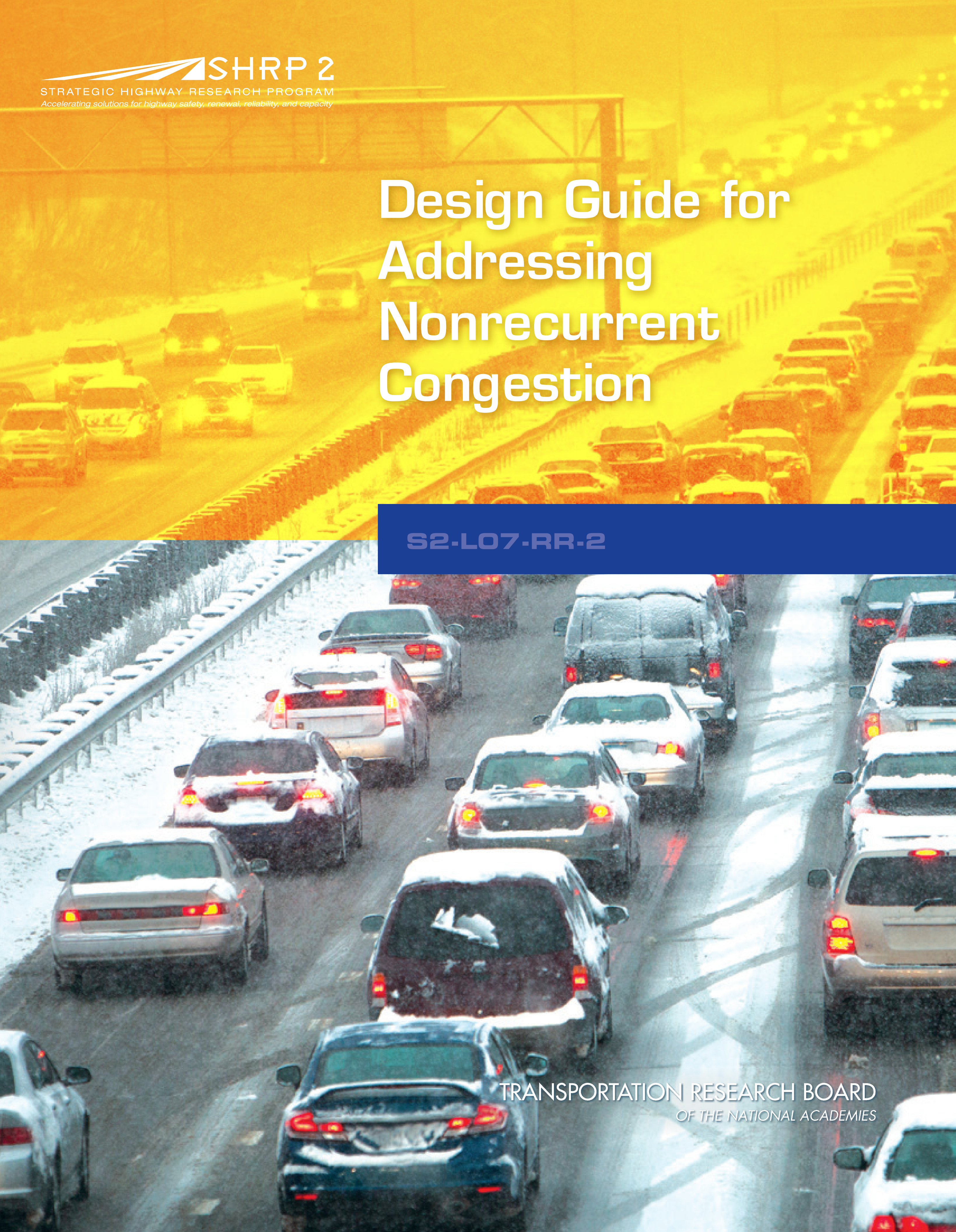
Design Guide for Addressing Nonrecurrent Congestion

DETAILS

158 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-27369-5 | DOI 10.17226/22475

AUTHORS

Potts, Ingrid B.; Harwood, Douglas W.; Hutton, Jessica M.; Fees, Chris A.; Bauer, Karin M.; and Lindsay M. Lucas



SHRP 2

STRATEGIC HIGHWAY RESEARCH PROGRAM

Accelerating solutions for highway safety, renewal, reliability, and capacity

Design Guide for Addressing Nonrecurrent Congestion

S2-L07-RR-2

TRANSPORTATION RESEARCH BOARD

OF THE NATIONAL ACADEMIES

TRANSPORTATION RESEARCH BOARD 2014 EXECUTIVE COMMITTEE*

THE SECOND STRATEGIC HIGHWAY RESEARCH PROGRAM

Design Guide for Addressing Nonrecurrent Congestion

SHRP 2 Report S2-L07-RR-2

Ingrid B. Potts, Douglas W. Harwood, Jessica M. Hutton,
Chris A. Fees, Karin M. Bauer, and Lindsay M. Lucas
MRIGlobal

Christopher Kinzel and Robert J. Frazier
HDR Engineering, Inc.

TRANSPORTATION RESEARCH BOARD

Washington, D.C.
2014
www.TRB.org

SUBSCRIBER CATEGORIES

Highways
Operations and Traffic Management
Planning and Forecasting

THE SECOND STRATEGIC HIGHWAY RESEARCH PROGRAM

America's highway system is critical to meeting the mobility and economic needs of local communities, regions, and the nation. Developments in research and technology—such as advanced materials, communications technology, new data collection technologies, and human factors science—offer a new opportunity to improve the safety and reliability of this important national resource. Breakthrough resolution of significant transportation problems, however, requires concentrated resources over a short time frame. Reflecting this need, the second Strategic Highway Research Program (SHRP 2) has an intense, large-scale focus, integrates multiple fields of research and technology, and is fundamentally different from the broad, mission-oriented, discipline-based research programs that have been the mainstay of the highway research industry for half a century.

The need for SHRP 2 was identified in *TRB Special Report 260: Strategic Highway Research: Saving Lives, Reducing Congestion, Improving Quality of Life*, published in 2001 and based on a study sponsored by Congress through the Transportation Equity Act for the 21st Century (TEA-21). SHRP 2, modeled after the first Strategic Highway Research Program, is a focused, time-constrained, management-driven program designed to complement existing highway research programs. SHRP 2 focuses on applied research in four areas: Safety, to prevent or reduce the severity of highway crashes by understanding driver behavior; Renewal, to address the aging infrastructure through rapid design and construction methods that cause minimal disruptions and produce lasting facilities; Reliability, to reduce congestion through incident reduction, management, response, and mitigation; and Capacity, to integrate mobility, economic, environmental, and community needs in the planning and designing of new transportation capacity.

SHRP 2 was authorized in August 2005 as part of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). The program is managed by the Transportation Research Board (TRB) on behalf of the National Research Council (NRC). SHRP 2 is conducted under a memorandum of understanding among the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), and the National Academy of Sciences, parent organization of TRB and NRC. The program provides for competitive, merit-based selection of research contractors; independent research project oversight; and dissemination of research results.

SHRP 2 Report S2-L07-RR-2
ISBN: 978-0-309-27369-5
Library of Congress Control Number: 2014946507

Note: SHRP 2 report numbers convey the program, focus area, project number, and publication format. Report numbers ending in "w" are published as web documents only.

NOTICE

The project that is the subject of this report was a part of the second Strategic Highway Research Program, conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical committee and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

The opinions and conclusions expressed or implied in this report are those of the researchers who performed the research and are not necessarily those of the Transportation Research Board, the National Research Council, or the program sponsors.

The Transportation Research Board of the National Academies, the National Research Council, and the sponsors of the second Strategic 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 the report.

SHRP 2 REPORTS

Available by subscription and through the TRB online bookstore: www.TRB.org/bookstore

Contact the TRB Business Office: 202.334.3213

More information about SHRP 2: www.TRB.org/SHRP2

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. Ralph J. Cicerone 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. C. D. Mote, Jr., 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, upon its own initiative, to identify issues of medical care, research, and education. Dr. Victor J. Dzau 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 Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. C. D. Mote, Jr., are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied activities annually engage about 7,000 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

SHRP 2 STAFF

ACKNOWLEDGMENTS

This work was sponsored by the Federal Highway Administration in cooperation with the American Association of State Highway and Transportation Officials. It was conducted in the second Strategic Highway Research Program, which is administered by the Transportation Research Board of the National Academies. The project was managed by Ralph Hessian, SHRP 2 Special Consultant, Capacity and Reliability.

FOREWORD

Ralph Hessian, P.Eng., FITE
SHRP 2 Special Consultant, Capacity and Reliability

The continuing growth of traffic congestion on the nation's highways is increasing the concerns of transportation agencies, the business community, and the general public. Congestion has recurring and nonrecurring components. Recurring congestion reflects routine delays during specific time periods where traffic demand exceeds available roadway capacity. Road users have come to expect these daily traffic patterns and adjust travel plans accordingly to achieve timely arrivals. Nonrecurring congestion, which comprises the majority of total congestion, results from random incidents that cause unexpected delays, such as crashes, weather, and work zones. Road users are frustrated by unexpected delays that can make for unreliable arrival times at their destinations. The delivery of travel time reliability is becoming an emerging business activity and performance measure for transportation agencies to meet the increasing expectations of the public and freight industry.

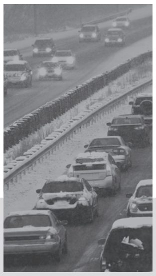
The purpose of this guide is to give transportation engineers, designers, planners, and decision makers an understanding and technical reference on how different highway geometric design elements can be deployed, in new designs or site retrofit actions, to contribute specifically to the reduction of nonrecurring congestion and travel time reliability improvement on both urban and rural freeways. The guide introduces the nonrecurring and travel time reliability topics and metrics, a catalogue of design elements, and a process for selecting candidate design elements to evaluate for a specific site. For individual design elements, example content includes a description of that element, advantages and disadvantages, factors to consider when selecting the element, applicability to nonrecurring congestion, design criteria and practices, safety effectiveness, typical applications, and costs. In addition, there is an evaluation procedure that allows practitioners to compare alternative design treatments and select the best treatment solution for a specific site.

The design guide is a product of SHRP 2 Reliability Project L07, Identification and Evaluation of the Cost-Effectiveness of Highway Design Features to Reduce Nonrecurrent Congestion. A companion product developed from Project L07 is the spreadsheet tool Analysis Tool for Design Treatments to Address Nonrecurrent Congestion, which predicts the changes in delay and travel time reliability resulting from the proposed application of a design treatment to specified baseline site and traffic conditions. This tool also calculates a cost-effectiveness metric and performs life-cycle benefit–cost analysis.

Together, this guide, the research report, and the analysis tool are intended to help transportation agencies and practicing professional engineers and planners consider the use of highway design elements in new designs and retrofits of existing facilities as a potential countermeasure for improving travel time reliability. They are also intended to provide requisite technical and analytical resources to assess alternative design solutions to support programming project investment decisions.

CONTENTS

Online version of this report:
www.trb.org/Main/Blurbs/169768.aspx.



INTRODUCTION

The purpose of this guide is to provide traffic engineers, highway designers, transportation planners, and decision makers with a catalog of highway design treatments that can be used to reduce nonrecurrent congestion and improve the reliability of urban and rural freeways. Nonrecurrent congestion is congestion outside of what is normally expected during daily traffic peaks. It can be caused by crashes, noncrash incidents, special events, weather, work zones, demand surges, or traffic control devices. Roadways that experience several of these events often have low reliability, and the drivers who use the facility have difficulty accurately estimating the amount of time their trip will take. The concepts of nonrecurrent congestion and reliability are discussed in Chapter 1 of this guide.

Although many agencies are familiar with the potential benefits of deploying real-time traveler information systems and roadside assistance programs to reduce the impacts of incidents, special events, and inclement weather, little consideration has been given to how the design of the roadway and roadside can play an important role in mitigating the congestion caused by these events. This guide considers the impact of both standard features (such as the provision of full-depth shoulders) and innovative features (such as queue-jump lanes) and explores the benefits they may provide during nonrecurrent congestion. Some treatments are used primarily to address nonrecurrent congestion, but others may be implemented for another reason, such as increased capacity during periods of nonrecurring congestion, and may have additional benefits during nonrecurrent congestion events. The full range of treatments included in this guide is presented in Chapter 2.

Chapter 2 also provides a process for narrowing the full list of treatments to those that may provide the most benefit in various situations. A decision tree is presented that walks the reader through the process of considering the main cause of nonrecurrent congestion and the means by which that nonrecurrent congestion might be mitigated.

Ideally, the reader will gain a handful of treatments from Chapter 2 that will be investigated further as candidates for possible implementation.

Chapter 3 of the guide catalogs the treatments and provides a range of information on each one, including the following:

- Description and primary objective of the treatment
- Typical applications of the treatment
- Design criteria or guidelines, if available, in design manuals or from research
- How the treatment can be used to address nonrecurrent congestion
- Factors that affect the treatment's effectiveness
- Cost considerations
- Resources for additional information

The reader may choose to browse through this catalog to learn more about several treatments or go directly to the descriptions of the treatments identified in Chapter 3 as potential candidates for implementation.

Chapter 3 provides information on how each treatment can be used to reduce nonrecurrent congestion and the factors that may make it more or less successful in doing so, but it does not provide guidance on quantifying the benefit of the treatment in terms of nonrecurrent congestion reduced or reliability improved. However, these benefits are real, and they can be monetized to allow for a benefit–cost calculation to be performed. To assist the reader in carrying the treatments identified in this guide through the next step of consideration for implementation, an Analysis Tool has been developed as a sister product to this guide. The tool allows the user to compare the benefit–cost ratio of several treatments, providing valuable information to design decision makers. The final report documenting the research project that developed these products provides detailed information on the principles and calculations that drive the Analysis Tool. These products are available on the SHRP 2 website.

Chapter 4 of this guide is a catalog of secondary treatments that complements the treatments in Chapter 3. Finally, Chapter 5 provides information about existing installations of several of the treatments included here, allowing the reader to identify agencies that have experience with various treatments and that may be able to provide insight and guidance to other agencies considering the treatment.

This guide can be used as a resource during all stages of the design process, but it will perhaps be the most beneficial before or during early project planning phases. Although some of the treatments presented can be easily retrofitted into existing facilities, others will be most cost-effective when incorporated into a planned construction or maintenance project. In addition, some treatments are most effective at reducing nonrecurrent congestion when incorporated with specific geometric or operational elements, and coordination of all aspects of the project in the early phases can help maximize benefits. Once potential treatments are identified, and their benefits to nonrecurrent congestion are understood, the Analysis Tool can be used to quantify those benefits. A benefit–cost analysis that captures delay reduction and reliability benefits can help justify the implementation of treatments that may otherwise have not been considered for a project.

1 INTRODUCTION TO NONRECURRENT CONGESTION AND TRAVEL TIME RELIABILITY

This chapter addresses the causes of nonrecurrent congestion, illustrates how nonrecurrent congestion is related to delay and reliability, and describes the costs associated with both delay and reliability.

NONRECURRENT CONGESTION

Traffic operational delay to motorists results from both recurrent and nonrecurrent congestion. The primary difference between recurrent and nonrecurrent congestion is one of predictability.

Recurrent congestion is predictable and typically occurs during the morning and evening peak hours. It is primarily caused by inadequate base capacity of the roadway during these time periods when demand is at its highest. Drivers who embark on trips during peak hour periods expect slower travel times and plan their departure and arrival times accordingly.

Nonrecurrent congestion, however, cannot be planned for because it is unpredictable. It results from random or unplanned events, varies from day to day and from one incident to the next, and creates unreliable travel times. Nonrecurrent congestion often causes the most frustration for drivers because the longer-than-expected trip time can lead to late deliveries, missed flights, delayed meeting times, and other undesirable consequences.

Although recurrent and nonrecurrent congestion each contribute to delay and play a unique role in travel time reliability, the focus here is on treatments that address nonrecurrent congestion.

There are six main causes of nonrecurrent congestion:

- Traffic incidents
- Severe weather
- Special events
- Work zones
- Demand fluctuations
- Traffic control devices

Each of these causes has specific characteristics that should be considered when attempting to quantify the nonrecurrent congestion they cause and the extent to which the design treatments presented in this guide may reduce it. Some of the important considerations associated with each of the six causes of nonrecurrent congestion are presented below.

Traffic Incidents

When most people hear the term *traffic incidents*, they think about crashes. Crashes are indeed traffic incidents, but they make up only a portion of all incidents. Incidents also include such events as stalled vehicles in a travel lane or on the shoulder, debris in the roadway, and the "rubbernecking" that occurs when drivers slow down to observe a crash or anything else that may catch their eye.

Incidents cause congestion in two primary ways. First, they tend to block lanes, reducing the capacity of the roadway for everyone trying to drive by. Even incidents confined to the shoulder slightly reduce the capacity of the highway, as drivers tend to slow down when passing a vehicle on the shoulder. Second, incidents tend to cause other drivers to slow down and look, which decreases the operating speed of the roadway and also reduces capacity.

The number of lanes blocked, the amount of time the lanes are blocked, and the rubbernecking effect tend to increase when emergency responders arrive on the scene, especially for more severe incidents. The design treatments most suited to reduce delay caused by incidents are those designed to reduce the frequency of incidents, minimize the number of lanes they block, reduce the time the lanes are blocked, and shield the incident from the view of passing drivers.

