds than the prevailing traffic, particularly on steep grades and in heavy traffic. This speed differential, along with other incompatibilities between the performance of cars and trucks, creates significant hazards. At the same time, vans, pick-up trucks, and sport-utility vehicles have become much more numerous in the vehicle fleet. These vehicles have higher centers of gravity than most cars. Mitigating these problems requires special roadway design, but recent research shows that large and multiunit trucks have not been adequately considered in many design standards, such as those for interchange ramps and for passing sight distance.

Elderly Drivers

As the U.S. population ages, a greater percentage of the driver population consists of older drivers. The aging of the population is expected to reach its peak by 2030, when approximately 22 percent of the population will be 65 or older (compared with 12 percent in 1990).⁶ This increase in the number of elderly drivers has considerable implications for highway safety.

As drivers age, certain physical and cognitive abilities degenerate, the most significant of these being night vision and reaction time. Older drivers also tend to drive more slowly, creating greater speed variation in the traffic flow. These and other diminished driving capabilities contribute to the increasing accident and crash involvement rates of the elderly, as depicted in figure 1-1.

Congestion and Changes in Highway Usage

Finally, changes in demographics, the number of vehicles, and user characteristics have created traffic patterns, problems, and congestion not originally envisioned by highway designers. Many highways constructed as links between communities have developed into industrial, commercial, or commuter corridors with higher demands and greater conflicting traffic patterns than anticipated. As development spreads and intensifies, more access points are required, thereby increasing the number of points of potential conflict. Development along the corridor also reduces the availability of adjacent land for highway improvements. So as demand increases along a stretch of highway, the means for meeting that demand are correspondingly restricted. Although the safety implications of traffic congestion are not yet well understood, highway agencies must consider how to decrease congestion without exacerbating safety problems.

Planning for the Future

Predicting Future Uses

An important factor in maintaining highway safety is the anticipation of future development and usage so that their implications for safety can be investigated. Each year, many projects are undertaken that focus only on the correction of existing operational and safety deficiencies or the extension of service life. While these are appropriate concerns, current efforts must consider how traffic density, user

characteristics, and other factors may affect safety. Project planners and engineers of current projects should use future traffic projections and local development plans and ordinances, as well as other resources, to estimate future traffic density and predict changes in the character of the facility (i.e., rural farm to market, suburban commercial, etc.). By understanding and designing for the future, agencies can avoid wasting time and money on improvements that soon will become inadequate or inappropriate.

Solutions through Technology

Technological developments may alleviate many current problems in highway and traffic management. Currently, several countries, including the United States, are developing automated highway systems. The systems envisioned for the future would electronically manage the vehicle within the traffic stream. The highway and the vehicle would interact, providing the driver with necessary navigational, regulatory, and warning information. Information systems, both in-vehicle and on-road, would warn the driver of impending hazards or unsafe vehicle operation.

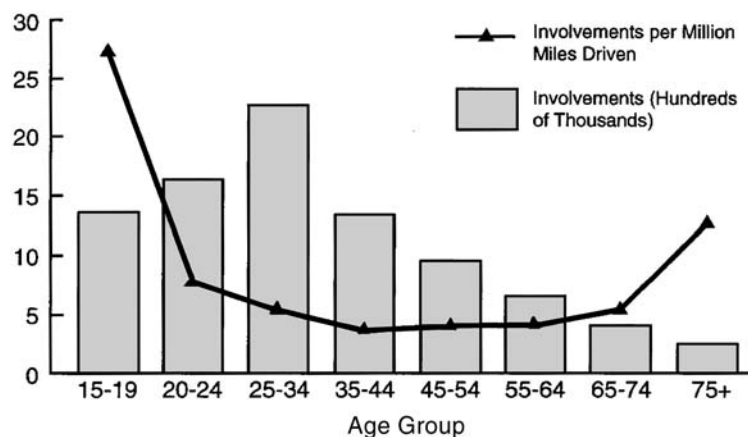


Figure 1-1. Driver involvement in traffic crashes and involvement rates by age.⁴

Purpose and Use of the Guide

Purpose

Over the past hundred years, the United States has constructed a comprehensive network of freeways, rural roads, and urban and suburban streets. Although some new highways will be built, the major emphasis will be on increasing the capacity of existing highways and extending their service life. When making changes to improve capacity or traffic operation, highway agencies also must consider the possible consequences for public safety. This guide identifies appropriate safety enhancements for consideration in nearly all other types of highway projects, particularly resurfacing, rehabilitation, and restoration (3R) projects. It also can also be used as a basis for field reviews during project planning, development, and evaluation. In this respect, the guide fulfills three purposes:

- It reemphasizes the need to incorporate current safety design standards and practices into all projects to the greatest extent possible.
- It introduces and consolidates new safety information.
- It suggests how existing situations might be upgraded to meet current standards and future needs.

Application

This guide presents good design and operational practices for numerous design elements and situations for all types of roads. The material included has been drawn from the results of research; from experiences, both bad and good, of highway jurisdictions; and from previously published documents. This document is not a stand-alone design guide. It should be considered a complement to the latest versions of existing AASHTO publications and national standards, including *A Policy*

on Geometric Design of Highways and Streets; the *Roadside Design Guide*; *Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals*; and the *Manual on Uniform Traffic Control Devices for Streets and Highways*.^(7,8,9,10) These documents, plus the jurisdiction's policies, should be the initial source for guidance in design and operations. Throughout the document, other references that should be used for additional guidance are cited. Also, each highway agency should carefully examine how the recommendations of this report apply to specific situations.

As noted in the 1974 edition of *Highway Design and Operational Practices Related to Highway Safety*,⁵ it is neither practical nor possible to immediately implement all the recommendations in this book on every U.S. road and street. The concepts should be applied to those projects under design that can be reevaluated and modified as necessary without unreasonable rework or redesign. Existing highway systems should be examined and prioritized for upgrading in a routine, organized fashion. With existing and foreseeable funding limitations, the improvement of the entire highway system to the safety levels promoted in this guide necessarily will be a long-range program.

Organization

This book is divided into six chapters. Chapter 2 covers the safety implications of various design concepts that, for the most part, apply to all classes of roads and streets. Chapters 3, 4, and 5 contain discussion of how these design elements and concepts specifically apply to freeways, rural highways, and urban and suburban highways, respectively. Chapter 6 is devoted to the role of maintenance and inspection in the preservation of highway safety standards.

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2 DESIGN CONCEPTS FOR SAFE HIGHWAYS

The level of safety provided to the roadway user depends to a large extent on the conscious consideration of safety from planning through final construction and operation. Although a single design exception for a highway feature may seem to have little effect on safety, the net effect of several such changes can be disastrous. Failure to consider safety consistently for each design component and for the interaction of design features can lead to problems that are not apparent until after a highway is open to traffic. Such safety problems must then be remedied at additional, unnecessary cost.

The highway designer needs to recognize how and when to take full advantage of the opportunities to design safety into the highway. The following general concepts for designing safe and efficient highways are presented to help the planner and designer identify possible problems and opportunities for safety enhancement.