Severe Weather

Driver behavior changes when weather conditions change. Rain and snow can cause slick pavement that may increase the frequency of crashes and slow traffic. Heavy rain or snow, blowing snow or sand, and fog can reduce visibility, which also increases the frequency of crashes and slows traffic. Heavy snow may cover the roadway, hiding lane delineations and significantly reducing the capacity of the roadway. Although no design treatment is available to reduce the frequency of these weather incidents, some of the design treatments presented in this guide can reduce the impact of severe weather. Some treatments help prevent snow or sand from blowing across the roadway, improving visibility and keeping lanes clear. Other treatments treat the roadway surface before a storm to limit accumulation of snow and ice. Some design treatments increase the speed and efficiency of lane-clearing practices to get roadways operating at full capacity as soon as possible during and after a weather event.

Special Events

Special events that cause nonrecurrent congestion often happen near arenas, stadiums, conference centers, and other large gathering spaces that host sporting events, concerts, and large meetings. Special events tend to create large demand surges during short periods of time, usually just before the event begins and just after it ends. Treatments to help alleviate such congestion include temporarily increasing capacity in the major direction of travel, diverting demand to alternative routes, and reducing congestion related to weaving (frequent lane changes near merge and diverge areas) by limiting freeway entrance and exit options.

Work Zones

Work zones are sections of the roadway or roadside on which construction, maintenance, or utility work activities are taking place. The degree to which work zones affect the reliability of the roadway is influenced by the length of time the work zone is in place, the number of lanes closed by the work zone, the specific hours of the day during which work is being performed, and the degree to which drivers are aware of the work zone and can plan for associated delays or choose an alternative route.

Short-term work zones can have a major impact on nonrecurrent congestion because they are often unexpected, and drivers are not able to plan their trips to account for the delay they cause. The first few days of a longer-term work zone, especially an emergency work zone or a work zone that was not well advertised to the public, may have a similar impact on traffic as a short-term work zone. However, the longer the work zone is present, the more drivers become aware of it and become familiar with shifted traffic patterns, alternative routes, and typical delays. As some drivers choose alternative routes, demand through the work zone is reduced, along with the delay caused by the work zone. In a long-term work zone, traffic patterns eventually reach a new equilibrium of lower demand and longer travel times than the prework zone condition, and once this occurs, drivers can again accurately estimate trip length. Although delay is still incurred, it becomes more like the delay from recurrent congestion, which drivers expect and plan for. Identifying the point at which congestion from work zones shifts from behaving like nonrecurrent congestion and having a negative impact on reliability to behaving more like recurrent congestion and regaining some of the lost reliability is not an exact science. It will depend greatly on the availability of alternative routes, driver familiarity with alternative routes, public awareness efforts made before the work zone was established, and other factors.

The impact of other causes of nonrecurrent congestion can be amplified in a work zone. For example, work zones often limit access to shoulders or pulloff areas, which can increase the lane-blocking time of crashes and other incidents that occur within the work zones. Thus, even in long-term work zones in which a new equilibrium of demand and travel time has been reached, delay and reliability may be affected by incidents, special events, and weather more than they would have been before the presence of the work zone.

Design treatments aimed at reducing the impact of work zones typically accomplish one of three things:

- ***Minimize the capacity lost due to the work zone.*** This can be done by providing shoulder areas or pulloff locations, "borrowing" capacity from the other direction of travel during work zone hours, and employing practices that allow work to be accomplished on one lane at a time.
- ***Reduce the time duration of work-zone lane closures.*** Depending on the work zone, this could be done by limiting lane closures to off-peak periods or by accelerating work schedules to finish the work as quickly as possible.
- ***Reduce the number of incidents in the work zone.*** Safe practices for managing entrances and exits of work equipment from the work zone may limit work zone–related crashes. In addition, providing locations for vehicles to move in the case of a crash or breakdown may reduce secondary crashes and rubbernecking in the work zone.

Many of the treatments used for minimizing the impact of work zones on congestion are operational in nature but may require geometric design considerations to implement. For example, the acceleration of a work zone schedule may require that alternative routes are improved or that separate express lanes are built to handle traffic while the existing facility is completely closed.

Demand Fluctuations

Demand fluctuation refers to the day-to-day variability in traffic demand that leads to higher traffic volumes on some days than on others. It also includes the seasonal and weekend spikes in demand that are experienced near vacation destinations. Another type of demand fluctuation that could be considered is that experienced during major evacuations. Treatments that can help address fluctuating demand include those that can temporarily increase capacity in the direction of the demand surge and those that divert demand to alternative routes.

Traffic Control Devices

Traffic control devices include traffic signals, ramp meters, speed limits, pavement markings, lane-use signs, and others. An example of nonrecurrent congestion due to a traffic control device that many drivers have experienced occurs when a traffic signal malfunctions and goes to flashing operation or falls "out of plan" during a high-demand period. Traffic may back up several blocks around a signal that is not functioning as it should. However, this guide focuses on treatments that address congestion on freeways where traffic signals are not used. Traffic control devices can cause nonrecurrent congestion on freeways when traffic management devices such as ramp meters, lane-use signs, or variable speed limit signs fail or malfunction. These treatments typically fall within the category of intelligent transportation systems, and are therefore not covered in this guide.

TRAVEL TIME RELIABILITY

The more often nonrecurrent congestion occurs, the less reliable the roadway is, and the more often drivers find that the time they have allocated for their trip is incorrect. For roadways that experience frequent nonrecurrent congestion, drivers often have to allocate more time to their trip than is normally required to ensure that they arrive at their destinations on time most of the time. Each driver may have a different tolerance limit for the number of times and amount of time it is acceptable to be late, but for all drivers making this calculation, the result is that they arrive at their destinations early for all of the times when nonrecurrent congestion does not occur. This buffer time that is built into drivers' estimates of how long it will take them to reach their destinations is wasted time in the sense that it cannot be allocated to the activities the drivers would prefer to be doing. However, if drivers do not build in this buffer, they will sometimes arrive late at their destinations, which can have consequences ranging from annoyance to significant financial loss, perhaps due to a missed flight or the disruption of a manufacturing process when a freight delivery is late.

The reliability of a roadway is related to the variance of the travel times experienced by drivers who travel along it. Reliable roadways have travel times with low variability; that is, most travel times are very similar to one another. For example, a roadway would be considered highly reliable if travel times ranged from 30 to 33 min 95% of the time. In contrast, a roadway with travel times ranging from 30 to 45 min 90% of the time, with even greater travel times 10% of the time, would not be considered as reliable. Delay from nonrecurrent congestion contributes to a decline in reliability because it increases the variability of trip time, but delay from recurrent congestion does not affect reliability as much because the delay is fairly constant and predictable. If a 5-mi trip on a freeway with a speed limit of 60 mph usually takes about 10 min during the evening peak, drivers are incurring delay due to recurrent congestion. However, if that travel time rarely varies from its 10-min average, the roadway is still reliable, because that trip time can be accurately planned for. If incidents are fairly common along the roadway that increase the delay on random days, causing the trip to take 15 or 20 min once or twice a week, the roadway is less reliable.

Reliability is an important component of roadway performance and, perhaps more importantly, of motorist perception of roadway performance. Reliability has only recently been gaining recognition as an important performance measure for roadways, but increasingly agencies are using reliability measures to assess their own performance and to communicate it to the public. Researchers have noted several reasons why measuring and managing reliability is important. These include the following:

- ***Motorists have less tolerance for unexpected delay than for expected delay.*** Motorists are frustrated by not knowing and being able to plan for unexpected delay. Motorists want to know what to expect, and knowing the extent and duration of congestion not only gives the motorist better options, it removes a significant stress point—the unknown.
- ***There are costs associated with planning for unreliable travel.*** Travelers who use particular highways regularly (e.g., commuters, delivery services) develop an

intuitive understanding of how events cause unexpected delay. As a result, they will pad their budgeted travel time to account for the possibility of unexpected delay so that they will arrive at their destinations on time (even if this means arriving early on some days). This padding or buffering has not been included in economic analyses of transportation, yet it is clear that it carries a cost. For example, the additional time budgeted for travel (i.e., buffer time) is time that could have been spent doing more desirable activities. Also, the cost of being late (due to extreme events that cause the actual time to exceed the buffer), is probably valued highly by travelers.

- ***Reliability is a valued service in other utilities and industries***. Ensuring that services delivered to customers are dependable and consistent is a hallmark of many nontransportation industries. Transportation services provided by public agencies should be no different.
- ***Reliability can be improved by implementing strategies to address nonrecurrent congestion***. By addressing the causes of delay, reliability can be improved. Transportation operations strategies such as incident, weather, and work zone management have proven to be cost-effective strategies for addressing congestion. Therefore, reliability measurement provides a glimpse into how well transportation operations strategies are working.

COSTS OF DELAY AND RELIABILITY

Many drivers will choose a path with reliable congestion over a path with highly unreliable travel times, even if the unreliable path will occasionally get them to their destination faster than the reliable one. This indicates that reliability has a value to drivers separate from the value of time and that reliability should be a factor in benefit–cost analyses of projects that may affect it.

It is well established that drivers incur a cost when they experience delay. The time lost due to delay on the highway can be assigned a monetary value, which is often measured in terms of lost productivity, represented by average hourly wages. These values can be calculated for delay caused by both recurrent and nonrecurrent congestion. The idea that the reliability of a roadway can also be assigned a cost is a newer concept, but one that is gaining acceptance among transportation planners. At present, there is no commonly accepted way to value reliability monetarily, but methods continue to be suggested, tested, and applied in current research. The most frequently used approach is to define a reliability ratio, which relates the value of reliability to the value of time. Reliability ratios that have been used in recent literature range from approximately 0.7 (meaning that reliability costs 70% as much as time) to 1.3 (meaning reliability costs 1.3 times the value of time). Different reliability ratios may be used for different trip types (such as commute, noncommute, and freight).

The benefits provided by the treatments included in this guide will likely vary widely from one application to another. For some, design options or constraints may affect the benefits available from the treatment, but for others, local policies and practices may affect the frequency of use and effectiveness of the treatment. As an example, crash investigation sites are affected in both ways. The design, location, and prevalence of such sites, which can range from extra-wide shoulders to paved and lit locations in the median of the freeway, affect how likely motorists are to use the sites. In addition, the policy of the emergency responders, as well as public awareness campaigns and signing, also affect how frequently the sites are used, and therefore, their effectiveness and benefits. The factors that are likely to affect the effectiveness of the treatments are included in the discussion for each treatment later in this guide. Roadway planners and designers should consider these factors when estimating the benefits they will achieve by implementing any given treatment.

REDUCING NONRECURRENT CONGESTION AND IMPROVING RELIABILITY

When nonrecurrent congestion is minimized, travel times become more predictable and reliability is improved. The remainder of this guide is dedicated to presenting several highway design treatments that use various mechanisms to mitigate congestion and delay due to incidents, weather events, special events, work zones, demand fluctuations, and traffic control devices. The following chapters provide detailed information about how to choose appropriate treatments and how to maximize their effectiveness.

2 SELECTING DESIGN TREATMENTS TO ADDRESS NONRECURRENT CONGESTION

This chapter introduces a variety of treatments that may be applicable to reducing nonrecurrent congestion on freeways. The treatments presented in this guide are primarily geared toward freeway facilities. Some are more appropriate for urban areas, and others tend to address nonrecurrent congestion issues more commonly found in rural areas. The breadth of treatments presented in this guide should ensure that it can serve as a resource to managers of any freeway system.

Table 2.1 presents the specific design treatments that are addressed in this guide. The treatments are categorized into two groups:

- ***Nonrecurrent congestion design treatments.*** This category includes treatments implemented through physical changes in the highway or roadside that are used primarily to reduce nonrecurrent congestion.
- ***Secondary treatments.*** This category includes two kinds of treatments: those that are operational in nature, but may require geometric infrastructure to implement; and those that are design treatments, but are primarily used for recurrent congestion (that also have potential application to nonrecurrent congestion situations).

For any of the general causes of nonrecurrent congestion discussed in this guide, there are several design treatments that may offer benefits. In addition, many of the treatments discussed in this guide can offer benefits in more than one nonrecurrent congestion scenario. The design treatments that should be considered for alleviating nonrecurrent congestion depend on a combination of the cause of congestion, the specific benefit that is desired, and the existing characteristics of the freeway segment. Figures 2.1 and 2.2 present decision trees based on the causes of nonrecurrent congestion and the specific means by which a treatment could reduce nonrecurrent congestion to help identify the most appropriate treatments to consider in a comparison of benefits and costs.

TABLE 2.1. DESIGN TREATMENTS

Nonrecurrent Congestion Design Treatments	Secondary Treatments
Medians	**Lane Types and Uses**
Emergency crossovers	Contraflow lanes for emergency evacuation
Movable traffic barriers	Contraflow lanes for work zones
Gated median barrier	High-occupancy vehicle and high-occupancy toll lanes
Movable cable median barrier	Dual facilities
Extra-height median barrier	Reversible lanes
Mountable/traversable medians	Work-zone express lanes
Shoulders	**Traffic Signals and Traffic Control**
Accessible shoulders	Traffic signal preemption
Drivable shoulders	Queue-jump and bypass lanes
Alternating shoulders	Traffic signal improvements
Portable incident screens	Signal timing systems
Vehicle turnouts	Ramp metering and flow signals
Bus turnouts	Temporary traffic signals
Crash Investigation Sites	Variable speed limits and speed limit reduction
Crash investigation sites	**Technology**
Right-of-Way Edge	Electronic toll collection
Emergency access between interchanges	Overheight vehicle detection and warning systems
Arterials and Ramps	**Emergency Response Notification**
Ramp widening	Reference location signs
Ramp closure	Roadside call boxes
Ramp terminal traffic control	**Weather**
Ramp turn restrictions	Fog detection systems
Detours	Road weather information systems
Improvements to detour routes	Flood warning systems
Truck Incident Design Considerations	Wind warning systems
Runaway truck ramp	
Construction	
Reduced construction duration	
Improved worksite access and circulation	
Animal–Vehicle Collision Design Considerations	
Wildlife fencing, overpasses, and underpasses	
Weather	
Snow fences	
Blowing sand mitigation	
Anti-icing systems	

The decision trees are provided to give the user a starting point for using the SHRP 2 Project L07 treatment evaluation tool. Figure 2.1 includes treatments categorized as nonrecurrent congestion design treatments, and Figure 2.2 includes treatments categorized as secondary treatments. Following the decision tree to the final branch that most accurately describes the cause of nonrecurrent congestion and the desired method of reducing that nonrecurrent congestion on the freeway segment of interest will provide a short list of the treatments that are typically well suited for that scenario. However, other treatments not listed may also provide benefits and can be included in the comparison if the user chooses to consider them. In addition, some of the treatments listed may not be appropriate for certain freeway segments. For example, alternating shoulders would not be a candidate treatment on a segment that already has full left and right shoulders available.

There were several possible ways to organize the treatments, as there are various frameworks for categorizing the causes of nonrecurrent congestion and the types of benefits provided by the treatments. The framework used here was chosen because it allows users to first answer the most basic question (what is the major cause of non-recurrent congestion?), and then guides them through considering the elements that contribute to that cause of congestion so that areas where improvement is desired can be identified.

In some cases, users may have certain treatments identified for consideration already, in which case, this treatment selection process is not needed. Users can certainly use the SHRP 2 Project L07 Treatment Analysis Tool without completing this process if they have already identified a treatment or treatments they would like to evaluate.

CHOOSING TREATMENTS FOR CONSIDERATION

To use the decision tree shown in Figure 2.1 for identifying treatments to be compared, the user should begin by identifying the primary cause of nonrecurrent congestion on the freeway segment of interest. Although six causes of nonrecurrent congestion are discussed in this guide, this tree begins with the four most common causes relevant to freeway segments:

- Incidents
- Weather
- Work zones
- Special events

Most freeway segments experience nonrecurrent congestion from more than one of these causes, but often agencies have identified one specific area on which to focus improvement efforts. In any case, the user can follow more than one decision path in the tree and choose to compare treatments from different lists.

Once the primary cause of congestion is identified, the decision tree then divides on the basis of the primary mechanism by which the cause of congestion could be minimized. For some mechanisms, the categories are further divided into more specific benefits. Once the decision tree has been followed to the final branch, there may be several appropriate treatments listed, which can be further narrowed according to the specific characteristics of the freeway segment of interest. For other branches, only one or two treatments may be listed. In this case, the user may choose to follow additional branches that could be provided by other treatments.