Identifying Highway Safety Levels

Crash Statistics

Highway safety is usually indicated by crash statistics, which give the injury and fatality rates per 100 million vehicle-kilometers of travel. These statistics estimate the relative risk associated with traveling on a particular highway. Using these measurements, levels of safety vary by highway type and location, as table 2-1 shows.

Because of the design features and standards for Interstate highways, this system has the lowest injury and fatality rate

of all the functional types of highways. Interstate design features that promote safety include access control, divided roadways, and wide clear zones. Unfortunately, not all highways can be designed and constructed with these design features. Consequently, other highway types have higher injury and fatality rates.

But crash rates present just part of the picture. Alone, they cannot indicate where limited resources should be invested for optimum safety results. A low crash *rate* does not necessarily mean a low *number* of crashes. On the Interstate system, the average annual frequency of fatal crashes per 1,000 kilometers (km) of highway is about 62. The Interstate system only makes up about 1 percent of all roadways, yet it carries more than 25 percent of all highway travel, as measured in vehicle-kilometers. The pre-Intermodal Surface Transportation Efficiency Act (ISTEA) Federal-Aid Primary System, about

Table 2-1. Injury and fatal accident rates by highway type and rural or urban classification.¹

Highway Type Classification ^a	Fatal Accidents Per 100 Million Vehicle-Kilometers	Injury Accidents Per 100 Million Vehicle-Kilometers
URBAN:		
Interstate	0.34	24
Primary arterial	0.81	74
Other arterial	0.69	88
Collector	0.55	76
Local	1.04	120
RURAL:		
Interstate	0.63	13
Arterial	1.31	35
Collector	1.81	59
Local	2.26	109

^a Data from certain classes are grouped.

5 percent of all roads, experienced about 30 fatal crashes per 1,000 km. The non-Federal-aid local roads, which accounted for 68 percent of the 6.3 million km of roads in the United States, experienced about two fatal crashes per 1,000 km. The lower classes of roads may have higher injury and fatality rates per million vehicle-kilometers of travel, but because they carry smaller volumes of traffic than the Interstate and arterial systems, the crash rate per kilometer of road is relatively low. Investments in safety improvements, thus, must consider the crash rate, severity of accidents, and volume of traffic for particular highways.

Causes of Crashes

Many analyses of motor vehicle crashes have shown driver error as the primary contributing factor in about 85 percent of the crashes, leading many people to assume that there is little the highway engineer can do for safety. In fact, good highway design that incorporates safety features can reduce the potential for driver error and the consequences of vehicle failures. If a driver error does occur, a highway designed with a “forgiving roadside” can help prevent or lessen the severity of a crash.

Opportunities for Efficient Safety Enhancement

The current rehabilitation and reconstruction of many parts of the highway system offer opportunities to incorporate safety improvements efficiently. Designers should make a strong case for safety improvements; otherwise, agencies looking solely at their limited budgets might miss these cost-effective ways to improve safety. Any assessment of the cost of implementing safety improvements should also take into account any savings accrued from reducing risk.

Safety Management

Safety management is the total integration of highway safety concerns into the decision-making process for the planning,

design, construction, maintenance, and operation of highway projects, programs, and activities. Safety management begins with the planning/budgeting phase of program development when decisions on the type and scope of projects are made and follows through the life cycle of the highway system. Thus, highway safety management is a dynamic process in which information on factors such as traffic, crashes, usage, and operational data is maintained, updated, and used in the decision-making process.

In accordance with the Intermodal Surface Transportation Efficiency Act of 1991, agencies must establish a Safety Management System (SMS) to ensure that safety is routinely incorporated into all highway programs. The SMS should have goals and a process for the following:

- Coordinating and integrating broad-based safety programs (such as motor carrier-, corridor-, and community-based traffic safety activities) into a comprehensive management approach for highway safety
- Identifying and investigating dangerous or potentially dangerous highway safety problems, roadway locations, and features (including railroad-highway grade crossings) and establishing countermeasures and priorities to correct the identified problems or potential problems
- Ensuring early consideration of safety in all highway transportation programs and projects
- Identifying the safety needs of special user groups (such as older drivers, pedestrians, bicyclists, motorcyclists, commercial motor carriers, and hazardous material carriers) in the planning, design, construction, and operation of the highway system
- Routinely maintaining and upgrading safety hardware (including highway-rail crossing warning devices), highway elements, and operational features

The SMS should identify individuals, positions, and agency units with direct

responsibility for providing maintenance procedures for the timely notification and repair or replacement of damaged safety hardware, the periodic update of standard specifications and plans used to construct and maintain highway features, the analysis of crashes on proposed projects, and the consideration of safety concerns and inclusion of appropriate safety enhancements in the cost-estimating process.

Good highway safety management procedures also provide the basis for an agency's management of risk and protection from tort liability. Courts often recognize that agencies have limited resources and frequently render favorable judgments when it can be shown that these resources are used in a manner to maximize their effectiveness.

General Design Considerations

Desirable Versus Minimum Design Criteria

In planning and designing safe highways, the first basic decision is the type of highway needed and level of service required. The next critical decision is the selection of design criteria. For many design elements, there is a range from a minimum to a maximum level. Consistent adherence to only minimum values is not advisable. While higher standards may be more expensive initially, they may prove to be more cost-effective in the long term, especially when greater traffic demand and mix are expected in the future. Problems occur when additional needs are imposed on existing highways with built-in design and right-of-way limitations, especially for high-speed, high-volume highways where development along the corridor can result in additional access and traffic conflicts.

Minimum design criteria may not ensure adequate levels of safety in all situations. When applied to the combination of highway features, minimum criteria may not meet all the potential needs of the highway. For example, at an interchange exit, a minimum-length deceleration lane combined with a minimum-

radius loop ramp may cause operational and safety problems, especially for large trucks.

The challenge to the designer is to achieve the highest level of safety within the physical and financial constraints of a project. This challenge requires the designer to go beyond the minimum levels of design to find the desirable level for each project. Cost-effectiveness analyses are required to balance financial, physical, and safety concerns during the design process. In recent years, research in cost-effective analyses has attempted to delineate the essential relationships between safety and design elements and to identify the best procedures. Designers should be aware of the latest research results and incorporate them into their processes.

Human Factors

Driver error, in the form of human actions or inactions, is the most often cited contributing factor in motor vehicle crashes. An understanding of human factors—driver, bicyclist, and pedestrian characteristics, abilities, performance, and limitations—is essential for good highway design, traffic operations, and safety. This understanding enables highway engineers to develop designs, information displays, and operational procedures that do not contribute to driver error. It enables them to accommodate a diverse and aging population and to develop systems that match user characteristics with systems requirements.

Factors Influencing Driver Error. Driver error can occur for many reasons: the abilities and disabilities of individual drivers, bicyclists, and pedestrians; the highway's design and operational deficiencies; and a combination of factors leading to overload of the driving task. Mitigation measures, such as eliminating known sources of driver error and enhancing driver information displays, can improve operation and safety. However, choosing the appropriate mitigation measure requires an understanding of the driving task, which can be broken into three broad levels: control,

guidance, and navigation. Increasing information-handling complexity and safety importance from control to guidance to navigation must be considered during the various design stages.

The key to successful driving is efficient gathering and processing of visual information. Drivers often have to perform multiple tasks within very short periods. Their need for information on all task levels must be met. The extent to which these information needs are met depends on the roadway design, the environment, and traffic control devices that provide the appropriate information at the right time and place. Planners, designers, and operators should determine what information the driver needs, where it should be located, and the appropriate format for conveying it. The goal should be to minimize confusing situations that could lead to driver error.

Positive Guidance. It is important to understand that the highway itself conveys information to the driver. “Positive Guidance” is a procedure for identifying information system deficiencies and providing suitable, expected information when needed, where required, and in a

form best suited for its intended purpose. The premise of Positive Guidance is that competent drivers, bicyclists, and pedestrians on properly designed roads with appropriate traffic control devices can avoid errors. Conversely, if designs are incompatible with driver capabilities, if the information displays are ambiguous or erroneous, or if expectations are violated, then drivers will commit errors.² For example, figure 2-1 shows a tangential intersection on a curve. The road actually curves left, but the design communicates information that may mislead the driver into thinking the road goes straight. Similar situations occur even on freeways, where exit ramps follow the tangent line while through lanes curve.

The Positive Guidance procedure is one tool that engineers can use to diagnose problems specific to a particular site and to develop safety and operational improvements. It combines the methods and procedures of highway and traffic engineering with an understanding of human factors to produce a highway information system matched to road-user attributes and situation demands. Although Positive Guidance applies to a



Figure 2-1. A highway condition that can confuse drivers.

range of problems, its primary application is in the development of low-cost, high-payoff, spot, and short-segment information system improvements.

The Elderly. As the U.S. population ages, transportation planners and designers increasingly must take into account the special needs of the elderly. Most older drivers retain their licenses and drive daily. Many experience reduced information-processing capabilities and some degree of visual and hearing impairment that worsens with age. Common problems include poor night vision and glare recovery, decreased visual acuity, hearing loss, increased reaction time, loss of short-term memory, and poor attention span. Older motorists compensate for some of these problems by driving slowly, avoiding stressful situations, and relying on experience. However, they have a higher-than-average crash rate and require special measures to aid their safety and mobility. Specific highway design or operational measures to address the needs of the elderly could include more frequent application of decision sight distance at complex situations; greater use of large, bright, easily understood single-message signs and traffic control devices; and use of advance, redundant sign and marking messages for special situations. Increased and wider pavement markings and larger lettering on signs also have proved especially helpful to older drivers.

Design Consistency

In the 1974 Yellow Book, design inconsistencies in the highway environment were briefly discussed. Since that time, the concept of design consistency has evolved. Highway design consistency is defined as “the avoidance of abrupt changes in geometric features for contiguous highway elements and the use of design elements in combinations that meet driver expectations.” Consistent highway design is extremely important to the driver because experienced drivers have subconsciously learned what to expect under certain conditions and how to react. Inconsistencies in the design of such features as highway

alignment; intersection layout; signal phasing and operation, location of access points, clear zones, and passing zones; and selection and location of operational features (such as signs) can violate driver expectations and contribute to indecision or error. For example, in the case of a long series of sharp curves that are consistent in characteristics and unbroken by long tangent sections, the alignment acts as a control on the driver's speed and results in operating speeds consistent with the character of the highway. However, curves or features that are substandard or substantially different can be problems because they tend to violate expectations.

Recognizing that inconsistencies in some design elements are present in nearly all highway designs, the designer's challenge is to minimize inconsistencies while ensuring that those that are inevitable do not render highway operation disruptive or unsafe. In general, design consistency is best achieved by selecting design criteria for all critical elements on a system rather than individual location basis.

Specific Design Elements

Design Speed

Identifying the appropriate design speed is one of the initial steps in planning and developing any highway project. Its selection is critical because almost all roadway and roadside design and operational criteria associated with a project are influenced by design speed. For new construction projects or reconstruction, rehabilitation, and resurfacing (3R) projects, the design speed should satisfy drivers' expectation for the type and character of the highway. Also, for 3R projects, design speed should reflect actual operating speeds, not necessarily the legal speed limit. Drivers are more apt to accept a lower speed limit where a difficult condition is obvious than where there is no apparent reason for it. In most cases, drivers adjust their speeds to physical limitations and traffic. Of course, there may be exceptions where it

is impractical to provide geometric and roadside design for the selected design speed. For these situations, a method should be devised to warn drivers of the condition, such as using curve-warning signs with speed advisory plates in advance of extremely sharp horizontal curves.

In designing a substantial length of highway, it is desirable to assume a constant design speed. Changes in terrain and other physical controls may dictate a change in design speed on certain sections within the project limits and at the terminal points. Where this occurs, transitional designs, such as long tapering of reduced pavement or shoulder width, should be used, and traffic control devices should be employed, following Positive Guidance principles, to change the drivers' operating speed.

Horizontal and Vertical Alignments

Providing optimum design criteria for vertical curvature allows for an aesthetically pleasing and comfortable ride. More important to safety, it affords long sight distances for the driver to view the road ahead. However, it may not be practical to satisfy the criteria for all vertical curves. Individual locations should be analyzed to ensure that there are no existing or potentially hazardous conditions nearby. When minimal or substandard horizontal curves must be used or left in place, as for a 3R project, designers should consider increasing superelevation or using wider, more traversable clear zones for these curves to mitigate their impact. The selected super-elevation should be consistent with the physical constraints of the location and appropriate for ice or snow where applicable.

While stopping sight distances are usually sufficient in developing horizontal and vertical alignment, decision sight distance criteria should be considered in freeway design, especially for complex and unexpected features. Drivers need the decision sight distances prescribed in AASHTO's *A Policy on Geometric Design of Highways and Streets*³ whenever there is a

likelihood for error in information reception, decision making, or control actions. Complex interchanges, left-side exit interchanges, changes in cross-section, lane drops, and toll plazas are examples of critical locations frequently found on freeways where these kinds of errors are likely to occur and where it is desirable to provide decision sight distance.

Flat grades combined with minimum cross slopes and long-radius curves tend to make water take excessively long drainage routes to reach the edge of the traveled way. This is noticeable in the areas between a full-crown section and the superelevated section for a flat curve and results in an extra-thick water film, even in a light rain, which increases the potential for hydroplaning.

Access Management

Access control is one of the most significant factors in the safe, efficient operation of a highway. The benefits of full access control were demonstrated in *Interstate System Accident Research Study*.⁴ This study found that crash, injury, and fatality rates on Interstate highways were 30 to 70 percent lower than rates on conventional highways that existed before the Interstate system.

On nonfreeway highways where full access control is not possible, access management, particularly at intersections, is often essential for safe and efficient operation. Access management is the practice of controlling access from adjacent property by managing the location, number, spacing, and design of access points, median openings, and traffic signals on the highway system. Access management is essential to enhance safety and improve operations of high-volume systems where traffic conflict points exist or are anticipated.