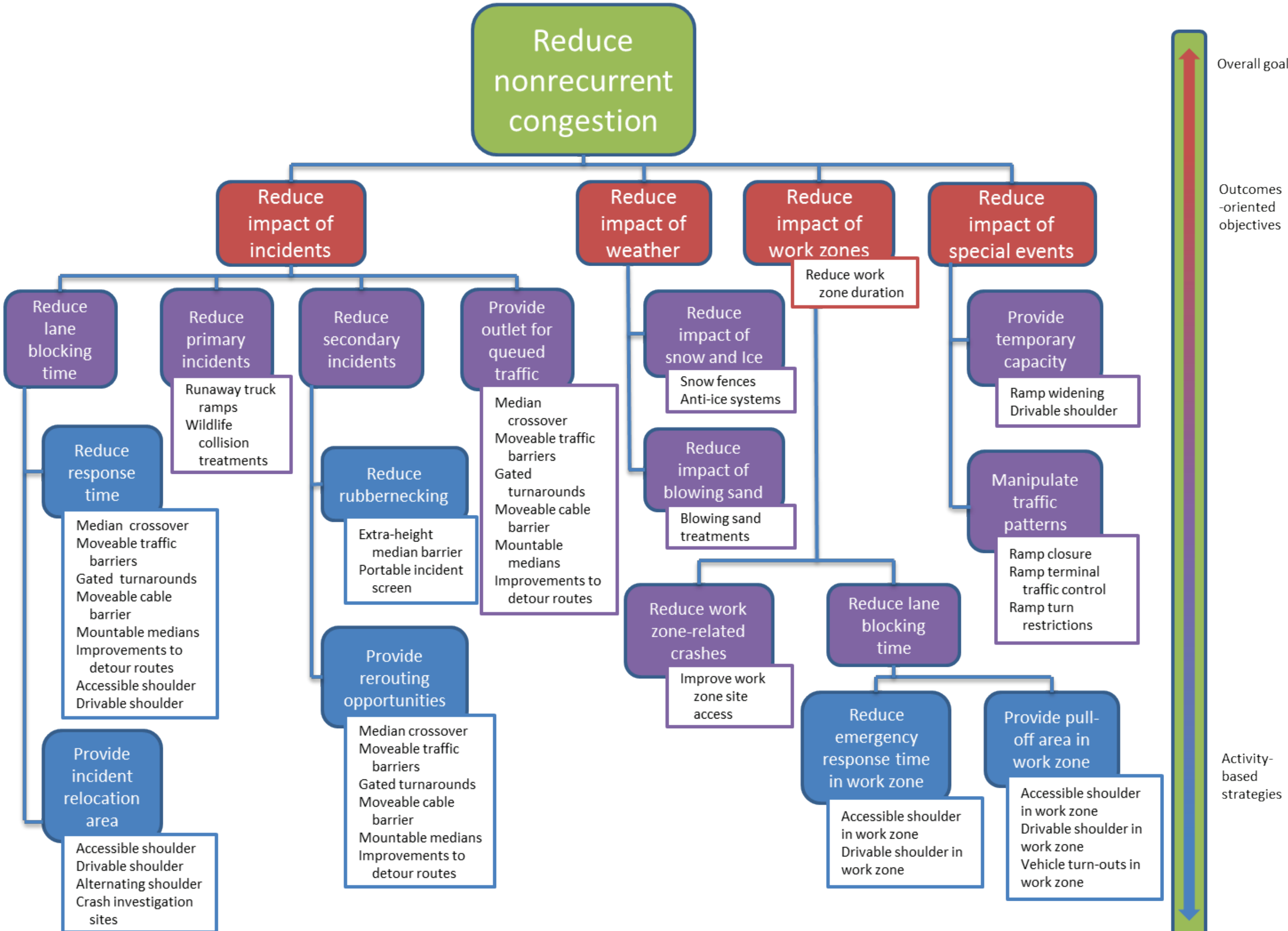


Figure 2.1. *Nonrecurrent congestion design treatments.*

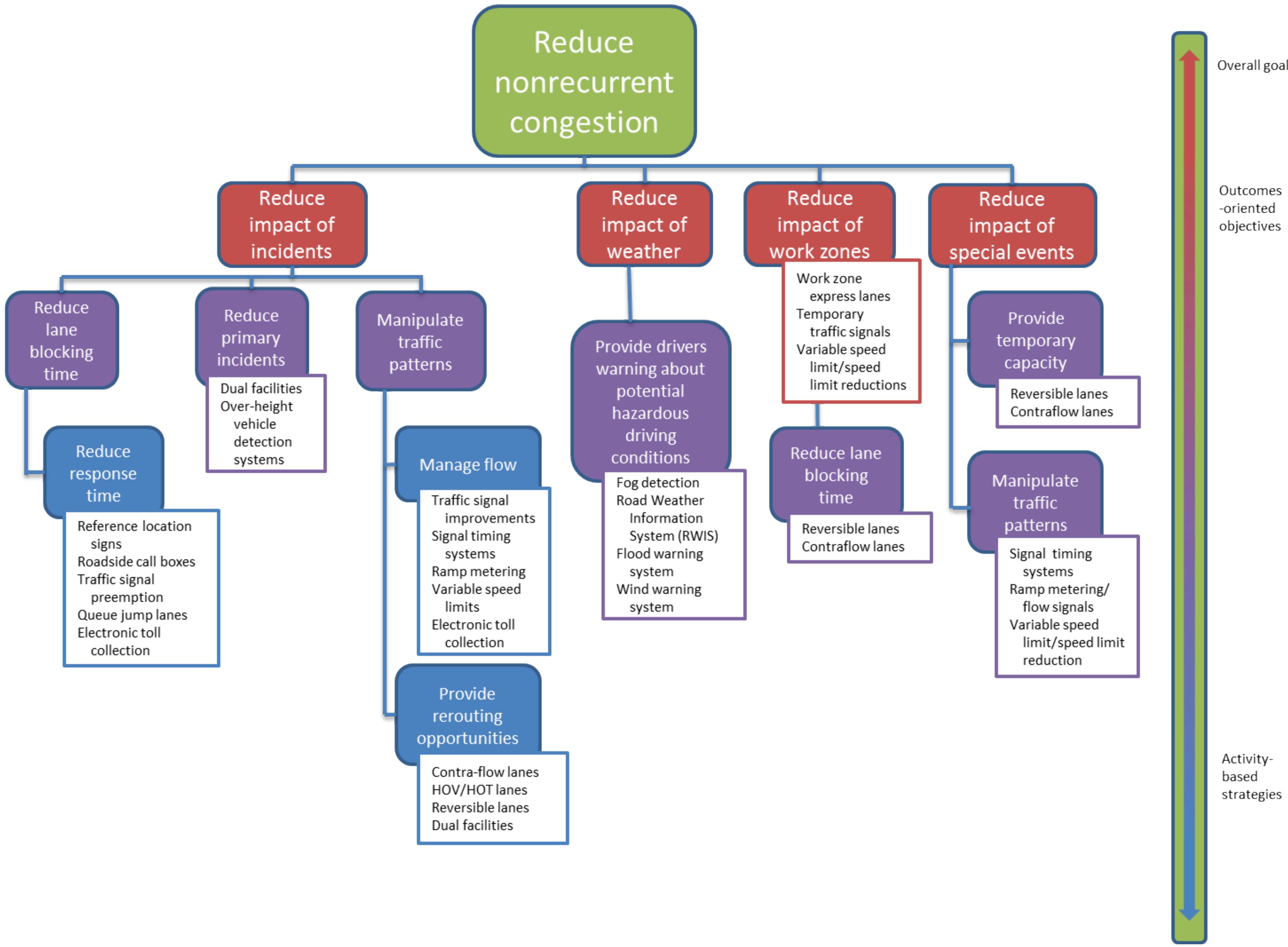


Figure 2.2. *Secondary treatments.*

EVALUATING AND COMPARING TREATMENTS

Ideally, users will identify two to five treatments from the decision tree shown in Figure 2.1 to evaluate and compare in the SHRP 2 Project L07 treatment Analysis Tool. The tool is applied to a specific segment of roadway on which nonrecurrent congestion occurs and compares the benefits and costs of the selected treatments as applied to that particular segment of roadway. The tool asks the user specific questions about the characteristics of the freeway segment on which the treatments are being considered for application, as well as questions about the intended implementation of the treatment. These questions may include information about geometrics, policies, or other factors that could influence the effectiveness of the treatment. These inputs allow the tool to estimate a change in the travel time reliability of that particular roadway segment that would be realized as a result of the various treatments' installation. With user-provided input on the cost of implementation, the tool will provide a benefit–cost ratio for each treatment being considered and allow comparison of this ratio among several treatments.

It is recognized that often treatments have costs and benefits beyond those that can be accounted for in an analysis tool, often related to political will, community support, environmental considerations, and others. Users are encouraged to use the benefit–cost ratio provided by the Analysis Tool as one variable in the decision-making process that must be balanced with the more subjective costs and benefits associated with a given treatment.

CATALOG OF NONRECURRENT CONGESTION DESIGN TREATMENTS

This chapter catalogs design treatments that can be considered for use in addressing nonrecurrent congestion. A detailed summary of each of the design treatments is provided that includes the following information:

- Description and objective
- Typical applications
- Design criteria
- How treatment reduces nonrecurrent congestion
- Factors influencing treatment effectiveness
- Cost

The design treatments are classified on the basis of similarities with respect to function or location on the roadway. Chapter 4 presents a catalog of the secondary treatments.

MEDIANS

Emergency Crossovers

Description and Objective

An emergency crossover is a median opening on a divided highway segment for crossing by emergency, law enforcement, maintenance, and traffic service vehicles. Other types of median crossovers are addressed elsewhere in this chapter:

- Crossovers for contraflow (see discussion under Contraflow Lanes for Emergency Evacuations)

- Temporary construction crossovers (see discussion under Contraflow Lanes for Work Zones)
- Median openings controlled by manual or automated gates (see discussion under Gated Median Barriers)

The objective of an emergency crossover is to provide better access for law enforcement and emergency vehicles responding to an incident, thus reducing the time between when an incident occurs and when emergency responders arrive on the scene. The sooner emergency responders can arrive on the scene of an incident, the sooner the incident can be cleared and normal freeway operations can resume. Figure 3.1 illustrates an example of an emergency crossover.

Typical Applications

Emergency crossovers are typically provided on rural sections of freeways where interchanges are spaced farther apart and a well-developed street network, providing options for alternate routes, is not available. At such locations, emergency responders are faced with excessive travel distances to reach an incident.

Emergency crossovers may also be considered for rerouting traffic, via a U-turn maneuver, in response to a major lane-blocking incident. When a major incident blocks traffic for a significant amount of time, traffic may back up behind the incident and cause significant delay to motorists. If an emergency crossover is used to reroute traffic to the opposite direction of travel, the queue in the direction of the incident can dissipate. These rerouted vehicles can return to the next closest interchange and proceed along an alternate route to their destination.

Figure 3.1. *Emergency crossover on I-435 in Kansas.*

Although emergency crossovers are typically provided on freeways, median openings on arterial roadways can also be used to provide better access for emergency responders and to allow for traffic to be rerouted from a major incident.

Design Criteria

Important design considerations for installation of emergency crossovers on rural freeways include interchange spacing, median width, and stopping sight distance. The American Association of State Highway and Transportation Officials (AASHTO) *Green Book* (2011) provides the following design guidance for emergency crossovers:

- Emergency crossovers may be provided where interchange spacing exceeds 5 mi.
- Between interchanges, emergency crossovers may be spaced at 3- to 4-mi intervals or as needed.
- Emergency crossovers generally should not be located closer than 1,500 ft from the end of a speed-change taper of a ramp or to any structure.
- Crossovers should be located only where above-minimum stopping sight distance is provided and preferably should not be located on superelevated curves.
- The width of the crossover should be sufficient for turning movements and should have a surface capable of supporting emergency vehicles and maintenance equipment.
- Emergency crossovers should be depressed below shoulder level to be inconspicuous to traffic.

The *Green Book* provides additional guidance for such issues as sideslope and median barrier treatment.

Emergency crossovers on controlled-access facilities are designed for authorized vehicle use only, and public use of these crossovers is prohibited unless directed by law enforcement (e.g., during major lane-blocking incidents).

How Treatment Reduces Nonrecurrent Congestion

Reduces Lane-Blocking Time of an Incident

Use of emergency crossovers reduces the time during which disabled, crash-involved, or police vehicles remain in the roadway or on the roadway shoulder by decreasing the response time of emergency personnel. By reducing the lane-blocking time of an incident, the nonrecurrent congestion associated with that incident is reduced. This reduction in nonrecurrent congestion results in increased reliability for the roadway segment.

Reduces Demand Volume During an Incident

When emergency crossovers are used to allow vehicles to perform U-turn maneuvers to alleviate congestion caused by a major lane-blocking incident, demand is essentially reduced on the segment with temporarily reduced capacity by rerouting traffic to alternate facilities.

Factors Influencing Treatment Effectiveness

Factors that may influence the effectiveness of emergency crossovers in reducing nonrecurrent congestion include the following:

- Average reduction in response time for those situations in which the emergency crossover is used
- Percentage of incidents (and incident type) for which the emergency crossover will be used to improve response time
- Frequency of lane-blocking incidents for which queued traffic may be rerouted

Cost

Factors affecting the cost of installing an emergency crossover include the following:

- Width and topography (cross slope) of the existing median
- Existing median control type (curb, cable median barrier, semirigid barrier), if any
- Material to be used for crossover surface (concrete, asphalt, gravel)
- New signing required

In general, emergency crossovers can be constructed for a relatively low cost. However, if significant cut, fill, or grading work is required to build a crossover, costs may be considerably higher.

Movable Traffic Barriers

Description and Objective

A movable traffic barrier (MTB) is a concrete, crash-worthy barrier (similar to a jersey barrier) that can be shifted from one side of a lane to another, as illustrated in Figure 3.2, to allow flexibility in the designated purpose or direction of travel flow for that lane. The MTB is moved using a specially designed vehicle that shifts each section laterally as the vehicle moves forward. The vehicle does not interfere with traffic in adjacent lanes. One mile of MTB can be shifted one lane in less than 15 min, according to manufacturers.

Figure 3.2. *Movable traffic barrier. Source: Federal Highway Administration website.*

Typical Applications

Crash-worthy barriers are used to enhance safety by reducing the potential for head-on collisions. An MTB provides similar safety benefits, but it also has the flexibility to change lane designations when needed. MTBs are used to help align capacity with demand to minimize the impacts of recurrent and nonrecurrent congestion.

MTBs can also be used to separate work zones from travel lanes. These devices can provide more space in the work zone during off-peak hours, while protecting both the traveling motorists and the construction workers. Shifting the barrier borrows a lane from operation as a travel lane and adds it to the space within the work zone, potentially allowing work to be conducted more efficiently during off-peak hours without adversely affecting travelers during peak hours.

Although the most common applications of MTBs are to alleviate recurrent congestion due to unbalanced flow during peak periods and to safeguard workers during long-term construction projects, the potential benefits to nonrecurrent congestion are considered here. Nonrecurrent congestion situations such as work zones and major incidents are candidates for MTB application. In these instances, the barrier can be shifted to add a lane in the direction of traffic where the incident is taking place, helping to balance capacity and alleviate congestion. Applications of an MTB system to address nonrecurrent congestion include the following:

- Providing flexibility in closing and opening lanes adjacent to work zones to accommodate traffic demand and work zone space needs during different times of the day, potentially reducing the duration of the work zone
- Using an MTB already installed for a recurrent congestion application to treat nonrecurrent congestion due to incidents or work zones

Design Criteria

Some state agencies have authored special provisions for MTBs wherever they are furnished, installed, operated, or maintained within the state. Specific design standards related to MTBs may address barrier reflector markers, the barrier transfer machine, end protection, and obstacle markers.

Barriers can be designed to facilitate the ability to open a section of the barrier wall in minutes by using hand tools. If desired, a gate may be installed for easier access where emergency turnarounds are needed. The length of the gate may be variable to meet specific needs. Gated median barriers are considered as a separate treatment and are described in a subsequent section of this guide.

How Treatment Reduces Nonrecurrent Congestion

Reduces Work Zone Impact

An MTB may be used during a work zone to provide an additional lane for the direction of travel with higher demand. For example, if a work zone is planned that will block two lanes, the MTB may "borrow" one lane from the opposing direction for the duration of the work zone, which will offset the negative impact of the work zone. The demand and capacity of both directions of travel need to be considered, however, to ensure that traffic operations in both directions are balanced.

Reduces Major Incident Impact

During a major incident, MTBs may be used to offset the reduction of available lanes in the direction with higher demand. For example, if a major crash blocks multiple lanes in the direction of heavy demand, the MTB could be shifted to provide additional capacity for the duration of the incident. After the crash is cleared and traffic operations have normalized, the lane could be shifted back to normal operation.

The use of MTBs in response to incidents is a function of the anticipated or observed severity of the incident-related congestion to the time required to move the barrier. In other words, if an incident can be cleared in less time than it would take to move the barrier, then it would not be useful to move it. However, the congestion resulting from crashes involving multiple vehicles and affecting multiple lanes could potentially be significantly alleviated through the use of MTBs.

It is expected that MTBs would only be employed to address the impacts of these incidents when already in place for other reasons. That is, it would not be expected that an agency would deploy an MTB for the sole purpose of responding to major lane-blocking crashes and incidents. Like the third scenario described above, the existing system is deployed to help reallocate capacity during major incidents (e.g., serious lane-blocking crashes, debris on the roadway, hazardous material spills) that occur on the roadway segment. It is assumed that during these incidents, the reallocation of lane space becomes a priority over maintaining the high-occupancy vehicle (HOV), high-occupancy toll, or express lanes in order to minimize congestion due to the incident.