Pavements

A good pavement must withstand the effects of weather, be smooth riding, not cause excessive tire wear and noise, be structurally sound, resist wear and polishing, drain well, and provide good skid

resistance. The degree to which these attributes are achieved affects highway safety. The skid-resistant characteristics of the pavement are particularly significant.

The interaction of the pavement surface and a vehicle's tires is critical to controlling and stopping the vehicle. The contact area of a typical passenger vehicle tire is only about the size of a human hand. The total contact area of the vehicle with the pavement is therefore very small. Almost any dry pavement provides adequate friction for safe traffic movement; however, when pavements have poor skid characteristics, as little as 0.02 millimeters (mm) of water on the pavement can reduce the tire/pavement friction by as much as 75 percent.⁵ This level of water can easily occur with only 0.2 mm of rainfall in an hour. Consequently, pavements must be designed and maintained to provide for the flow of water off the surface and ensure that an adequate friction surface is maintained throughout the life of the pavement.

Roadsides

About 60 percent of all fatal crashes each year involve a single vehicle; for crashes in rural areas, the proportion is even higher. Seventy percent of these crashes involve vehicles that leave the traveled way and either overturn or collide with a fixed object. The reasons for leaving the roadway are varied; most are unintentional or based on driver errors, such as excessive speed, falling asleep, fatigue, inattention, reckless behavior, diminished skills because of alcohol or drugs, or combinations of these. Some departures from the traveled way are intentional, for example, to avoid an errant vehicle or a fixed object dropped on the roadway. Whatever the reason, the driver who leaves the roadway frequently embarks on a potentially hazardous journey.

The concept of a forgiving roadside, including an adequate recovery area or "clear zone," arose in the late 1960s. The concept has been treated and expanded on in a succession of AASHTO docu-

ments, the most current and definitive of which is the *Roadside Design Guide*, which succeeded and replaced the *Guide for Selecting, Locating and Designing Traffic Barriers*.^{6,7} However, rapidly accumulating knowledge derived from research—especially in the area of crash testing—under the auspices of the National Cooperative Highway Research Program, FHWA, and others is stimulating work that will eventually lead to an updated roadside design guide.

The concept of clear zone—that is, an area adjacent to the traveled way in which slope, surface, and an absence of fixed obstacles can permit recovery of an errant vehicle—is important to providing a safer roadside. Initial guidance related to this concept in the 1974 *Highway Design and Operational Practices Related to Highway Safety* called for a 9-meter (m) clear zone measured from the edge of the travel lane. Later experience has led to considerable refinement of this initial guidance, with a variable clear zone depending on design speed, average daily traffic volume, and, particularly important, roadway geometry elements, which include the presence and degree of horizontal curvature, location in a fill or cut section, amount of parallel slope, presence or absence of cross slopes from approaching roadways or driveways, and steepness of these slopes.

Ideally, the clear zone should feature side slopes that will not cause vehicles to overturn and do not contain any fixed objects. While a 1:3 slope is technically traversable by a passenger vehicle, it is of marginal safety value.⁶ Errant drivers trying to recover control of their vehicles often cannot successfully steer or brake on a 1:3 slope. Slopes of 1:3 become potentially dangerous when other features, such as breakaway devices, trees, or erosion ditches, are located on or adjacent to the slope. In fill sections, providing a slope at least 1:4 or flatter within the clear zone limits, or beyond if possible, is a typical feature of recent designs. Repositioning fixed roadside hardware to less vulnerable areas outside the clear zone is preferred. Where this is not possible, using break-

away designs for such hardware can provide the needed roadside forgiveness. Fixed objects not susceptible to these treatments should be shielded by properly designed and installed traffic barriers or energy-absorbing crash cushions. Obstacles that cannot be treated in any of these ways should be positively delineated through one or more approved techniques to alert motorists.

For all types of highway projects, the clear zone locations should be determined or identified and forgiving roadsides established. Programs should also be undertaken to ensure that established clear zones are maintained throughout the life of the highway. It is equally important to understand that a vehicle can easily go beyond the clear zone and, whenever practical, agencies should continue to implement the concepts of the forgiving roadside beyond the clear zone. Many of the common safety treatments available today, such as crashworthy sign supports and traversable inlet grates, cost the same as their noncrashworthy counterparts. The term “crashworthy” is used here to mean that a device has been successfully crash-tested in accordance with nationally accepted procedures.

Trucks

Many existing highway design and operational standards are based on passenger car characteristics when truck characteristics may be more critical. Consequently, there is a need to reexamine current highway design and operational criteria to ensure that they consider the characteristics of all current and future users.

Research has established several highway design and operational criteria that are sensitive to truck performance characteristics. They include stopping sight distance, intersection and channelization geometrics, pavement widening on horizontal curves, vertical gradient, and warning sign placement. Changes to several standards are required, but it will take some time before policy changes can be achieved relative to design standards.

To accommodate large trucks more safely, it is important to consider their performance characteristics when designing highways expected to have significant large-truck traffic and to use current available information. The FHWA report entitled *Truck Characteristics for Use in Highway Design and Operation* is recommended.⁸

Pedestrians and Bicyclists

Pedestrians and bicyclists are an increasing portion of the everyday highway population, and attention must be paid to their presence in rural as well as urban areas. All highways other than controlled access highways should be planned, built, operated, and maintained considering the use and needs of pedestrians and bicyclists. It is often difficult to accommodate pedestrians and bicyclists safely in urban areas, particularly when the effort is made as an afterthought rather than during the planning and design of a project. In both urban and rural areas, planners must consider the evolution of the area. Planners and designers should develop projects that will satisfy the future needs of pedestrians and bicyclists. The additional right-of-way required to accommodate pedestrians and bicycles should be identified and acquired whenever practical. Designers should provide features such as sidewalks, crosswalks, pedestrian islands, pedestrian signal heads and detectors, bicycle lanes, multipurpose trails or walkways, and curb cuts and ramps for persons with disabilities.

Pedestrians and bicyclists include persons of all ages and abilities. Their actions are less predictable than those of motorists. No special schooling or licensing is required to walk or to ride a bike, and enforcement of traffic laws pertaining to pedestrians and bicyclists is, at best, lax. Engineers must be sensitive to this situation and to the fact that roadways are designed more for motorists than for other users. Designing with pedestrian and bicyclist needs in mind makes it easier to accommodate all user groups.



Adverse Environmental Conditions

Adverse environmental conditions such as rain, fog, snow, ice, and blowing dust are temporary conditions that increase driving risks. Research has shown that approximately 14 percent of fatal crashes and 20 percent of all crashes occur on wet pavements. Crashes in snow and fog are much less frequent but still represent a significant problem. Fatal crashes during snow-fall occurred 736 times in 1995. Sleet, fog, and other poor weather conditions accounted for an additional 812 fatal crashes in 1995.⁹ The National Transportation Safety Board (NTSB) studied the Fatal Accident Reporting System data for 1981 through 1989 and found that about 500 to 800 fog-related fatalities occur on U.S. highways each year.¹⁰ The distribution of these crashes is almost equal between daylight and dark conditions. Considering that traffic decreases at night, especially after 10 P.M., this statistic indicates that a much more dangerous situation exists at night in adverse weather.