Factors Influencing Treatment Effectiveness

Because an MTB may negatively affect the opposing direction of traffic by temporarily borrowing one of the lanes, the following factors may influence the effectiveness of an MTB in reducing nonrecurrent congestion:

- How many lanes will be shifted
- Traffic volume for each direction
- Roadway capacity in each direction

In the case of an MTB being used during typical minor work zones (e.g., restriping, pavement repair), factors that may influence its effectiveness include the following:

- Number of lanes blocked during a typical minor work zone
- Expected number days per year when a minor work zone will be in effect

In the case of an MTB being used for major incidents, the factors that may influence its effectiveness include the following:

- Average expected duration of a major incident for which an MTB would be used
- Expected number of such events per year
- Time that it takes to shift the barrier over

Generally, using an MTB system to reduce nonrecurrent congestion will be most beneficial in cases for which (1) demand-to-capacity (d/c) ratios are high and minor road work is often needed, or (2) d/c ratios are high and major incidents occur frequently.

Cost

The higher cost that may be associated with MTBs suggest that they are unlikely to be constructed for the sole purpose of reducing nonrecurrent congestion. Rather, an MTB system might be installed to reduce recurrent congestion, and its potential application to nonrecurrent congestion would be an important ancillary benefit.

Factors that affect the cost of installing and operating an MTB system include the following:

- Length of roadway where MTB will be used
- Type of barrier-moving machine used
- Number of barrier-moving machines needed
- Frequency of use of the system
- Movable barrier installation costs
- Changes to pavement markings
- Additional signing required
- Ongoing operating costs
    - Machine operator wages (or additional wages, if an MTB system is already in place but currently used for recurrent congestion only)
    - Fuel, maintenance, and repairs for barrier-moving machine

Gated Median Barriers

Description and Objective

A gated median barrier consists of adding a gated section within a continuous median barrier. Typically, these gates, which may be manually or automatically operated, provide access to maintenance personnel, emergency responders, and other authorized users. An example of a gated median barrier is shown in Figure 3.3.

The objective of a gated median barrier is to provide quicker access for emergency responders arriving on the scene of an incident. The faster emergency responders arrive on the scene, the sooner the incident can be cleared and normal operations can resume. Gated median barriers offer this benefit while preventing unauthorized access.

Typical Applications

Gated median barriers are typically provided on urban sections of freeway, but where interchanges are spaced farther apart. Where interchange spacing is relatively long, emergency responders may be faced with excessive travel distances to reach an incident. Gated median barriers allow emergency responders to access the incident site more directly and quickly.

Gated median barriers can also be used to reroute traffic, via a U-turn maneuver, in response to a major lane-blocking incident. If a major incident blocks traffic for a significant amount of time, traffic may back up behind the incident and cause significant delay to motorists. If a gated median barrier is opened to allow traffic to be rerouted to the opposite direction of travel, the queue in the incident direction can dissipate. These rerouted vehicles can return to the next closest interchange and proceed along an alternate route to their destination.

Figure 3.3. *Gated median barrier in Atlanta, Georgia.*

Design Criteria

The Federal Highway Administration (FHWA) report *Facilitating Incident Management Strategies on Freeways* (Parham et al. 1999) provides design guidance for gated median barriers:

- *Weight*. The weight of the gate should not exceed 40,000 lb.
- *Crashworthiness*. The gate should meet the crashworthy recommendations presented in NCHRP Report 350 (Ross et al. 1993) for longitudinal barriers.

How Treatment Reduces Nonrecurrent Congestion

Reduces Incident Duration

Gated median barriers reduce the period of time during which disabled, crash-involved, or police vehicles remain in the roadway or on the roadway shoulder by decreasing the response time of emergency personnel. By reducing the lane-blocking time of an incident, the nonrecurrent congestion associated with that incident is reduced. This reduction in nonrecurrent congestion results in an increased reliability for the roadway segment.

Factors Influencing Treatment Effectiveness

The following factors may influence the effectiveness of gated median barriers at reducing nonrecurrent congestion:

- Average response time reduction for the instances when the treatment is used
- Percentage of each incident type that will use the treatment to improve response time

Cost

Factors that affect the cost of installing a gated median barrier include the following:

- Type of gated median barrier (manually operated, automated)
- Operational and ongoing maintenance costs
- Cost of removing existing barrier
- Installation of new signing to discourage unauthorized use of turnaround

Movable Cable Median Barriers

Description and Objective

A movable cable median barrier involves construction of a specially designed wire cable barrier system that can be removed to allow median crossovers. The system is constructed such that the cables can be detached from the posts individually and the posts can be removed from their base. This deconstruction can be done over a short segment of the length of the cable to provide a temporary median opening for emergency vehicles in the event of a crash or other major incident. This machine- and tool-free process is designed such that the cable median barrier can be reassembled with minimal effort to restore the barrier system to its permanent state.

The objective of movable cable median barriers is to provide a temporary access point for emergency vehicles. In the event of a major incident that results in significant queuing, a temporary median opening in the cable median barrier can also be used to reroute traffic, via a U-turn maneuver, to dissipate the queue. These rerouted vehicles can return to the next closest interchange and proceed along an alternate route to their destination. Figure 3.4 illustrates a movable cable median barrier.

Typical Applications

Movable cable barriers are typically used along roadway segments with a crash history of frequent head-on collisions. When movable cable barriers are used in medians, the capability of creating access points is most effective where the median is easily traversable.

Movable cable median barriers may be considered on roadways where a cable barrier exists or is needed and where flexibility is desired in providing access points along the median for emergency vehicles or for rerouting traffic around an incident or work zone.

Design Criteria

Design criteria for the movable feature of the cables and posts are vendor specific; several companies have developed movable cable median barriers. The key components of the movable cable median barrier are (1) wires that can be easily detached from the posts and (2) posts that can be easily removed from their foundation.

Figure 3.4. *Standard three-strand movable cable median barrier.*

How Treatment Reduces Nonrecurrent Congestion

Reduces Incident Duration

Movable cable median barriers reduce the time during which disabled, crash-involved, or police vehicles remain in the roadway or on the roadway shoulder by decreasing the response time of emergency personnel. By reducing the lane-blocking time of an incident, the nonrecurrent congestion associated with that incident is reduced. This reduction in nonrecurrent congestion increases reliability for the roadway segment.

Factors Influencing Treatment Effectiveness

Factors that may influence the effectiveness of a movable cable median barrier at reducing nonrecurrent congestion include the following:

- Average reduction in response time when the treatment is used
- Percentage of each incident type that will use the treatment to improve response time

Cost

The following factors can affect the cost of installing a movable cable median barrier along a roadway section:

- Type of installation (new construction or retrofit)

- Length of proposed barrier section
- Existing barrier type (modular concrete, semirigid, nonmovable cable)
- Removal costs for the existing median barrier
- Installation costs for the movable cable median barrier
- Expected frequency of use for emergency access or queue dissipation

Extra-Height Median Barriers

Description and Objective

An extra-height median barrier (EHMB) obscures motorists' view of the opposite direction of travel. This effect is often achieved through design of a barrier taller than driver eye height, but it can also be achieved by the addition of material on top of an existing barrier. EHMBs can be used to reduce nonrecurrent congestion in the following ways:

- Minimize rubbernecking by blocking the view of opposing lanes of traffic during an incident ("gawk screens")
- Prevent crashes caused by headlight glare from opposing traffic at night (often referred to as "glare screens" and commonly used in work zones)
- Prevent cross-median collisions involving taller vehicles that may not be stopped by a traditional height barrier (i.e., an EHMB must be crashworthy)

Depending on the material used to provide the extra height, a particular installation of an EHMB may serve more than one of these purposes.

Rubbernecking causes delay and degrades reliability in two major ways:

- Rubbernecking during an incident causes traffic to slow, thereby reducing capacity and increasing congestion on the roadway.
- Gawking can lead to secondary collisions when a driver's attention is focused on an incident and not on the traffic in front of or around him.

Although reducing headlight glare can be beneficial for drivers, there is no clear research indicating what effect it might have on reducing nonrecurrent congestion or improving travel time reliability. Reducing cross-median collisions involving trucks is an important safety benefit of tall concrete EHMBs.

Various methods of providing extra height to median barriers have been implemented. These include installing concrete barriers that are designed to be taller, adding planters and shrubs on top of the barrier, installing metal or plastic paddles or screens on top of the barrier, or using tall shrubs instead of a concrete barrier in the median. An example of an EHMB is illustrated in Figure 3.5.

Typical Applications

EHMBs may be considered at high-crash locations where vehicles in one direction of travel are visible to drivers in the other direction of travel and where rubbernecking at incidents in the opposite direction of travel is problematic. Application of an EHMB

Figure 3.5. *Extra-height median barrier in Atlanta, Georgia.*

must consider the horizontal and vertical geometry of the roadway (see Design Criteria below).

Design Criteria

For purposes of calculating vertical design criteria (such as sight distance), the AASHTO *Green Book* (2011) uses a driver eye height of 42 in. A barrier must certainly be no lower than this height to visually obstruct the opposing traffic lanes, and larger heights are probably needed to effectively perform this function (especially for taller vehicles). The area over which the median barrier blocks the view of opposing lanes is referred to as the *influence area*.

In addition to ensuring that the median barrier is sufficiently tall to reduce visual distraction caused by incidents on opposing lanes of the divided highway, several other factors that will affect treatment effectiveness should be considered:

- ***Roadway geometry***. Vertical and horizontal alignment will affect the driver's sight lines and the influence area of the EHMB.
- ***Opacity of barrier design***. Widely spaced "paddles" may reduce headlight glare for approaching vehicles a significant distance away, but they may not eliminate incident-induced gawking, especially as the driver approaches the incident and can look between the paddles. The influence area of the barrier in this case may be significantly reduced.
- ***Crashworthiness***. Only some materials used to add height to barriers are intended to reduce cross-median crashes. If reducing nonrecurrent congestion due to severe cross-median crashes is a goal, a design that reduces these types of crashes will be required.

How Treatment Reduces Nonrecurrent Congestion

Reduces Number of Gawking Events

EHMBs reduce rubbernecking by obscuring drivers' view of incidents on the other side of the barrier (the opposite direction of travel). Without an EHMB in place, drivers tend to gawk at incidents that occur in the opposite direction of travel. This gawking usually involves a reduction in speeds as drivers slow down to get a better view of the incident on the opposite side of the roadway. An EHMB can improve reliability by blocking the view of drivers in this situation, such that they are unaware of opposite-direction incidents. By reducing the number of gawking events, EHMBs can reduce the delay associated with the lower speeds during these events and improve reliability.

Reduces Incident Frequency

When drivers gawk at incidents in the opposite direction, their attention is diverted from the task of operating their vehicle. As a result, crashes can occur in the primary direction that are a direct result of gawking at an opposite-direction incident. These crashes are termed "secondary crashes."

To the extent that gawking at opposite-direction incidents causes secondary crashes, an EHMB will eliminate these secondary crashes. By eliminating these secondary crashes, delay in the primary direction is reduced and reliability is improved.

Reduces Incident Severity

EHMBs may reduce cross-median crashes involving tall vehicles (such as tractor trailers), which are often severe in nature. Although the barrier will not prevent a crash from occurring, it works to reduce the severity of the crash by absorbing impact and redirecting the vehicle onto the shoulder. Assumptions based on local experience will help determine whether this treatment benefit will reduce nonrecurrent congestion on the roadway.

Factors Influencing Treatment Effectiveness

Factors that may influence the effectiveness of EHMBs at reducing nonrecurrent congestion include the following:

- ***Number of gawk-inducing incidents***. Roadways with frequent crashes, disablements, work zones, or other gawk-inducing incidents will receive more significant improvement to operations from EHMBs than roadways with few gawk-inducing incidents. Rubbernecking may not have a significant effect on congestion if traffic flow is relatively light at the time of the incident. Low traffic volumes also reduce the probability of the occurrence of a secondary incident.
- ***Influence area of median barrier***. Barriers that only block a driver's view over a short distance along the road will be less effective than those that block the driver's view over a longer distance. Influence area is a factor of median design and roadway geometry.
- ***Truck volume***. Areas with high truck volumes are more likely to see a reduction in crash severity by reducing the frequency of cross-median crashes involving heavy vehicles.

Cost

Factors that affect the cost of implementing EHMBs along a roadway section include the following:

- Construction type (new roadway or retrofit of existing roadway)
- EHMB material (reinforced concrete, planted shrubs)
- Length of roadway over which treatment will be installed
- Maintenance required (e.g., caring for vegetation, repair or replacement required when vehicle collides with barrier)

Mountable/Traversable Medians

Description and Objective

Mountable/traversable medians do not physically prevent vehicles from crossing from one direction of travel to the other. Examples of this treatment include the following:

- Flush or painted medians
- Two-way left-turn lanes (TWLTL) (illustrated in Figure 3.6)
- Raised (but traversable) medians

The objective of mountable/traversable medians is to provide better access for law enforcement and emergency vehicles responding to an incident, thus reducing the time between when an incident occurs and when emergency responders arrive on the scene. The sooner emergency responders can arrive on the scene of an incident, the sooner the incident can be cleared and normal freeway operations can resume.

Figure 3.6. *Two-way left-turn lane.*

Typical Applications

Mountable/traversable medians are primarily used to provide emergency access, as described above, while still providing a visual separation between opposing directions of travel. Various traversable and nontraversable median types are found in every metropolitan area around the nation.

Design Criteria

Following are descriptions of three specific types of traversable medians:

- ***Flush medians***. Typical widths for a flush median on an urban street can range from 4 to 13 ft. To accommodate a separate left-turn lane, a flush median should be 13 ft wide.
- ***Flush TWLTL***. AASHTO recommends a TWLTL width of between 10 and 16 ft for left-turning vehicles. The usual design widths for flush TWLTLs are 11, 12, or 13 ft. There is some evidence that wide TWLTLs encourage drivers to place their vehicles in an angular rather than parallel turning position and thereby cause encroachments on adjacent through lanes.
- ***Traversable TWLTL***. Where a mountable 2-in.-high curb is used to delineate the edges of a median, this median is designated as a traversable median, and traffic is allowed to turn left across the median. The normal traversable TWLTL median width for new construction is 16 ft. As discussed for the flush TWLTL, wide traversable TWLTL medians also may encourage drivers to store in an angular position. Therefore, wider widths should not be provided.

How Treatment Reduces Nonrecurrent Congestion

Reduces Incident Duration

Mountable/traversable medians reduce the period of time during which disabled, crash-involved, or police vehicles remain in the roadway or on the roadway shoulder by decreasing the response time of emergency personnel. By reducing the lane-blocking time of an incident, the nonrecurrent congestion associated with that incident is reduced. This reduction in nonrecurrent congestion results in an increased reliability for the roadway segment.

Factors Influencing Treatment Effectiveness

Factors that may influence the effectiveness of mountable/traversable medians at reducing nonrecurrent congestion include the following:

- Average response time reduction for the instances when the treatment is used
- Percentage of each incident type that will use the treatment to improve response time

Cost

Factors that affect the cost of installing a mountable or traversable median along a roadway section include the following:

- Existing median type (raised curb, TWLTL, none)
- Proposed median type (TWLTL, mountable curb, painted median)
- Length of section to be improved

SHOULDERS

Accessible Shoulders

Description and Objective

An accessible shoulder consists of a wider shoulder or an improvement to the surface of an existing shoulder (e.g., replacing a gravel shoulder with a paved shoulder) such that the shoulder can serve one or both of the following functions:

- As a pulloff for disabled or incident-involved vehicles (as illustrated in Figure 3.7 and Figure 3.8)
- As a "bypass lane," allowing emergency responders to go around queued mainline traffic and reach the incident scene more quickly

Improving a shoulder to allow mainline traffic to use the shoulder as a travel lane is addressed elsewhere in this chapter (see discussion under Drivable Shoulders).

Typical Applications

Accessible shoulders may be considered for roadway segments with shoulders that cannot accommodate disabled, incident-involved, or emergency vehicles due to insufficient width or surface type.

Figure 3.7. *An accessible shoulder in use during a crash investigation. Source: U.S. Fire Administration (2008).*

Figure 3.8. *A vehicle fire on the left shoulder of a freeway.*
Source: U.S. Fire Administration (2008).

Design Criteria

The AASHTO *Green Book* (2011) states that

> desirably, a vehicle on the shoulder should clear the edge of the traveled way by at least 0.3 m (1 ft), and preferably by 0.6 m (2 ft). These dimensions have led to the adoption of 3.0 m (10 ft) as the normal shoulder width that is preferred along higher speed, higher-volume facilities. Heavily traveled, high-speed highways and highways carrying large numbers of trucks should have usable shoulders at least 3.0 m (10 ft) wide and preferably 3.6 m (12 ft) wide; however, widths greater than 3.0 m (10 ft) may encourage unauthorized use of the shoulder as a travel lane. . . . [A]lthough it is desirable that a shoulder be wide enough for a vehicle to be driven completely off the traveled way, narrower shoulders are better than none at all. For example, when a vehicle making an emergency stop can pull over onto a narrow shoulder such that it occupies only 0.3 to 1.2 m (1 to 4 ft) of the traveled way, the remaining traveled way width can be used by passing vehicles.

How Treatment Reduces Nonrecurrent Congestion

Reduces Number of Lanes Blocked by an Incident

With the installation of an accessible shoulder, crash-involved vehicles and noncrash incidents (such as disabled vehicles) that block travel lanes can be relocated to the shoulder, resulting in reduced lane-blocking time. This decrease in average lane-blocking time reduces the nonrecurrent congestion associated with the incident, thus reducing delay and improving reliability.