Rain, fog, snow, ice, and blowing dust or sand have some characteristics in common but many others that are fundamentally different. Each condition reduces visibility. Each condition is a recurring event in certain parts of the country; therefore, precautions should be taken even though it is impossible to predict precisely when and where an event will occur. Each highway agency needs to evaluate how to react to such events and formulate a procedure to follow. Just as important, the probability of such events and preventive measures should be evaluated during the planning and design stages of a highway project.

Traffic Management

Traffic management strategies include human, institutional, regulatory, hardware, and software components designed to eliminate the onset of traffic congestion or reduce the duration of congestion when it does occur. Specific strategies include surveillance, control, motorist

information systems, incident management, and spot capacity improvements to relieve geometric and operational bottlenecks. Although often thought of only in terms of congestion mitigation, traffic management strategies also have significant safety benefits.

Ramp metering systems, for example, have consistently been credited with reducing merge-related crashes by 30 to 50 percent on urban freeways during peak-travel periods. In fact, several highway agencies use higher-than-average crash rates at on-ramp merge areas to warrant the installation of metering. Incident management programs reduce the duration of incidents and thus the length and duration of the resultant congestion, reducing the potential for secondary crashes. Service patrols and other incident detection systems can help locate and remove disabled motorists, which reduces the potential for pedestrian crashes. Motorist information systems can help notify motorists already on the highways and motorists about to enter the highways of congestion and other unusual occurrences, thus minimizing secondary crashes.

While many of the crash reduction and other safety benefits of traffic management strategies have not been fully quantified, there is no question that the benefits do exist. Traffic management strategies can be applied on any type of highway system and are particularly appropriate for freeways, where speeds and traffic volumes are the greatest.

Transportation Systems Management

Because comprehensive design requires considering all modes of travel, transportation engineers, in their safety analysis, should consider automobiles, pedestrians, bicycles, and public transit vehicles to improve safe interaction among these modes of travel. To do so effectively requires a systems approach to safety.

To maximize safety in the system, the number of conflict points should be minimized by limiting access, designating



bicycle and pedestrian routes, and reducing the number of at-grade rail-highway crossings. All of these factors need to be considered in the design phase, the most desirable time to address problems.

Conflict between the modes of transportation is inevitable. Designing for conflict points should include consideration of human factors, consistency, operator or pedestrian expectations, design speed, sight distance, adequate warning, and signing. Aside from proper design, problems with facilities may be ameliorated through public education, signing, and pavement markings. Examples include educating the public on correct bicycle operation, placing illuminated pedestrian signs above the roadway, and using pavement markings to prevent wrong-way movements.

Intelligent Transportation Systems

New technology offers many opportunities for improving highway safety in the future. In particular, Intelligent Transportation Systems (ITSs) are quickly moving from concept to reality in many areas of application. While original interest and applications have been in rapidly removing inci-

dents and improving driver route guidance and systems use information, its largest payoff may be in providing a higher safety level. An evaluation of the Chicago Area Expressway Surveillance and Control system, a first-generation smart highway system, showed an 18-percent reduction in peak-period crashes. Experts are predicting substantial reductions in crashes, injuries, and fatalities with the adoption of advanced technologies.¹¹

Whereas many safety measures developed over the years have been aimed at lessening the consequences of crashes, many ITS functions are directed toward preventing crashes. Technologies that involve sensing potential problems and vehicle-to-vehicle communications will initially be designed to warn the driver automatically, providing enough lead time for evasive actions. The technologies may also assume some control functions that are now totally the responsibility of drivers, thereby compensating for some of their limitations and allowing vehicles to operate safely closer together. As new ITS technologies become available, agencies should look for opportunities to incorporate those that are most cost-effective for their roadway systems.

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3 FREEWAYS

Freeways, especially those built to Interstate standards, are the safest of the various classes of highways. While control of access, which limits vehicle conflicts, is a primary factor in relatively low accident, injury, and fatality rates, other design features, such as wide medians and shoulders, roadsides clear of obstructions, and the extensive use of protective barriers, are key factors as well. The higher design speeds used for freeways result in long sight distances due to long radius horizontal curves and long vertical curves, and other desirable design features that create a safe driving environment. Although most of the nation's freeways enjoy this relatively high level of design and safety, there are many opportunities for further enhancements. Safety improvements on freeways can also result in substantial savings in life and property because freeways carry 25 percent of the nation's total traffic.

This chapter provides safety information that should be considered in the planning, design, and rehabilitation of freeways. Included is information from the 1974 edition of the *Highway Design and Operational Practices Related to Highway Safety*, which still applies, as well as new information from research and field practice.¹ Like all guidance provided in this document, these principles should be considered supplemental information to current design and operation standards.

Roadway Design Features

Design criteria for freeways are established in AASHTO policy publications *A Policy on Design Standards—Interstate System* and *A Policy on Geometric Design of Highways*

and *Streets* for non-Interstate freeways.^{2,3} These criteria apply to new construction, reconstruction, and to resurfacing, restoration, and rehabilitation (3R) projects. Although chapter 2 provides information about basic safety concepts for all types of roads, this chapter focuses on the particular application of these concepts to freeway design and operation.

Design Speed

For the reasons noted in chapter 2, selecting the design speed for a freeway is an important safety element because most geometric criteria are related to or depend on it. In general, 110 kilometers per hour (km/h) should be the design speed for the mainline of a freeway, but it may need to be lower in areas of severe terrain or heavy development. For reconstruction and 3R projects, the design speed should not be less than the original design speed or the current legal speed limit of that highway section.

Design speeds for interchange ramps depend on the type of ramp selected, for example, loop, diamond, or direct, and the low-volume running speed of the intersecting highway. Usually, the design speed is established by the most restrictive element of the ramp, typically the sharpest curve. Whatever design speed is selected, adequate transitions from the freeway proper and at the ramp terminal or merge point should be developed. Interchange features are discussed later in this chapter.

Lane and Shoulder Width

Safe and efficient traffic operations depend on adequate lane and shoulder widths as outlined in *A Policy on Geometric Design of*

Highways and Streets.³ The need to accommodate more traffic within existing or limited additional right-of-way on high-volume urban freeways has led some agencies to increase capacity by exchanging full-lane or shoulder widths for additional travel lanes with reduced widths. Any proposed use of less-than-full-standard cross-sections must be analyzed carefully on a site-by-site basis. Experience indicates that 3.3-m lanes can operate safely if there are no other less-than-standard features; however, combined with shoulder-width reductions, substandard sight distance, and other features, 3.3-m lanes may not provide the same safe operation. Converting shoulders to travel lanes for additional capacity through a short bottleneck section has been shown to significantly reduce congestion-related accidents on some projects. Removing shoulders for several kilometers, however, has not had the same result.

Generally, experience indicates that, where shoulders are converted to a travel lane, removing the left-side shoulder is preferable to removing the right-side shoulder. Motorists clearly prefer to stop on the right side, and enforcement and maintenance personnel have expressed a strong preference for the right-side shoulder. Where a highway with a narrow median and median barrier is being considered for using the median shoulder for a travel lane, curves should be checked for adequate stopping sight distance. Comprehensive incident detection and response systems should be considered for sections with substandard lane and shoulder widths. Extensive mitigating measures must be considered if both shoulders are removed. Mitigating measures include adequate advisory and regulatory signing, constructing frequent emergency pullouts, active overhead and side-mounted changeable message signs and signals (for part-time travel lane or shoulder use), continuous lighting, truck lane-use restrictions, dedicated service patrols and other enhanced incident management

measures, and continuous evaluation and monitoring to ensure that unforeseen problems are identified and corrected rapidly.

When adequate right shoulders cannot be provided along a significant section (approximately 1.5 kilometers or more) of a freeway, appropriately spaced, adequately signed emergency pullouts should be considered where feasible. When adequate shoulders are not available or cannot be economically furnished during a reconstruction project, pullouts are also appropriate for long viaduct-type structures. Figure 3-1 illustrates a typical emergency pullout for a long bridge. The pullout should be of sufficient length and width to accommodate large trucks and should be safely terminated, such as with crash cushions, to prevent serious injury to errant motorists.

Pavement Markings and Markers

Pavement markings, such as lane lines, edge lines, channelizing lines at interchanges and ramps, and word and symbol markings, provide important information to the driver. Pavement markings define separate lanes of traffic traveling in the same direction, inform drivers of lane restrictions, and convey certain regulations and warnings that would not otherwise be clearly understood. Pavement markings are particularly important at night and during inclement weather and, therefore, must be retroreflective. While well-maintained painted pavement markings are acceptable, thicker, long-life markings, such as thermoplastic or pre-formed tapes, may perform better in wet weather and heavy traffic. Some studies have been made regarding the benefits of wider edge line markings (150 to 200 mm versus the standard 100 mm width). The wider markings may particularly benefit older drivers.

Raised or recessed retroreflective pavement markers significantly enhance all types of standard markings, especially

during heavy rain at night when standard markings are not readily visible. Hence, they are recommended for use on free-ways whenever cost-justified. Raised markers are placed on the pavement surface, and recessed markers are placed in shallow ground-out troughs. (See figure 3-2.) Both markers have good records of retaining their retroreflectivity. The recessed markers are becoming more prevalent in states where only light snowfalls are expected, while the armored, raised pavement markers are used in states with heavy snowfalls. Cost-benefit studies by several states indicate a favorable benefit-to-cost ratio, even for the more expensive snowplow-resistant markers.

Delineation

Post-mounted delineators—retroreflective buttons or sheeting placed at the tops of posts erected in series near the roadway edge—are effective for defining the roadway alignment at night. The *Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD)* provides standards for their use on expressway and freeway roadways.⁴

A common practice in several states is to supplement the roadside delineation with delineators placed on the sides or tops of roadside and median barriers. (See figure 3-3.) These supplemental delineators, commonly placed at 15- to 30-m intervals, depending on the alignment, provide the driver with information on both the roadway alignment and the presence of barriers.

Delineators should not be used as the primary device to warn drivers of obstacles such as barrier terminals, utility poles, sign supports, rock outcroppings, culvert structures, and other fixed objects, or to restrict vehicle entry into an area. There are other appropriate devices for these situations as identified in the *MUTCD*.⁴

Signing

Sign Messages. It has been estimated that 8 billion hours of excess travel occur each year because of navigational errors that are partly due to inadequate signing, amounting to an average of 34 hours per year for every person in the United States.⁵ Appropriate highway information systems are needed to ensure that motorists have adequate time to acquire and process the information for control, guidance, and navigation. On the other hand, the lack of signs or misleading signs can contribute to driver confusion, loss of attention, and erratic maneuvers.



Figure 3-1. Illustration of an emergency pullout.

Signing for freeways should be planned concurrently with the geometric design. Trying to sign after interchange geometrics and spacings have been finalized has often resulted in poor signing design and operational problems. However, poor freeway design cannot be overcome by signing. Freeway signing should be consistent, easy to read, and unambiguous for the benefit and direction of drivers who are unfamiliar with the highway. In rural areas, the tendency to group all signing near the interchange should be avoided. Signs should be adequately spread on the approach to and departure from each interchange. They should be placed at natural target loca-

tions to command the driver's attention, especially where there are long distances between interchanges and the alignment is relatively constant.

In areas with relatively close interchange spacing, the principle of sign spreading should be followed. Sign spreading helps disperse information so that motorists are not overloaded with a group of signs near the gore where path direction decisions are finalized. Figure 3-4 shows an example of the sign-spreading concept; more details are provided in the *MUTCD*.⁴ Information on supplemental guide signs is contained in *Guidelines for the Selection of Supplemental Guide Signs for Traffic Generators Adjacent to Freeways*.⁶ Using larger-than-standard letters can also help all drivers, particularly older drivers, in high-demand situations.⁷

Where interchanges are so close together that major guide signs cannot be adequately spaced, they may be supplemented with interchange-sequence-series signs that identify the next two or three interchanges. If the interchange spacing is less than 250 m, then the series signs should be used in lieu of advance guide signs. When the series signs are used, it is preferable to use them over the entire length of the freeway or expressway within that urban area.

Advance signing for exits should be uniform. Freeway-to-freeway splits, tangential freeway exits, and interchanges with lane drops deserve special consideration. The *MUTCD*⁴ presents additional guidelines to sign these situations. Operational problems have occurred at freeway-to-freeway splits that feature a multilane exit and a second-route-choice decision point on the exit ramp. Typically, there is no advance sign for the second decision point due to spacing limitations. Consequently, the signs normally mounted over the second decision point are the first signs the driver sees indicating the appropriate lane for each direction on the destination freeway. Advance lane assignment is a signing concept that specifies the appropriate lanes for each



Figure 3-2. Two types of marker systems for use in snow areas.

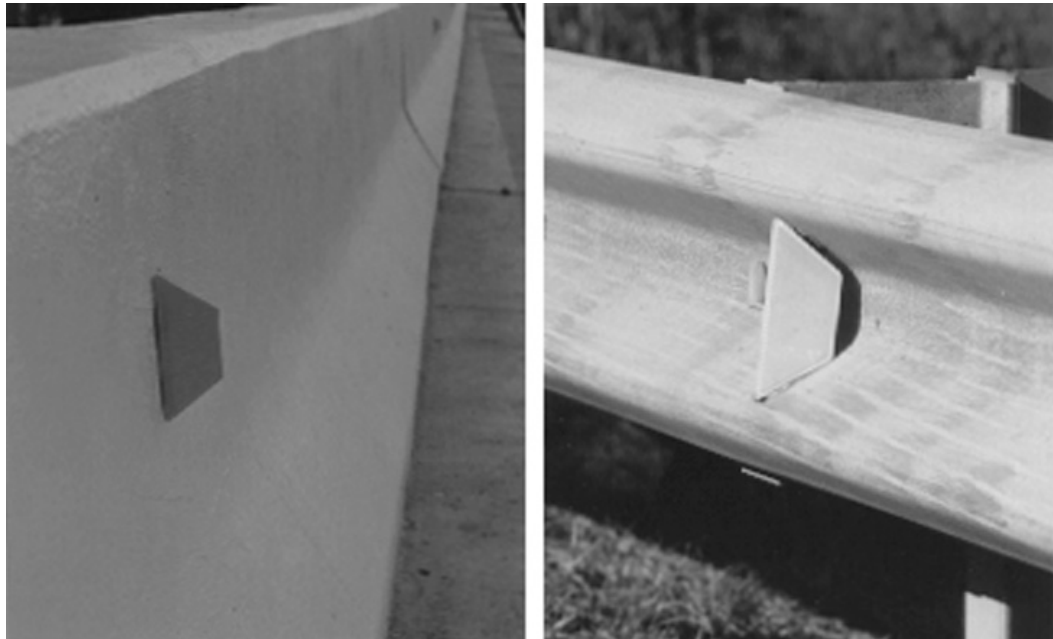


Figure 3-3. Delineators used with a guardrail and barrier.