Reduces Incident Response Time

An accessible shoulder can be used for emergency vehicle access. In this case, emergency responders use the shoulder to bypass traffic congestion on the roadway and reach the crash site earlier. This decrease in response time reduces the total incident duration, so lanes are blocked for a shorter period of time, delay is reduced, and reliability is improved.

Reduces Frequency of Incidents

The provision of a shoulder has been shown to be associated with a reduction in incident frequency. The *Highway Safety Manual* (AASHTO 2010) provided crash modification factors for provision of a shoulder.

Factors Influencing Treatment Effectiveness

Factors that may influence the effectiveness of accessible shoulders at reducing nonrecurrent congestion include the following:

- ***Existing and planned usable shoulder width***. An improvement that widens a 2-ft shoulder to a 12-ft shoulder will experience more benefit than an improvement that widens an 8-ft shoulder to a 12-ft shoulder.
- ***Existing and planned shoulder surface type (paved or unpaved)***. Only paved shoulders will allow emergency vehicles the opportunity to bypass congestion to reach the scene of an incident faster. In addition, reductions in incidents due to shoulder widening are for paved shoulders only.
- ***Frequency of incidents requiring emergency vehicle response in congested conditions***. The shoulder benefits crashes or other emergencies that require an emergency response vehicle that would have a difficult time reaching the incident scene in a timely manner without the use of the shoulder.
- ***Typical emergency response time***. The expected reduction in emergency response time when a shoulder is available for use should be compared with typical emergency response times.
- ***Frequency of lane-blocking incidents***. The proportion of lane-blocking incidents that could be moved to a shoulder, as well as their frequency, should be considered.

Cost

Factors that affect the cost of implementing an accessible shoulder along a roadway section include the following:

- Shoulder material (concrete, asphalt, gravel, or earth)
- Width of shoulder (before and after)
- Availability and purchase cost of right-of-way for shoulder widening
- Topography of roadside (especially in mountainous conditions where considerable cut or fill may be required to provide a shoulder)
- Necessary clearing and grubbing of roadside to increase shoulder width

- Temporary traffic control costs during construction
- Removal or addition of striping
- Addition or reinstallation of rumble strips

Drivable Shoulders

Description and Objective

A drivable shoulder can be temporarily used by mainline traffic as a travel lane. Drivable shoulders can be used to restore lost capacity by routing traffic around a lane-blocking incident, such as a work zone or a crash. Several examples of drivable shoulders are illustrated in Figures 3.9 through 3.11.

Typical Applications

Though the practice of temporarily routing traffic around work zones or incidents is not widespread in the United States, Germany has implemented drivable shoulders (termed *shoulder-use lanes* or *hard shoulder running*) to address nonrecurring congestion. In Germany, a hard shoulder is required for temporarily routing traffic around scenes of accidents or 1-day work zones. England also uses shoulder-use lanes as a temporary measure for work zones.

Design Criteria

The *Green Book* (AASHTO 2011) does not provide design guidance for drivable shoulders in the context of converting a shoulder to a travel lane, rerouting traffic around an incident or work zone, or providing emergency vehicle access to an incident.

NCHRP Report 254: Shoulder Geometrics and Use Guidelines (Downs and Wallace 1982) provides application and design guidance for converting a shoulder to a travel lane. According to this report, when a shoulder is used to route traffic around

Figure 3.9. *Drivable shoulder in Germany.*
Source: Kuhn (2010).

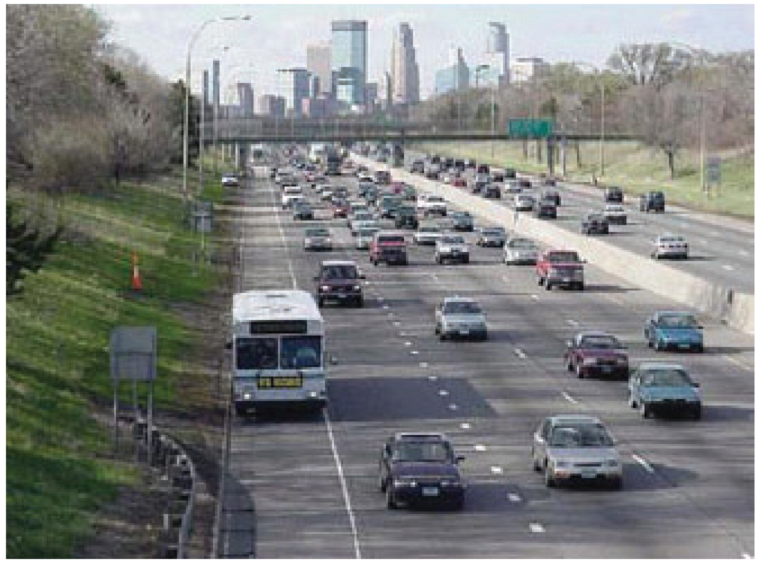


Figure 3.10. *Bus-only drivable shoulder on I-35 in Minneapolis, Minnesota. Source: DeCorla-Souza (2007).*

Figure 3.11. *Buses allowed on shoulder in Atlanta, Georgia.*

a work zone, 9 ft of shoulder width is considered acceptable, and 12 ft of shoulder width is considered optimal.

Most agencies will not route traffic around an incident unless the incident is in the lane adjacent to the shoulder because of the difficulty of communicating all the necessary lane shifts for other incident locations.

How Treatment Reduces Nonrecurrent Congestion

Increases Roadway Capacity During an Incident

Incidents cause nonrecurrent congestion and delay by blocking one or more lanes for the duration of the incident. If local policy allows, some of the incidents that block the rightmost lane of the roadway may be treated using drivable shoulders by diverting traffic around the incident on the right shoulder.

Factors Influencing Treatment Effectiveness

The following factors may influence the effectiveness of drivable shoulders at reducing nonrecurrent congestion:

- Number of days that the shoulder will be used as a lane during each work zone
- Percentage of incidents (by magnitude) occurring in outside lane during the analysis period
- Percentage of outside-lane incidents (by magnitude) during which treatment is expected to be used
- Effective capacity of shoulder
- Protocols for opening a shoulder lane during an incident (e.g., severity, location)
- Hours of the day and days per year shoulder is used as general-purpose lane

Cost

Factors that may affect the cost of providing a drivable shoulder along a roadway section include the following:

- Length of roadway section
- Width of pavement addition
- Type of pavement (asphalt, concrete)
- Temporary traffic control required during installation (or whether shoulder widening will be done along with a construction project that is already planned)
- Frequency of incidents during which traffic will be rerouted onto the shoulder
- Pavement construction costs
- Sign installation costs
- Ongoing costs to personnel directing traffic around incidents (e.g., law enforcement)

Alternating Shoulders

Description and Objective

Alternating shoulders are used on roadways without sufficient width to provide full shoulders on both sides of the roadway. Instead of providing narrow shoulders on both sides of the roadway, a full width shoulder is provided for one direction of travel for a specified length of roadway, and then provided for the other direction of travel for the next segment of roadway.

Alternating shoulders are often used in work zones where limited roadway width is available. In particular, this treatment is commonly used when one side of a divided roadway is shut down for a work zone and traffic is moved to the other side of the divided roadway, resulting in two-way traffic operations on that side. Rather than having a full shoulder for one direction of travel and little or no shoulder for the opposing direction of travel, a full shoulder is provided for one direction for some distance, and then the full shoulder is shifted to the opposite direction for some distance.

Alternating shoulders may also be implemented as a permanent treatment when one shoulder has been converted to a travel lane to meet increased demand, or where paved shoulders on both sides of an undivided roadway are narrow. Illustrations of two types of permanent alternating shoulder installations are shown in Figure 3.12.

Typical Applications

Alternating shoulders may be considered when one side of a divided roadway is shut down for a work zone, resulting in two-way traffic operations on the other side. A typical example would involve converting the cross section on that side of the roadway as follows:

- From same-direction travel lanes to opposite-direction travel lanes
- From a 4-ft inside shoulder to a barrier between travel lanes
- From a 10-ft outside shoulder to a 10-ft alternating shoulder

Figure 3.13 illustrates a typical cross section on one side of a divided roadway before and after converting it to a cross section with alternating shoulders.

Design Criteria

The AASHTO *Green Book* (2011), which provides general guidance for shoulder design, states that 10 ft is a typical shoulder width along freeways and that a width of 12 ft may be desirable on high-speed facilities with heavy truck volumes. In some work zones, the use of 6- to 8-ft shoulders may be warranted, especially if these widths allow the provision of shoulders for both directions of travel. The *Green Book* also states that "although continuous shoulders are preferable, narrow shoulders and intermittent shoulders are superior to no shoulders." This guidance seems to imply that if shoulders of at least 6 to 8 ft cannot be provided along a roadway segment, intermittent shoulders of at least that width would be an acceptable alternative.

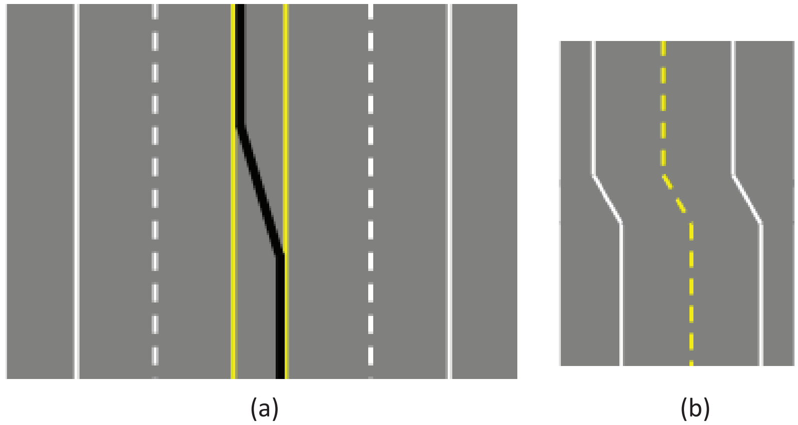


Figure 3.12. *Alternating shoulder examples: (a) median shift and (b) lane shift.*

The *Green Book* does not provide guidance on the recommended length of each intermittent shoulder. However, lengths of a quarter mile to a half mile have been reported by highway agencies. Intermittent shoulder spacing should not be so long that a disabled vehicle in a section without a shoulder would not be able to be relocated to the next available shoulder section.

When the alternating shoulder is designed in such a way that the lanes are shifted back and forth, the length of the transition between a shoulder on one side of the road and the other side will be somewhat dependent on travel speed. The faster traffic is moving, the longer the transition will need to be. The taper along a shoulder section that is transitioning into a section with no shoulder should be long enough to

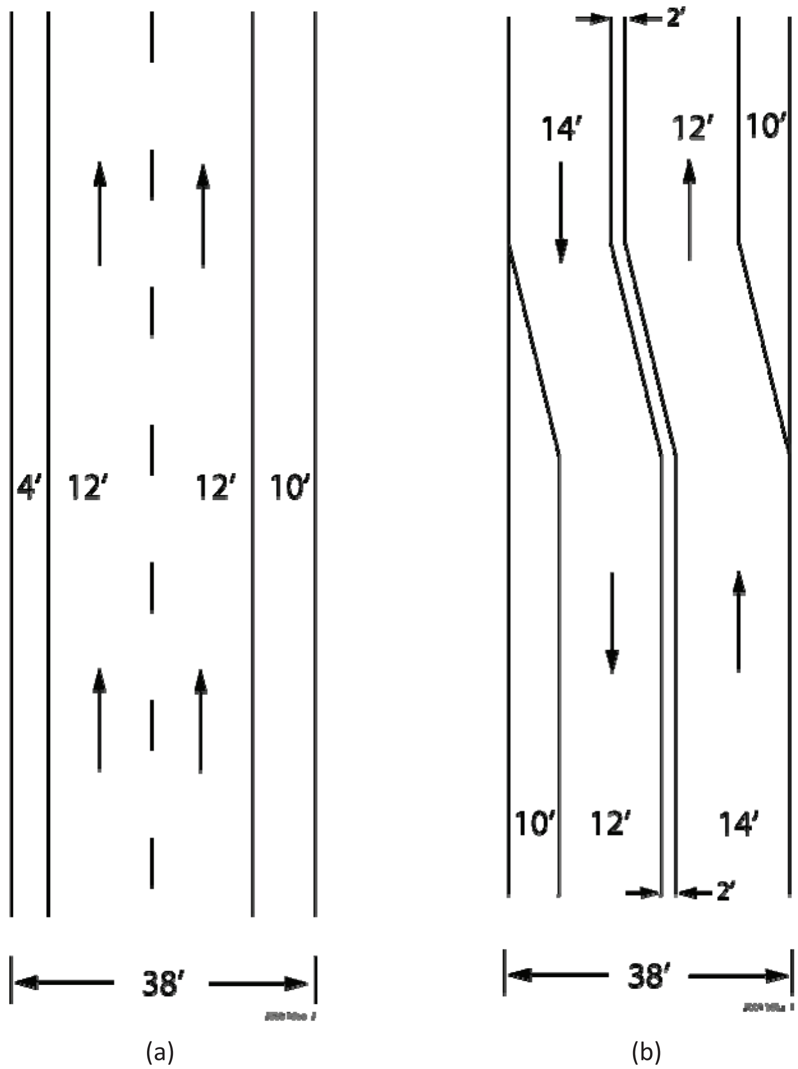


Figure 3.13. *(a) Before and (b) after conversion of a roadway to two-way operation with alternating shoulders.*

accommodate a vehicle trying to reenter the roadway. This is especially true for alternating shoulders in the median, where the reentering vehicle will be merging into the fastest lane of traffic.

How Treatment Reduces Nonrecurrent Congestion

Reduces Frequency of Crashes

The provision of a shoulder tends to reduce incident frequency. Zegeer et al. (1988) reported that a reduced crash rate can be calculated on the basis of shoulder width and shoulder type (paved or unpaved). To account for the fact that the wider shoulder is provided on only a portion of the freeway segment, a weighted average is calculated. For example, if 40% of the study segment has a shoulder, the weighted average crash rate is 0.4 times the lower crash rate plus 0.6 times the higher crash rate.

Reduces Lane Blocking by Incidents

With the installation of a shoulder, crash-involved vehicles that block lanes can be relocated to the shoulder. This results in a decreased lane-blocking time for these crashes. This reduction in average lane-blocking duration reduces the nonrecurrent congestion associated with crashes, thus reducing delay and improving reliability.

Factors Influencing Treatment Effectiveness

Factors that may influence the effectiveness of providing alternating shoulders include the following:

- Existing and planned usable shoulder width (e.g., an improvement that widens a 2-ft shoulder to a 12-ft shoulder will experience more benefit than an improvement that widens an 8-ft shoulder to a 12-ft shoulder)
- Existing and planned shoulder type (paved or unpaved)
- Frequency of lane-blocking incidents, and proportion of those that could be moved to a shoulder
- For a given direction of travel, the cumulative length (or percentage of segment) for which a full-width shoulder is available

Cost

Factors that may affect the cost of implementing an alternating shoulder include the following:

- Whether the alternating shoulder will be installed in the median of a divided road or on the outside shoulder
- Whether the alternating shoulder is designed as a permanent treatment or a temporary treatment during a construction project
- The interval spacing that will be used (or how many times the shoulder will switch sides over the length of the treatment implementation)
- Need for additional pavement construction

- Barrier and impact attenuator costs (moving existing, adding new, or replacing)
- Costs associated with removing and adding pavement marking
- Temporary traffic control (discussed in more detail below)
- Permanent signing

In work zones where previously divided two-way traffic is shifted to one direction of the divided roadway, a modular concrete barrier may be required. Impact attenuators may also be necessary at the end points of the barrier. If modular concrete barriers are not necessary (perhaps on lower-speed or lower-volume roadways), reflective delineators, cones, or barrels may be used to separate traffic and reduce the likelihood that vehicles will travel in lanes designated for the opposite direction of flow.

Similarly, permanent designs that involve a median shift may require relocating existing median barriers or adding new barriers along the new median shoulder alignment. Both temporary and permanent alternating shoulders will require additional guidance signs to inform drivers of the new alignment, and additional signs, such as speed limit reduction signs, may also be needed. Finally, additional law enforcement presence may be beneficial to ensure motorists are using the alternating shoulders properly and obeying all traffic controls.

Some costs may be incurred regardless of the treatment installation, such as restriping costs on a project that also includes resurfacing. Careful project planning and staging may help minimize costs associated with this treatment.

Portable Incident Screens

Description and Objective

Portable screening devices placed around an incident (typically along the roadside) obscure motorists' view of the incident and reduce congestion caused by rubbernecking (or "gawking"). The primary objective of this treatment is to reduce rubbernecking caused by the presence of an incident. By reducing rubbernecking, this treatment can reduce nonrecurrent congestion and secondary incidents.

Typical Applications

Portable incident screens are used to block motorists' view of an incident and incident-response activities, which can be distracting to motorists passing by. Screens may improve safety and traffic flow when traffic volumes approach roadway capacity because they discourage gawking (and slowing) by other motorists.

Application guidance regarding appropriate traffic, site, and emergency management conditions include the following.

Traffic Conditions

- The incident is likely to take more than 3 h to clear.
- The incident is likely to cause secondary congestion due to rubbernecking, and it is believed that deployment of the incident screen is likely to reduce this.