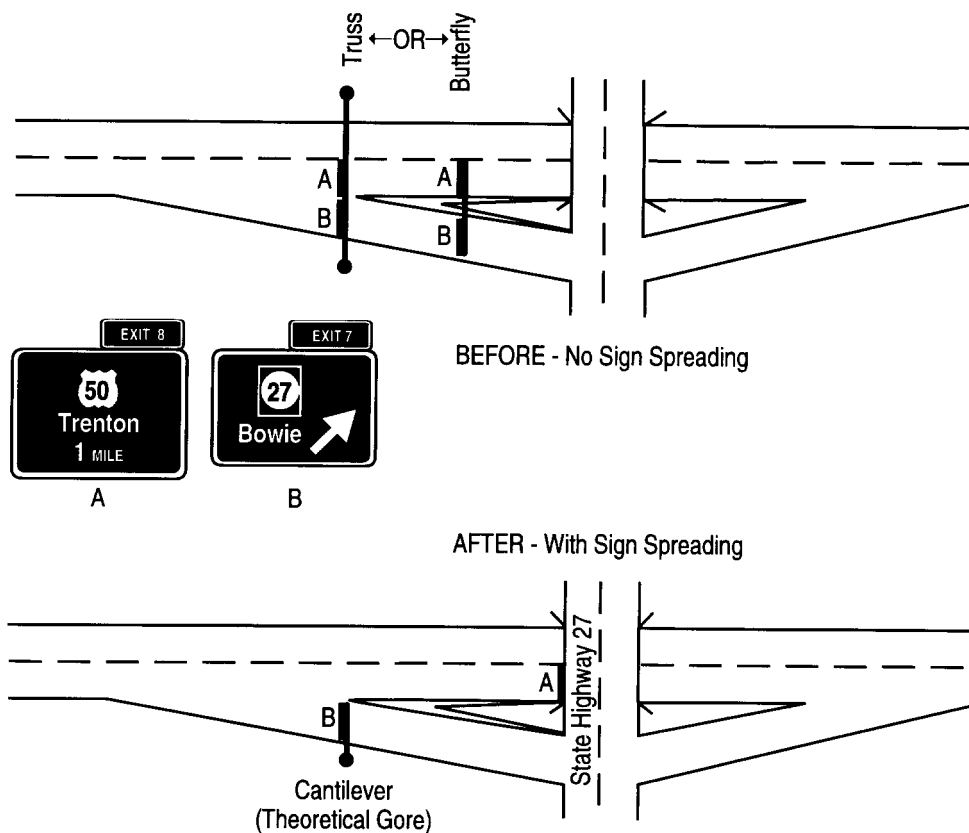


Figure 3-4. Sign spreading.⁴

direction on the intersecting freeway well before the decision point. Figure 3-5 illustrates the concept of advance lane assignment.

Sign Support Systems. Because sign supports are roadside obstacles, a safe sign support is one that either yields when a vehicle impacts it or is shielded by a crash

cushion or barrier. Even though a sign support is an approved breakaway design, it should be located where it is least likely to be struck by an errant vehicle. Large slip-base designs may not always release quickly enough in side impacts, and smaller base-bending supports may contribute to vehicular instability following a

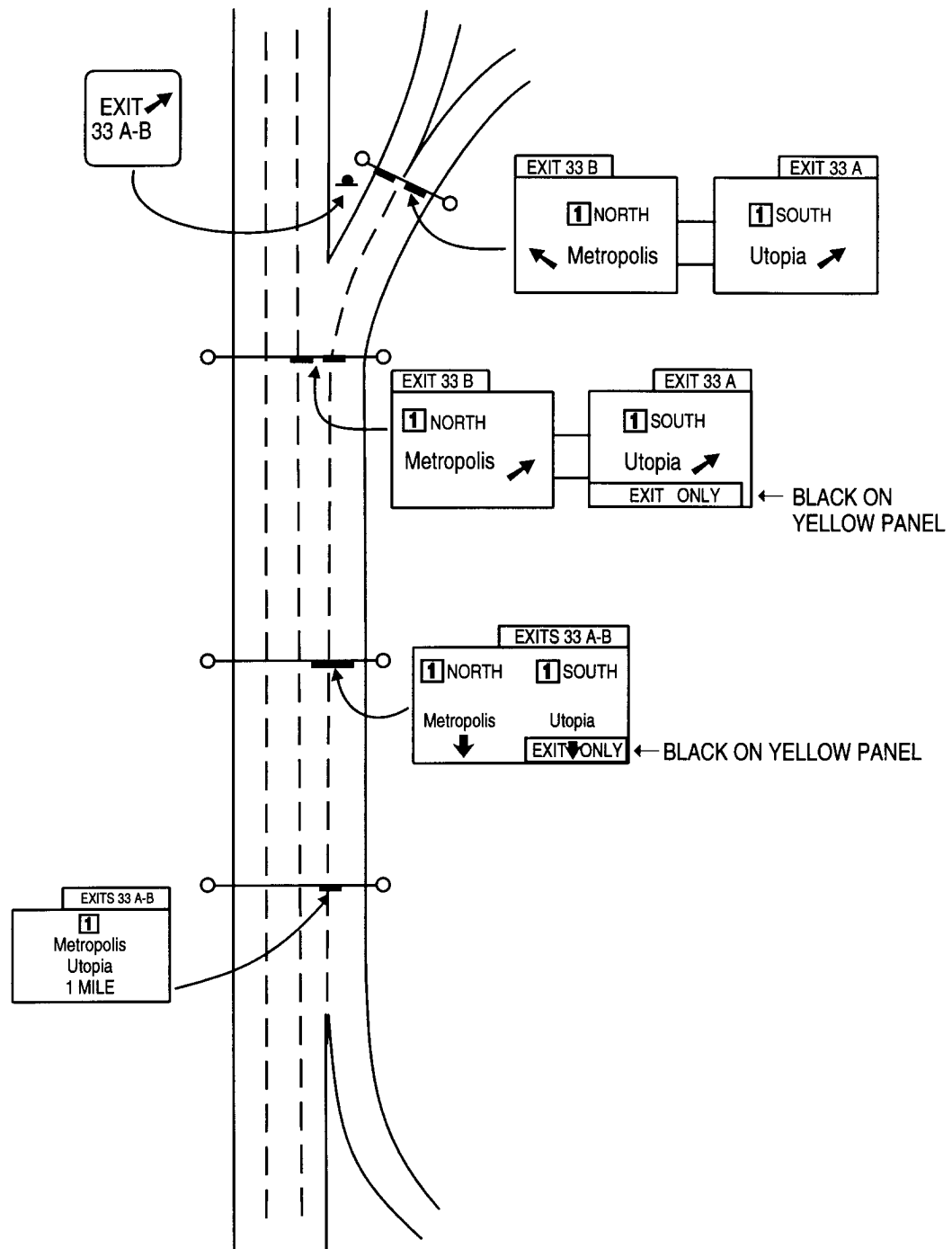


Figure 3-5. An application of the advance lane assignment signing concept.