- Traffic volumes on the opposite roadway from the incident are expected to be relatively high or expected to become high during the anticipated duration of the incident.

Site Conditions

- It is possible to deploy the incident screen while maintaining at least 3.9 ft (1.2 m) between the incident screen and traffic lanes.
- It is possible to maintain an incident-side safety zone of at least 3.9 ft (1.2 m) from the screen at all times while the screen is being set up, is in place, and is being dismantled. (Vehicles and personnel should not enter the safety zone except in an emergency or to maintain the screen. If the safety zone cannot be provided, the screen should not be deployed.)
- Weather conditions are appropriate for the use of the screen. In particular, the screen should not be deployed in conditions of snow, ice, poor visibility, or high winds exceeding the maximum wind speed permitted for the stability classification of the screen.

Emergency Management Considerations

- The police must confirm that they do not consider that use of the screen would disrupt their operations.
- The ambulance, fire, and rescue services must agree to the use of the screen in the situation in question.
- The emergency services must confirm that it is not expected that a helicopter will land in the vicinity of the incident.
- The presence of the incident screen must present no hazard to or interfere with the work of the emergency services (including any operations of the air ambulance service), all other incident-related activity, or any ongoing work activities.

Design Criteria

The FHWA *Manual on Uniform Traffic Control Devices* (MUTCD) (2009) provides the following guidance: "Screens should not be mounted where they could adversely restrict road user visibility and sight distance, and adversely affect the operation of vehicles."

One of the most important operational factors in deployment of incident screens is their ability to remain stable in ambient wind conditions. United Kingdom guidelines identify the following stability criteria:

- A free-standing incident screen must comprise the following:
  - A rigid, flexible, or semiflexible sheet material that is restrained at the top, bottom, and both sides by attachment to a rigid (i.e., nonfolding) supporting structure to form a panel.

    - A series of portable bases to support one or more panels, the stability of which may be augmented by means of sandbags.
- The size and weight of the screen bases must be such as to ensure the stability of the free-standing incident screen system.
- Any sheet material used for either barrier-mount or free-standing incident screen panels is permitted to have a provision for reducing wind loading. This may be through either of the following methods:
    - Being porous over the entire area of the sheet material (wind-porous material).
    - Having vents in the sheet material that are effective from both sides.

How Treatment Reduces Nonrecurrent Congestion

Reduces Number of Gawking Events

A portable incident screen reduces rubbernecking within its influence area by obscuring drivers' view of incidents. Without a screen in place, drivers will tend to gawk at incidents in their direction of travel. This gawking usually involves a reduction in speeds as drivers slow down to get a better view of the incident. A portable incident screen can improve reliability by blocking the view of the drivers, such that they are unaware of the incident. By reducing the number of gawking events in the primary direction, portable incident screens can reduce the delay associated with the lower speeds during these events and improve reliability.

Reduces Incident Frequency

When drivers gawk at incidents, their attention is diverted from the task of operating their vehicle. As a result, crashes can occur that are a direct result of gawking at an incident. These crashes are termed *secondary crashes*.

To the extent that gawking at incidents causes secondary crashes, a portable incident screen will eliminate these secondary crashes. By eliminating these secondary crashes, delay is reduced and reliability is improved.

Factors Influencing Treatment Effectiveness

Factors that may influence the effectiveness of portable incident screens at reducing nonrecurrent congestion include the following:

- Expected number of incidents on the roadway
- Proportion of incidents that are gawk inducing (i.e., that cause rubbernecking)
- Percentage of gawk-inducing incidents that use screens
- Response time of screen crew to incident scene
- Treatment deployment time

Roadways with high numbers of incidents and with a high proportion of gawk-inducing incidents will receive the most benefit from portable incident screens. Faster response and set-up times of screen crews will also result in a larger benefit for this treatment.

Cost

Factors that may affect the cost of portable incident screens include the following:

- Level of wind resistance needed
- Type of screen (e.g., fabric screen with metal tube support structure, chain link fence with opaque covering, or other)
- Screen purchase cost
- Total length of screen needed
- Screen maintenance and storage costs
- Cost for multipanel connections
- Cost for stabilizing hardware (e.g., sandbags)
- Cost for vehicle or trailer for transporting screens to the site
- Other transportation-related costs (e.g., maintenance and fuel)
- Personnel required for deployment

Vehicle Turnouts

Description and Objective

Vehicle turnouts are short sections of shoulder provided on routes that have either no shoulder or very narrow shoulders. Vehicle turnouts allow a disabled or crash-involved vehicle to pull completely out of the travel way. Vehicle turnouts are typically at least 8 ft wide and are most often found on rural, two-lane highways with less than an 8-ft paved shoulder.

Typical Applications

Typical applications of vehicle turnouts include the following:

- Rural two-lane roads with little or no passing opportunity
- Scenic routes where travelers may want to slow or stop their vehicle to enjoy the scenery
- Locations without safe locations for law enforcement officers to monitor and enforce traffic violations
- Urban or suburban areas without paved shoulders wide enough to accommodate emergency stops
- Along freeways or on freeway ramps where space is needed for maintenance vehicles

Design Criteria

Design elements for turnouts include turnout width, turnout length, taper length, pavement marking, and signing. These characteristics depend on traffic characteristics and roadway characteristics. Roadways with higher design speeds require longer taper lengths to allow a vehicle to safely and smoothly leave the traveled way and merge back onto it.

Turnouts are often provided in rural locations when queues of traffic typically form behind slow-moving vehicles, causing impeded vehicles to make risky passing maneuvers that may result in crashes. In urban and suburban areas, turnouts are often provided in locations that have experienced a high number of incidents resulting from vehicles blocking all or part of a travel lane. They may also be located along freeways and ramps to accommodate maintenance vehicles during roadway maintenance activities. Turnouts are sometimes provided as a low-cost alternative to providing or widening a shoulder.

How Treatment Reduces Nonrecurrent Congestion

Reduces Number of Lanes Blocked by an Incident

With the installation of a vehicle turnout, crash-involved vehicles that block lanes can be relocated to the turnout. This results in a decreased lane-blocking time for these crashes. This reduction in average lane-blocking duration reduces the amount of nonrecurrent congestion associated with crashes, thus reducing delay and improving reliability.

Factors Influencing Treatment Effectiveness

Factors that may influence the effectiveness of vehicle turnouts in reducing nonrecurrent congestion include the following:

- Existing and planned usable turnout width (e.g., an improvement that widens a 2-ft shoulder to a 12-ft shoulder will experience more benefit than an improvement that widens an 8-ft shoulder to a 12-ft shoulder
- Existing and planned shoulder type (paved or unpaved)
- Frequency of lane-blocking incidents
- Proportion of lane-blocking incidents that could be moved to a turnout
- Cumulative length of turnout (or shoulder) (e.g., if there are two turnouts of 300 ft each, this value would be 600 ft)
- Shoulder material and depth (i.e., whether the shoulder is stable enough to be used as a travel lane during a work zone)

Cost

Several factors may affect the cost of installing vehicle turnouts along a roadway section:

- Width of the shoulder to be added
- Shoulder material (asphalt, concrete, gravel, or earth)
- Depth of shoulder material
- Availability of right-of-way

- Topography of roadside (especially in mountainous conditions where considerable cut or fill may be required)
- Percentage of roadway segment that will have shoulder (e.g., 100% would be a continuous shoulder)

Bus Turnouts

Description and Objective

A bus turnout (or bus pullout) is a designated paved area to the side of the roadway for buses to pick up and drop off passengers. The bus turnout allows vehicles on the roadway to continue without being obstructed by a stopped or idling bus. Bus turnouts are often found on suburban arterial roads and include tapers or acceleration–deceleration lanes, a paved bus bay area, and a passenger waiting area.

A bus turnout reduces disruptions to traffic flow due to bus stops along major roadways. It improves passenger safety during boarding and deboarding and can reduce the potential for rear-end crashes. Bus turnouts also provide a safe place for passengers to wait that is offset from the main travel lanes.

Typical Applications

Bus turnouts are typically constructed along high-volume, high-speed suburban corridors in growing areas where sufficient right-of-way is available. Transit agencies with considerable experience with bus turnouts are located in states such as Florida, Washington, and California. However, bus turnouts exist in various forms all over the United States.

Design Criteria

On streets with operating speeds of 40 mph or greater and where a bus blocking a travel lane causes unacceptable delay or presents a potential safety concern, a bus turnout should be considered. The bus turnout should be at least 12 ft wide (Darnell & Associates 2006).

How Treatment Reduces Nonrecurrent Congestion

Reduces Frequency of Lane-Blocking Stops

If no bus turnout is provided, buses will stop in the travel lane while passengers board and deboard the bus. Traffic flow is interrupted during these lane-blocking events, and congestion occurs. Bus turnouts can reduce the frequency of these events and the associated congestion, thus improving reliability.

Reduces Frequency of Incidents

Bus turnouts help reduce the potential conflicts between buses and general traffic. Reducing these conflicts can reduce the frequency of incidents and crashes (particularly rear-end crashes). By reducing the frequency of incidents and crashes, this treatment reduces the congestion associated with these incidents and improves reliability.

Factors Influencing Treatment Effectiveness

Bus turnouts are effective in maintaining uninterrupted traffic flow along the main thoroughfare. They also potentially improve safety by removing stopped vehicles from the roadway. However, they sometimes create delay for bus riders due to the need for buses to merge back into the flow of traffic. Some states have enacted yield-to-bus laws and developed various placards and signs, but driver adherence to these laws is sometimes limited. The merge can also create potential safety issues.

TCRP Report 19: Guidelines for the Location and Design of Bus Stops reports that bus drivers will not use a bus bay when traffic volumes exceed 1,000 vehicles per hour per lane (Fitzpatrick et al. 1996). Drivers explain that the heavy volumes make it extremely difficult to maneuver a bus out of a midblock or nearside bay and that the bus must wait an unacceptable period of time to reenter the travel lane. Consideration should be given to these concerns when contemplating the design of a bay on a high-volume road. Using acceleration lanes, signal priority, or farside (versus nearside or midblock) placements are potential solutions.

Cost

Factors that may affect the cost of installing a bus turnout along a roadway section include the following:

- New pavement
- Signs
- Pavement markings
- Lighting
- Additional right-of-way
- New curb and gutter

CRASH INVESTIGATION SITES

Description and Objective

A crash investigation site (CIS) is a paved area provided near highways to allow the relocation of crash-involved vehicles from the crash site to a safer area out of the way of traffic where crash investigations can be conducted. In addition to providing a location for crash investigations, these sites can be used to make cell phone calls, change a tire, or even as a rest area. Each of these uses can make mainline travel safer by reducing the number of emergency stops made in or near the roadway.

CISs reduce nonrecurrent congestion by minimizing the time during which vehicles remain in the roadway or on the roadway shoulder after an incident. Some typical installations are shown in Figures 3.14 through 3.16. The first figure shows a CIS within a freeway interchange in Chicago, Illinois, the second figure shows an off-system CIS in Minnesota, and the third figure shows a roadside CIS in Atlanta, Georgia.

Figure 3.14. *Aerial view of a crash investigation site (on the right side of the photo) within a freeway interchange in Chicago, Illinois.*
Source: © Google Earth 2013.

Typical Applications

CISs are typically used on high-volume urban freeways, where crash investigations on the roadway shoulder have the greatest potential to create congestion.

Design Criteria

It is important that a CIS be clearly identified through signing and other markings. The more accessible that a CIS is, the more likely it is that motorists will make use of the site. Therefore, locating CISs near the freeway and making them easily accessible is recommended. Providing sufficient lighting and a paved area greater than 1,000 ft^2 are also recommended to encourage CIS use (Dudek et al. 1988). CISs are typically used in the following types of location:

- A gravel or paved area separated from the roadway and accessible from the mainline (see Figure 3.14)
- A widened shoulder area or purpose-built parking area on a freeway off-ramp
- A widened shoulder area on the arterial crossroad near a freeway off-ramp terminal
- A widened shoulder area on a side street off the arterial crossroad in the vicinity of a freeway off-ramp terminal

Police officers generally prefer CISs that are directly accessible from the mainline. When possible, it is preferable that police be consulted during the design and placement of CISs in order to identify the most ideal locations where both officers and motorists will be encouraged to use the sites.

Figure 3.15. *Roadside crash investigation site in Minnesota.*

Figure 3.16. *Crash investigation site in Atlanta, Georgia.*

How Treatment Reduces Nonrecurrent Congestion

Reduces Lane-Blocking Time of Incidents

By providing a preestablished relocation spot, this treatment can reduce the time during which disabled, crash-involved, or police vehicles remain in the roadway or on the roadway shoulder. This reduction in lane-blocking time reduces the congestion associated with these incidents and increases the reliability of the roadway.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of a CIS at reducing nonrecurrent congestion:

- Expected number of crashes per year (by severity)
- Proportion of crash-involved vehicles that are physically movable (by type)
- Proportion of physically movable vehicles that are drivable
- Presence or absence of local agency policy to move crash-involved vehicles to a nearby CIS, when appropriate
- Number of CISs on the analysis segment
- Location and accessibility (mainline, ramp, crossroad)
- Presence of ancillary signing to identify and encourage the use of CISs

Cost

Factors that may affect the cost of constructing a CIS along a roadway section include the following:

- Number of CISs to be installed along the roadway section
- The total square footage of each
- The material used for construction of the CIS (concrete, asphalt, gravel)
- Right-of-way cost and availability
- Need to install signs identifying the CIS and directing motorists into the site
- Pavement marking

RIGHT-OF-WAY EDGE

Emergency Access Between Interchanges

Description and Objective

Gated emergency access points can be provided between standard interchanges to connect a freeway facility with the local street system for the purpose of providing quicker access to remote locations not directly served by an interchange for fire, medical, and other emergency vehicles. These types of access points can also be used for maintenance access to remote utility facilities and, as part of right-of-way considerations, to provide land access to remote and otherwise inaccessible properties. As this treatment is not intended to provide freeway access to the public, locked gates are typically installed at the freeway right-of-way line to restrict access. FHWA requires special approval to provide locked gate access to or from roadways in the Interstate highway system, and many state agencies have followed suit in requiring permission to provide locked gate access to or from freeway facilities. Some agencies, such as Caltrans (the California DOT), have developed policies prohibiting these types of access points.

The primary objective of locked gate access, as illustrated in Figure 3.17, is to allow emergency and utility vehicles to access the local street network or a specific site from the freeway in remote locations where ordinary access is not provided via freeway ramp interchanges. In the reverse direction, these access points could also prove beneficial if an emergency services agency or utility company would have an unusually circuitous route to access the freeway.

Typical Applications

Where interchange spacing is relatively long, emergency responders may have to travel a long distance past an incident site to reach an interchange, exit, and return to the incident site. Gated emergency access points allow emergency responders to access the incident site more directly and quickly, and the greater the interchange spacing, the greater the amount of time saved.

Gated emergency access points can be used to reroute traffic via a U-turn maneuver in response to a major lane-blocking incident. When a major incident blocks traffic for a significant amount of time, traffic may back up behind the incident and cause significant delay to motorists. If an emergency access gate is opened to traffic, motorists can exit the freeway system and make their way to their destinations via alternate routes, thus dissipating the freeway queue and reducing delay.

Design Criteria

The *Federal Aid Policy Guide* (FHWA 1998) provides specific guidance for obtaining permission to use locked gate emergency access:

- "Locked gate access points on the Interstate system are used primarily to provide access for fire, medical and other emergency vehicles to reduce travel time, for maintenance activities at remote utility facilities and as part of the right-of-way consideration, to provide land access in remote locations.
- "Any request for locked gate access should be reviewed to ensure that vehicles can enter the Interstate safely, appropriate sight distance is available to and from the access, and the access is located such that the intended function is served (distance to nearest interchange and/or median crossover). Each new locked gate access approval needs to incorporate the following conditions:
  - The gate shall be locked at all times except when opened for passage of the authorized vehicles. The distribution of keys for the lock should be limited.
  - The access roadway will be constructed of an inconspicuous natural material to discourage unauthorized use.
  - The purpose of the access should be specified."

Limited information about locked gate access points, outside of federal and state regulations and policies, is available in the literature.

Figure 3.17. *Emergency access between interchanges.*
Source: © Google 2013.

How Treatment Reduces Nonrecurrent Congestion

Reduces Incident Duration

A gated emergency access point between standard freeway interchanges reduces the time during which disabled, crash-involved, or police vehicles remain in the roadway or on the roadway shoulder by decreasing the response time of emergency personnel. By reducing the lane-blocking time of an incident, the nonrecurrent congestion associated with that incident is reduced. This reduction in nonrecurrent congestion results in an increased reliability for the roadway segment.

Factors Influencing Treatment Effectiveness

Factors that may influence the effectiveness of emergency access between interchanges on nonrecurrent congestion include the following:

- Average response time reduction for the instances when the treatment is used
- Percentage of each incident type that will use the treatment to improve response time

Cost

Factors that may affect the cost of installing emergency access between interchanges include the following:

- Type of control to be used (manually operated gate, automated gate, temporary barricades)
- Pavement surface to be used (gravel, asphalt, concrete)
- Length of pavement required to connect to local road network
- Width of pavement connection
- Signs needed to identify and discourage unauthorized use of gated emergency access points

ARTERIALS AND RAMPS

Ramp Widening

Description and Objective

This treatment consists of widening a freeway ramp by the construction of additional pavement. The benefits of this treatment discussed in this section relate specifically to the increased ramp capacity associated with ramp widening.

The objective of ramp widening is to increase the capacity of a ramp by providing additional lanes or additional maneuvering space within the existing lanes, as illustrated in Figure 3.18. This capacity increase is intended to eliminate (or preemptively

Figure 3.18. *A two-lane off-ramp in Minnesota.*

avoid) the situation in which a ramp queue backs up onto the freeway mainline. Such queues can be detrimental to mainline operations and can result in significant delays and reduced reliability.

In addition, this treatment can reduce nonrecurrent congestion by eliminating some of the crashes that occur on or near the ramp. Additional ramp width can provide additional maneuvering space that can sometimes be used by drivers to avoid a collision. By eliminating crashes, this treatment can eliminate the congestion associated with these crashes.

Typical Applications

Ramp widening may be considered at any ramp–arterial intersection where long queues form. FHWA's *Ramp Management and Control Handbook* (Jacobson et al. 2006) provides the following reasons for widening a ramp:

- Entrance ramps
    - Need for additional storage capacity (e.g., metered ramps where traffic frequently backs up into the adjacent arterial may be a candidate for widening)
    - Need for enforcement zones where personnel can be stationed safely and where ramp meter operations are clearly visible
    - Need for adequate room to perform maintenance activities (e.g., removing debris, trimming nearby vegetation, or repairing infrastructure)
    - Need for designated lanes for special classes of vehicles, such as HOVs (the additional capacity in these situations will promote use of transit and carpooling and vanpooling by providing benefits in terms of reduced delay for these vehicles
- Exit ramps
    - Need for more storage at the ramp terminal traffic signal to keep queues from backing onto the freeway
    - Need to separate traffic movements at the traffic signal to provide efficient or safe signal operations
    - Need for additional turn lanes to efficiently handle high traffic volumes

Design Criteria

The MUTCD (FHWA 2009) and the *Green Book* (AASHTO 2011) offer information on various design considerations for any ramp or arterial intersection. Widening entrance or exit ramps is often implemented in conjunction with adjustments to traffic signal timing to prevent queues from forming on the arterial or freeway. On exit ramps, ramp widening is often implemented with pavement markings to separate different traffic movements.

Design considerations for ramp widening include the following:

- Storage capacity of the existing ramp and storage capacity needed to eliminate queuing on the freeway or arterial

- Required lane width for buses or other special vehicles, if added lane is to be an HOV lane or restricted to certain vehicles
- Available right-of-way
- Potential use of existing shoulder
- Space for right-of-way maintenance to occur outside of lanes
- Space for law enforcement outside of lanes
- Ramp meters, if in use or if planned for future use
- Auxiliary lanes on the arterial or freeway to accommodate additional lanes on the ramp

Whenever construction is needed to widen a ramp, practitioners may find it beneficial to complete additional work, if needed, while the ramp is being widened. Such work may include fixing geometric deficiencies, repairing the roadway surface, and posting additional signs. In these situations, it may be more cost-effective to complete additional work if the ramp is already closed or if the resources are readily available. This practice reduces the level of effort required to close the ramp and to set up work zone–related equipment (e.g., signs, barriers, cones). If the ramp must be closed, completing additional work may also reduce the number of times the ramp must be closed, which consequently reduces the impact on motorists.

Ramp widening can have a positive effect on roadway safety by providing more maneuvering space, which can allow some crashes to be avoided. The safety effectiveness of a ramp-widening project will depend on several factors, including the following:

- Safety concerns before the widening project (e.g., crash frequency near the ramp, queues around the ramp)
- Allocation of space after the widening (e.g., additional lanes, HOV lane, enforcement zone, wider shoulders)
- Traffic control changes in conjunction with the widening (e.g., signal timing changes at interchange, addition of meters)

How Treatment Reduces Nonrecurrent Congestion

Reduces Frequency of Queue Spillback Events

Ramp widening can reduce the occurrence of off-ramp queues backing up onto the mainline of the freeway by increasing the capacity of the ramp. Because a queue effectively blocks a freeway lane until it dissipates, such events can have a significant effect on freeway reliability. By reducing the frequency of these lane-blocking events, this treatment can reduce the delay associated with these events and improve the reliability of the freeway segment.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of ramp widening at reducing nonrecurrent congestion:

- Frequency of off-ramp queues backing up onto the freeway mainline
- Frequency of treatment use
- Percentage capacity increase to off-ramp movements associated with ramp widening
- Frequency of ramp-related crashes that could have been avoided if more maneuvering space were available

Off-ramps with high demand-to-capacity (d/c) ratios will tend to benefit most from this treatment, particularly where the available storage space on the ramp is limited, because a high d/c ratio creates a situation in which queues may frequently back up onto the mainline. The mainline demand volume is also important, because the effect of a queue blocking a freeway lane will be significantly stronger where mainline d/c ratios are high.

Cost

Factors that may affect the cost of ramp widening include the following:

- Available right-of-way
- Amount of proposed widening
- Ramp grade
- Length of proposed widening
- Associated improvements or additions of auxiliary lanes
- Associated changes to traffic control
- Temporary traffic control required during construction
- Type of pavement to be constructed (concrete, asphalt)
- Changes to pavement markings
- New signing required
- Installation of additional signal heads
- Adjustments to signal timing

Ramp Closure

Description and Objective

A ramp closure is a method of managing traffic patterns on and surrounding freeway ramps. Closures may be implemented with the use of automatic gates, barriers, or gates that need to be moved manually or by physically removing a ramp. There are three general types or classifications of ramp closures: (1) permanent, (2) time of day or scheduled, and (3) temporary. Permanent and time-of-day (or scheduled) ramp closures are applicable to recurrent congestion, and temporary ramp closures are applicable to nonrecurrent congestion. Only temporary ramp closures are considered here.

Temporary ramp closures may be done in response to one of the following sources of nonrecurrent congestion: (1) major incidents, (2) work zones, (3) special events, or (4) inclement weather conditions. Temporarily closing a ramp will decrease the mainline demand, leading to a reduction in mainline congestion and improved reliability. This decrease in mainline demand necessarily results in an increased demand on alternate routes, which can cause increased congestion and reduced reliability on these routes. To mitigate this problem, improvements to the alternate routes should be considered (see Improvements to Detour Routes in this chapter). Figure 3.19 illustrates an example of a gate used to close a ramp.

Typical Applications

Temporary ramp closures may be done in response to one of the following sources of nonrecurrent congestion: (1) major incidents, (2) work zones, (3) special events, or (4) inclement weather conditions.

Design Criteria

Design considerations for temporary ramp closures include ramp layout, traffic control equipment, traffic control layout, and signal timing. These elements of the design are determined by traffic conditions, ramp geometry, length of closure, and reason for closure. Some of these design considerations are briefly discussed below.

The ramp closure layout depends on a variety of factors, including the length of the closure and the reason for closure. Guidance can be found in the MUTCD (FHWA 2009).

Figure 3.19. *An automated gate used to close access in response to severe weather conditions.*
Source: Jacobson et al. (2006).

Barricades are often used for temporary closures because they are a low-cost option for infrequent closures. However, as setting up and removing barricades can be labor intensive, they are less desirable when closures are expected to be implemented more frequently. Semipermanent barriers such as flexible pylons or water-filled barrels may be used for planned full ramp closures. In locations where ramp closure is expected to occur periodically (such as for snow and ice, fog, planned special events, or peak period ramp closures), automatic ramp gates may be used. Gates may be controlled manually by staff in the field or remotely from a traffic management center, and they may swing vertically or horizontally. Ramp design may have to accommodate the path of horizontally swinging gates. The various types of equipment used to control the gates have various degrees of flexibility and various levels of required maintenance.

Drivers should be provided advanced warning that a ramp is closed. Signs, flags, and pavement markings can all be used to indicate to the driver that the ramp is not accessible. Changeable or dynamic message boards should be used in advance of the ramp where available. Static signing may also be used. At ramp approaches with dedicated lanes, those lanes should be closed with cones, signing, or pavement marking in advance of the closed ramp.

Even for ramp closures that are short in duration, the disruption to traffic flow may be significant, and the consequences to those who use the ramp may be severe. Outreach is especially important when ramps will be closed during peak times. For planned activities, such as special events and construction activities, travelers should be made aware of the closure well in advance and should be provided with information about alternate routes. This can be accomplished through electronic and print media, such as newsletters, website postings, e-mail distribution lists, and 511 systems.

How Treatment Reduces Nonrecurrent Congestion

Reduces Mainline Demand

Ramp closures improve traffic operations on the mainline by shutting off access to the mainline at one or more ramp locations. Decreasing access reduces mainline demand, which decreases mainline congestion and improves reliability.

Reduces Frequency of Queue Spillback Events

The occurrence of off-ramp queues backing up onto the mainline of the freeway is reduced by closing the off-ramp during special events. Such events can have a significant effect on freeway reliability, because the queue effectively blocks a freeway lane until it dissipates. By reducing the frequency of these lane-blocking events, this treatment can reduce the delay associated with these events and improve the reliability of the freeway segment.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of ramp closure at reducing nonrecurrent congestion:

- ***Duration of the mainline event.*** Ramp closures will have a more prominent effect when a mainline work zone or other incident is expected to reduce the roadway capacity for a significant period of time.
- ***Frequency of treatment use.*** Ramp closures that are used multiple times per year (e.g., for recurring special events like baseball games) will tend to see a greater benefit from this treatment than infrequently used ramp closures.
- ***Capacity of alternate routes.*** If alternate routes are already badly congested, this treatment will be less effective (from a global system perspective) because the congestion will only be shifted from the mainline to other routes. Conversely, if alternate routes are operating well below capacity, ramp closures will be much more beneficial because traffic can divert to these other routes without significant delay increase to the roadway system in general.

Cost

Factors that may affect the cost of closing a ramp include the following:

- Frequency of closure
- Barrier or gate type (temporary barricades, permanent railroad crossing–type gates, permanent gates that require manual operation)
- Personnel and time required to deploy closure

Ramp Terminal Traffic Control

Description and Objective

Ramp terminal traffic control involves increasing the traffic capacity at the termination of a freeway off-ramp. These capacity improvements may involve the following:

- Installation of signals
- Improved signal timings
- Installation of a roundabout
- Installation of turn lanes
- Changes to signing, striping, or signals used at the ramp terminal to control the movement of traffic
- Manual traffic control by law enforcement (most commonly used during a special event)

The objective of ramp terminal treatments is to increase the capacity at the terminal of a ramp to eliminate (or preemptively avoid) the situation in which a ramp queue backs up onto the freeway mainline. Such queues can be detrimental to mainline operations and can result in significant delays and reduced reliability. Figure 3.20 illustrates a ramp terminal intersection. Figure 3.21 illustrates a signalized roundabout at a ramp terminal; the signal is triggered when a detector on the ramp detects a queue on the ramp.

Figure 3.20. *Ramp terminal intersection.*
Source: Hughes et al. (2010).

Typical Applications

Coordinating ramp terminal signal timing with other signals along the arterial corridor can reduce delay and increase traffic flow, resulting in fewer conflicts and crashes near the ramp terminal. Peak period spillback onto the freeway or arterial, which can also lead to crashes, can be reduced or eliminated by phasing adjustments, which can help clear peak period ramp queues.

Properly assigned turning lanes on exit ramps and extra storage can help prevent queues from spilling back onto the freeway. Advanced signing for lane assignments and directional information can assist drivers in making lane placement decisions early and can prevent weaving and unexpected movements that lead to crashes near the ramp terminals. Clear pavement markings can assist in this, as well.

(a) (b)

Figure 3.21. *(a) Aerial image of Maryland roundabout and (b) photo showing the signalized arterial leg of the roundabout.*
Source: © Google 2013.

Traffic control provided by law enforcement is a common treatment at interchanges near arenas, stadiums, and concert halls when high volumes of traffic are arriving or leaving at the same time. Although police presence is not directly design related, certain design elements may provide assistance to police officers or help make their directions more clear. Some examples may include permanent variable message signs, changeable lane-control signs, clear striping, median refuges, appropriate placement of signal boxes, and others. Police presence may also be used at a ramp terminal to direct traffic in cases of incidents that occur on or near a ramp.

One example of an innovative ramp terminal treatment is found on Maryland Highway MD-100 near Baltimore, Maryland. At this location, a roundabout was used at the ramp terminal. Peak hour traffic flowing from the arterial toward the freeway entrance ramp was quite heavy. This steady stream of traffic prevented vehicles on the exit ramp from entering the roundabout, and therefore caused those vehicles to queue back onto the freeway. To address this problem, the Maryland State Highway Administration installed a signal above the arterial leg of the roundabout that coordinates with an advanced detection loop on the ramp. When vehicle queues reach a determined interval on the ramp, the signal shows a red indication to the arterial traffic. This provides a gap for ramp traffic to enter the roundabout. After the queue dissipates, the signal indication changes to allow the arterial traffic to continue onto the roundabout.

Design Criteria

Ramp terminal improvements may be implemented wherever issues are occurring at or near a ramp. Specific criteria for implemented treatments have not been defined in the literature; typically, the decision to implement one or more of the treatments outlined below is based on engineering judgment in response to observed problems such as excessive delay, spillback queuing onto the freeway or arterial, increase in crashes at or near ramps, or inadequate vehicle storage. The MUTCD (FHWA 2009) provides guidance and standards for various applications of traffic signals, signing, and striping.

Improved signal timing and clear signing and striping have documented safety effects; however, these treatments are not typically evaluated for their specific impact at ramp terminals. It is expected that these treatments, particularly when they address ramp queue spillback onto the freeway, reduce conflicts that can lead to crashes.

How Treatment Reduces Nonrecurrent Congestion

Reduces Number of Queue Spillback Events

Ramp terminal traffic control reduces the occurrence of off-ramp queues backing up onto the mainline of the freeway. Such events can have a significant effect on freeway reliability, because the queue effectively blocks a freeway lane until it dissipates. By reducing the frequency of these lane-blocking events, this treatment can reduce the delay associated with these events and improve the reliability of the freeway segment.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of ramp terminal traffic control at reducing nonrecurrent congestion:

- Frequency of off-ramp queues backing up onto the freeway mainline
- Frequency of treatment use (applicable specifically to treatments that require ongoing activity, such as manual control by law enforcement)
- Capacity increase expected from a particular ramp treatment (e.g., the addition of a turn lane will increase capacity significantly more than a small adjustment to signal timings)

Off-ramps with high d/c ratios will tend to benefit most from this treatment, particularly when the available storage space on the ramp is limited, because a high d/c ratio creates a situation in which queues may frequently back up onto the mainline. The mainline demand volume is also important, because the effect of a queue blocking a freeway lane will be more significant when mainline d/c ratios are high.

Cost

Factors that may affect the cost of implementing improved ramp terminal traffic control include the following:

- Type of proposed change (e.g., signal installation, signal retiming, turn lane construction, roundabout installation)
- Personnel needed (e.g., police officer to direct traffic)
- Construction costs
    - Pavement construction
    - Signal installation
    - Signal retiming
    - Changes to pavement markings
    - Roundabout installation
- Ongoing costs
    - Personnel deployment to direct traffic
    - Resources to monitor ramp and determine when treatment should be deployed (e.g., use of a traffic management center)

Ramp Turn Restrictions

Description and Objective

Ramp turn restrictions can be implemented at the ramp–arterial intersection to better manage traffic operations. Ramp turn restrictions to limit access to a ramp may be implemented to intentionally divert traffic away from a ramp either because (1) the ramp does not have enough storage capacity for turning vehicles, or (2) queues that form on the arterial exceed the storage limits of the turn lane and, because of this, traffic flow on the mainline is impeded.

Ramp turn restrictions limit access to an arterial in order to increase capacity at the ramp terminal. This capacity increase is intended to eliminate (or preemptively avoid) the situation in which a ramp queue backs up onto the freeway mainline. Such queues can be detrimental to mainline operations and can result in significant delays and reduced reliability.

Typical Applications

Ramp turn restrictions may be considered at any ramp–arterial intersection where long queues form. Turn restrictions may be implemented for specific time frames (e.g., weekdays from 7:00 to 9:00 a.m.), during specific events when demand is particularly high (such as sporting events or concerts), or permanently.

Design Criteria

Ramp turn restrictions are implemented along the arterial street network at the ramp location or on the ramps near the intersection with the arterial. Ramp turn restrictions are often deployed using temporary signing and barriers and enforced on site by enforcement personnel. However, at locations where turn restrictions may be used on a more regular basis (e.g., near stadiums or arenas), consideration may be given to attaching dynamic message signs to traffic control devices at the ramp–arterial intersection. For example, at signalized intersections near special event locations, prefitted dynamic message signs can be installed to implement ramp turn restrictions on demand. Cameras may also be installed along sections of roadway or at intersections to allow personnel to better manage operations, particularly surrounding special events.

A key consideration in the planning and design of ramp turn restrictions is to maintain good flow on the arterial and manage the queues that may form either on the ramp or on the arterial turn lane. Consideration should be given to where traffic will reroute in response to these restrictions and whether the roadways in these areas can accommodate increased traffic demands.