crash. Existing recovery areas should not be cluttered with sign supports of any type if more prudent (i.e., less vulnerable) locations can be identified.

For freeways, certain signs should be in an overhead location where they are equally visible to all traffic and can be used efficiently to assign traffic to specific lanes. Because the supports for overhead signs are fixed-base and unyielding, they should be placed in protected locations to the maximum extent possible. For example, they may be located near other major features, such as bridges, culverts, or on high fills where guardrail shielding is normally provided. Butterfly-type signs and other overhead sign supports should not be erected in gores or other exposed locations.

Large roadside signs are usually supported by two or more metal sign supports. If not shielded adequately by a crash cushion or barrier, they should be designed as a breakaway system following current standards using breakaway slip bases and hinge mechanisms.⁸ For signs with two or more posts separated by 2.1 m or more, a hinged breakaway mechanism is used. A horizontal slip base is used with a hinge plate located just below the sign panel. On impact, the slip base is activated, causing rotation of the post about a hinge plate on the back of the post. This action allows the vehicle to pass under the sign panel, minimizing the damage to the vehicle and preventing injury to the occupants. Ordinarily, the hinge height above the breakaway base plate should be at least 2.1 m to allow vehicles to pass beneath the hinge point. For sites where a support is located outside the clear zone or where it is unlikely to be hit by a vehicle, a height of less than 2.1 m may be acceptable.

Lighting

For all roads, the nighttime fatality rate is approximately two to three times higher than the daytime rate. Roadway lighting, when used in appropriate locations, can be a cost-effective countermeasure to reduce nighttime accidents.

Nighttime traffic volumes and geometric complexity at specific sites significantly influence whether lighting will be a cost-effective safety improvement. Urban freeways with closely spaced interchanges and substantially developed adjacent areas are generally illuminated. The geometric and traffic complexities are such that drivers need to detect and react to conditions 150 to 350 m in front of them. Also, vehicle headlamps cannot be relied on to provide adequate lateral visibility on very wide roadways.

Because interchanges have the greatest probability for traffic conflict requiring quick driver decisions, lighting at high-density, complex freeway interchanges can be a useful tool with a high potential for accident reduction. Two types of interchange lighting systems are commonly used: complete and partial. Complete interchange lighting provides considerably better driver performance and traffic operations than partial. Partial interchange lighting is sometimes used on the premise that it provides some of the benefits attributable to complete interchange lighting at a lower operating cost. With partial interchange lighting, only the freeway gore area, any major change in ramp alignment, and the area where the ramp joins the crossroad are lighted. Using high-mast lighting techniques should be seriously considered to provide the driver with better orientation and guidance information, as well as improved visibility of the entire visual field.

The ability of the human eye to adjust its visual sensitivity (i.e., transient visual adaptation) is relatively slow as drivers move from areas with higher levels of luminance to those with lower levels. When there is such a change, higher levels of target contrast are required for target detection during the several seconds it takes for the eye to adjust to the new ambient level, a problem for older drivers especially. The number of such transitions should be used to a minimum. On urban freeways where a series of closely spaced interchanges would be lighted, continuous lighting should be used to provide a better



operating environment and to eliminate light-to-dark transitions.

On suburban freeways without lighting, a reduction in visual sensitivity due to transient adaptation effects can also result from light spillover from adjacent development. This ambient illumination is distracting to the driver, causes veiling glare, and reduces attention to freeway signs. In areas where the surrounding areas are brightly illuminated, freeway lighting or screening the view of the surrounding area should be considered.

In rural areas, lighting is sometimes deemed justified at interchanges, especially those with complex geometry or multiple merging traffic points. Energy availability and routine maintenance costs are important factors that influence the type of lighting system selected. Warrants to justify and design all types of lighting systems are contained in *An Informational Guide for Roadway Lighting* and in *American National Standard Practice for Roadway Lighting*.^{9,10}

Traffic Management

Freeways are designed to move large volumes of vehicles safely at high speeds. As traffic demand approaches and then exceeds capacity, however, freeways do not operate efficiently. For example, an eight-lane freeway operating at level-of-service F due to excessive demand serves only about the same number of vehicles in a given time period as a six-lane freeway operating at capacity. A six-lane freeway with the left lane blocked by an accident loses 50 percent of its capacity in the direction of travel with the lane blockage and up to 25 percent of its capacity in the other direction. When there is congestion, accidents increase, and the possibility of more severe accidents increases as high-speed traffic approaches stopped or slow-moving traffic. Traffic management strategies are designed to help maintain the operating efficiency and safety of a freeway by reducing the occurrence and duration of traffic congestion. Traffic management strategies can be classified several ways, but the three that are most appro-

priate for this guide are surveillance and control, motorist information, and incident management.

Surveillance and Control. The most common form of control used on freeways in the United States is ramp metering. Ramp meters are traffic signals on freeway entrance ramps that supply traffic to the freeway in a measured or regulated amount to break up platoons of vehicles released from nearby signalized intersections. The freeway mainline, even when operating near capacity, can accommodate merging vehicles one or two at a time. On the other hand, when groups of vehicles attempt to force their way into traffic, it creates turbulence that causes mainline flow to break down. Reduced turbulence in the merge zones decreases the number of sideswipe and rear-end-type accidents associated with stop-and-go, erratic traffic flow. Reductions of 20 to 50 percent in the number of merge-related accidents during the peak period have consistently been reported after metering is installed. Proper ramp design, advance warning, and other measures have been shown to reduce the potential for ramp accidents caused by a stopped queue.

Freeway control techniques also include overhead lane control, variable speed limits, and mainline metering. In theory, all are designed to provide advance warning and to reduce speed differential, thus reducing high-speed conflicts that result in accidents. In the United States, the use of these techniques has been limited, but in Europe, where they are more prevalent, the results have been positive. The key to the effectiveness of control strategies is the quantity and quality of real-time surveillance data. In time, technologies developed under the ITS program will make freeway control strategies even more feasible and effective due to broader, more reliable surveillance systems, better control algorithms (including predictive algorithms), and other advanced traffic management strategies.

Motorist Information. Motorist information systems, in the context of traffic management, are systems designed to advise