The MUTCD (FHWA 2009) and *Green Book* (AASHTO 2011) offer information on various design considerations for any ramp or arterial intersection. Each highway agency may also have its own guidelines and policies regarding temporary traffic control for nonrecurrent congestion situations.

The primary purpose of implementing a ramp turn restriction is to improve the operational effectiveness of the ramp–arterial intersection. However, ramp turn restrictions may have safety benefits, as well, particularly if ramp queues have been extending onto the highway. The following safety-related issues should be given consideration:

- Are drivers given sufficient warning about the ramp turn restriction?
- Is secondary congestion being created as a result of the ramp turn restriction, and does this create a safety issue?
- Does the ramp turn restriction affect pedestrian and bicycle maneuvers at the intersection?

How Treatment Reduces Nonrecurrent Congestion

Reduces Frequency of Queue Spillback Events

Ramp turn restrictions reduce the occurrence of off-ramp queues backing up onto the mainline of the freeway. Such events can have a significant effect on freeway reliability, because the queue effectively blocks a freeway lane until it dissipates. By reducing the frequency of these lane-blocking events, this treatment can reduce the delay associated with these events and improve the reliability of the freeway segment.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of ramp turn restrictions at reducing nonrecurrent congestion:

- Frequency of off-ramp queues backing up onto the freeway mainline
- Frequency of treatment use
- Percentage capacity increase to off-ramp movements associated with turn restrictions

Off-ramps with high d/c ratios will tend to benefit the most from this treatment, particularly where the available storage space on the ramp is limited, because storage limitation creates a situation in which queues may frequently back up onto the mainline. The mainline demand volume is also important, because the effect of a queue blocking a freeway lane will be significantly stronger where mainline d/c ratios are high.

Cost

Factors that may affect the cost of ramp turn restrictions include the following:

- Duration of restriction (all hours or select hours only)
- Permanent signing required
- Use of dynamic signing on ramp
- Use of dynamic signing on signal mast arm
- Need to change pavement markings
- Frequency of use of manual ramp restrictions
- Personnel required for manual restrictions
- Materials required for manual restrictions (such as barriers and traffic barrels)
- Construction costs (e.g., permanent signing, dynamic signs, changes to pavement markings)
- Ongoing costs (e.g., personnel needed to manually restrict turns at ramp and equipment such as traffic cones and vehicles needed for manual traffic direction)

DETOURS

Improvements to Detour Routes

Description and Objective

Detour routes are designated roadways set up to carry traffic along a secondary route to bypass a congested location on the primary route. Detour routes typically connect to the primary route at locations in close proximity to the point of congestion both upstream and downstream. The roadways that serve as detours (typically arterials and minor streets) must serve not only the displaced traffic, but also their normal traffic volumes. Thus, improvements to the corridor are often advantageous, if not necessary, to provide adequate service to motorists using the route while the detour is in effect.

The objective of this treatment is to provide acceptable levels of service to mainline traffic that will be negatively affected by a work zone, incident, or other major event. By increasing the capacity of a detour route, the traffic demand on the mainline can be reduced, thus easing congestion and improving reliability.

Typical Applications

Most detour route improvements on streets and arterials center on reallocating available roadway space to meet the new traffic demands. This includes restriping or temporarily designating lanes to allow vehicles to use shoulders or on-street parking space to increase the route's capacity. For freeways and limited-access highways designated as detour routes, additional improvements involve eliminating normal lane restrictions that might have been present.

As an example, after the I-35W Mississippi Bridge collapse in the Minneapolis–St. Paul, Minnesota, metropolitan area, Trunk Highway 280 was designated as the detour route to service the predominant traffic flows heading to and from the downtown area. To accommodate the new demand, additional lanes were created by using shoulders and narrowing existing lanes. The other major improvement was the closing of all at-grade intersections along the detour stretch to create, in effect, a limited-access freeway environment.

Design Criteria

FHWA's *Alternate Route Handbook* (Dunn Engineering Associates 2006) is an available resource for assessing and implementing effective detour routes. Any improvements to the route that involve changes to the geometry or traffic control of the roadway should be done in consultation with such manuals as the AASHTO *Green Book* (2011), the MUTCD (FHWA 2009), and agency standards for work zone design and implementation.

A variety of treatments may be used to improve a detour route, but the primary objective is to improve the detour route so that it can provide an acceptable level of service to the additional traffic it will be required to handle. Improvements may include the following:

- Providing additional lanes by using existing pavement surface for traffic through the use of shoulders or on-street parking areas

- Providing additional surface area with new pavement to increase the number of usable lanes
- Restriping or resigning routes to accommodate additional volumes
- Minor widening at intersections
- Retiming signalized intersections to give additional green time to directions of travel with increased volumes
- Accommodating trucks and other large vehicles that may not have used the detour route previously (e.g., by increasing weight limits of bridges or increasing turning radii)
- Improving the road surface, limiting access, improving sight distance, and other improvements that may allow a higher speed limit
- Reconstructing isolated bottlenecks
- Using high-quality pavement markings and stripes for unfamiliar drivers to follow
- Using upgraded size and retroreflectivity of warning signs due to increased traffic load
- Adding stop and yield signs or even traffic signals if existing intersection controls are inadequate for increased traffic loads
- Adding temporary lighting to reassure drivers that they are following correct detour route
- Adding an asphalt overlay before detour implementation to accommodate increased traffic load if detour is located on a poor pavement surface
- Using a partial detour diversion such as keeping semitruck traffic (left lane) on the highway while passenger vehicles (right lane) exit the highway and enter the detour (the detour would lead those exiting users back onto the highway at a later mile marker)
- Implementing a truck diversion (opposite of previous bullet) and allowing the highway to carry the remaining traffic load (however, nighttime detour of truck traffic may be objectionable to residential neighborhoods)
- Providing advance notice, especially during nighttime detours, to allow commuters and other drivers who frequent the route to plan an alternative route

Detour routes that are expected to be used frequently or that may not be capable of handling Interstate traffic volumes may be improved proactively, before an event requiring the use of the route as a detour is ever needed. Computer simulation can be a useful planning tool in determining the effects that a certain improvement may have on a detour route.

During unplanned events or emergencies, traffic must be rerouted immediately, leaving little time for analysis, planning, or improving the detour routes. Proactive detour planning may help an agency identify routes that are appropriate for use as detours before an incident occurs, and improvements can be made to these routes if it is determined that they are likely to be used frequently (near high-crash locations) or potentially for long periods of time (near locations susceptible to severe damage, such as bridges near fault lines). When unplanned events requiring a detour occur where a detour has not been planned, and the detour is expected to be long-term, it may be appropriate to improve the detour route after it is in use. Examples of major events that fall into this category would be the closure of the Santa Monica Freeway after the Northridge earthquake of 1994, and more recently the closure of I-35W in Minneapolis–St. Paul after the bridge collapse across the Mississippi River in 2007.

How Treatment Reduces Nonrecurrent Congestion

Reduces Mainline Demand

Detour route improvements improve traffic operations by increasing the capacity of detour routes. When a detour route has higher a higher capacity, some of the mainline traffic demand can be diverted to the detour route. This diversion results in a decreased demand on the mainline, which decreases mainline congestion and improves reliability.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of improvements to detour routes at reducing nonrecurrent congestion:

- ***Duration of the mainline event.*** This treatment will have a more prominent effect when a mainline work zone or other incident is expected to reduce the roadway capacity for a significant period of time.
- ***Directness of the detour.*** Detour routes that divert traffic farther out of the way will tend to be used less.
- ***Capacity effectiveness of the improvement.*** Adding lanes, for example, will have a greater effect on improving mainline reliability than simply improving the pavement surface of the detour route.

Cost

Factors that may affect the cost of improvements to a detour route include the following:

- Length of roadway to be improved
- Type of improvement (construction of new pavement, restriping, traffic signal adjustments)
- Material to be used for improvement (concrete, asphalt)

TRUCK INCIDENT DESIGN CONSIDERATIONS

Runaway Truck Ramps

Description and Objective

A runaway truck ramp (or truck escape ramp) is typically a long sand- or gravel-filled lane (sometimes a paved lane) adjacent to a roadway that is designed to slow or stop heavy vehicles that have lost control or are unable to stop due to brake failure on a downgrade.

The objective of a runaway truck ramp, illustrated in Figure 3.22, is to reduce crashes involving heavy vehicles on or near downgrades by providing a path for out-of-control trucks to come to a safe stop away from other traffic.

Crashes involving heavy vehicles can cause significant nonrecurrent congestion because they are often quite severe, involving several vehicles and blocking multiple lanes of travel. Runaway truck ramps reduce nonrecurrent congestion by preventing such heavy-vehicle crashes.

Typical Applications

Runaway truck ramps have been in use for over 40 years in the United States, as well as internationally. They are typically found near the bottom of steep downgrades or along extended downgrades, especially where a heavy vehicle might be required to slow or stop, such as before a horizontal alignment change (curve) or an intersection. Most often, runaway ramps are found along rural Interstates in mountainous regions, where prolonged braking can cause truck brakes to overheat and fail. However, escape ramps can also be found in suburbs and some urban areas where a runaway truck would have a higher likelihood of crashing with other vehicles and causing injuries or fatalities.

Figure 3.22. *Runaway truck ramp. Source: Washington State Department of Transportation (2009).*

The AASHTO *Green Book* (2011) provides guidance on where runaway truck ramps should be located. It suggests that on existing facilities, a truck ramp should be provided as soon as need is established. This need could be determined by operational problems on downgrades reported by truck drivers, law enforcement, or the general public. It could also be determined by characteristics of the roadway, such as alignment, gradient, length of grade, and vehicle speed, all of which influence the potential for out-of-control vehicles. In addition, evidence of highway segments that may benefit from a truck ramp, such as damaged guard rails and gouged pavement, may be found in a field study. These considerations should be combined with engineering judgment to assess the need for truck ramps. In some cases, the potential damage that could be caused by a runaway truck might be enough to justify building a ramp even if no previous problems have been documented.

Design of runaway truck ramps should take into account various site characteristics to most effectively reduce out-of-control truck crashes. Site characteristics that should be considered include the following:

- ***Topography***. Roadways in mountainous regions tend to have greater need for runaway truck ramps than rolling or level topography.
- ***Grade***. Both the length of grade and percentage grade are important considerations.
- ***Speed***. The design speed, operating speeds, and posted speed limit can be important factors in estimating the potential speed of an out-of-control truck.
- ***Crash rates***. Roadway segments with a high number of recorded crashes involving out-of-control trucks can be good candidate locations for a runaway truck ramp.

The grade severity rating system, a technique developed in the early 1980s by FHWA for analyzing operations on a grade, can be used to determine expected brake temperatures along a downgrade. Ramp locations can be determined by identifying the points along the grade where expected brake temperatures exceed the temperatures at which brakes may fail.

Ramps should be built in advance of road alignments that may not be able to be safely negotiated by an out-of-control truck and in advance of populated areas. Escape ramps should be clearly signed in advance of the ramp, and ramp exits should be on the right side of the travel way. Ramps should be tangent to the roadway to minimize the control required by the driver to navigate the truck from the lanes onto the ramp.

Design Criteria

The AASHTO *Green Book* (2011) classifies ramp types in three general categories: gravity ramps, which slow trucks by relying primarily on gravitational forces; sandpile ramps, which slow and stop vehicles by significantly increasing rolling resistance; and arrester beds, which are long gravel ramps that gradually slow trucks by increasing rolling resistance. Arrester beds can be descending, horizontal, or ascending in grade; in either case, grade affects the ramp length required to slow and stop the truck.

Gravity ramps are typically paved or composed of densely compacted aggregate. The steep ascending grade prevents forward motion of the truck but cannot prevent it from rolling backwards and jackknifing.

Sandpile ramps consist of loose, dry sand that quickly decelerates trucks entering the ramp. Weather can affect the rolling resistance provided by the sand in this type of runaway truck ramp. The severe deceleration provided by sandpile ramps makes them a less desirable option than arrester beds, but it also allows for a shorter ramp because trucks are slowed to a stop more quickly. Typically, sandpile escape ramps are less than 400 ft long and can be used in locations where there is inadequate space for other types of ramps.

Arrester-bed escape ramps use loose aggregate to increase rolling resistance and slow the truck. A descending grade arrester-bed ramp will be longer than the other types of ramps because gravity will work against slowing the vehicle. These ramps should have a clear path back to the highway so that trucks that are not completely stopped on the ramp can reenter traffic at a much slower speed. Ascending grade arrester beds are the most common, using both gravity and rolling resistance to slow vehicles.

The *Green Book* provides design considerations for truck escape ramps that are based on the assumption that an out-of-control truck will rarely, if ever, exceed a speed of 80 to 90 mph. Some design considerations follow:

- The ramp must be sufficient in length to dissipate the kinetic energy of the out-of-control vehicle.
- The ramp should be wide enough (preferably 30 to 40 ft wide) to accommodate more than one vehicle.
- The aggregate depth in the arrester bed should be at least 3 ft deep, which is tapered from a 3-in. depth at the start of the bed to the full depth within 100 to 200 ft of the bed length.
- Arrester beds should include a means of drainage to minimize freezing and contamination.
- The departure angle of the ramp from the roadway should be equal to or less than 5°; adequate site distance should be provided in advance of the ramp; and the driver should be able to see the entire length of the ramp.
- The ramp should be delineated and visible at night; illumination is desirable.
- A service road should be provided along the side of the escape ramp to allow service and maintenance vehicles to access the ramp without becoming trapped in it.
- Anchors should be located adjacent to the arrester bed at 150- to 300-ft intervals to assist wreckers in returning a captured vehicle to the roadway.

If the only practical ramp location may not provide enough distance for a vehicle to stop, or when the consequences of a vehicle overrunning the end of the ramp are severe, including an impact attenuator at the end of the ramp may be desirable. Impact attenuators are protective systems that dissipate the energy of out-of-control vehicles in order to decelerate the vehicle more smoothly. Examples of impact attenuators include crash cushions (steel or wood members of the cushion sheer at impact to dissipate energy) and inertial barriers (plastic containers are filled with sand or water, exploding on impact to dissipate energy). To be considered as a ramp-end treatment for a runaway truck ramp, the advantages of the impact attenuators should outweigh the disadvantages.

How Treatment Reduces Nonrecurrent Congestion

Reduces Frequency of Incidents

The FHWA *Desktop Reference for Crash Reduction Factors* (Bahar et al. 2007) indicates that the installation of truck escape ramps has a crash reduction factor of 18% for all crashes, 75% for run-off-road crashes, and 33% for rear-end crashes. In an evaluation of several safety projects, Caltrans found that 75% of runaway truck crashes were eliminated with the use of truck escape ramps.

Runaway truck ramps can reduce the annual number of runaway truck crashes. This reduces the number of hours during the year that lanes are blocked due to truck crashes, which reduces congestion and improves reliability.

Factors Influencing Treatment Effectiveness

Factors that influence the effectiveness of a runaway truck ramp include the following:

- ***Frequency of out-of-control or brake failure–related truck crashes along the roadway***. The more crashes experienced and expected, the bigger the treatment's impact will be.
- ***The location and number of truck ramps used along the roadway***. Truck ramps are not helpful to a truck that experiences brake failure beyond the ramp, so placing ramps where brake failure is most likely to occur, or periodically along the roadway, will maximize the chances of an out-of-control truck having a nearby, downstream ramp to use.
- ***Traffic volumes***. Truck crashes are more likely to involve multiple vehicles when traffic is heavy. Higher volumes also mean that a truck incident will lead to more congestion. Eliminating truck crashes in high-volume areas will provide more congestion and reliability benefit than in areas with low volumes.

Cost

Factors that may affect the cost of installing a runaway truck ramp for a roadway section include the following:

- Dimensions of the escape ramp (length, width, depth)
- Material used for the escape ramp
- Availability of right-of-way for ramp location (especially in urban or suburban areas)
- Topography of ramp location (especially in mountainous conditions where considerable cut or fill may be required)

Itemized Cost List

To construct a runaway truck ramp, the following actions may be needed:

- Construction of a gravel arrester-bed ramp
- Construction of a gravel gravity ramp
- Construction of a sand arrester-bed ramp
- Clearing and grubbing
- Grading
- Installation of impact attenuators
- Installation of new signs

CONSTRUCTION

Reduced Construction Duration

Description and Objective

Reduced construction duration is a treatment category that encompasses innovative techniques that can be implemented to reduce the duration of a work zone or other construction project. Such techniques may include total road closures, night work, and the use of innovative construction materials. Figure 3.23 presents an example of a construction project causing extensive freeway congestion.

Typical Applications

Innovative techniques to reduce construction duration include implemented management techniques, contracting types, and material usage. These techniques are often used in combination.

Simple strategies, such as notifying the public in advance of project work to allow motorists to find alternative routes, can alleviate congestion resulting from the work zone. Project websites can be used as a communication tool in urban areas, notifying users of lane closures, access restrictions, and alternative routes to reach local businesses. In designing detours, highway agencies should consider safety, geometrics, truck-turning needs, shoulder widths, and pavement condition. The alternative route should be able to withstand any high-volume traffic that results from the detours. Installing temporary concrete barriers to provide local access and to separate the work zone from the traffic zone can help minimize the inconvenience to local stakeholders.

Design Criteria

Among the innovative techniques discussed above to reduce construction duration, only full road closure is truly a directly design-related treatment to reduce nonrecurrent congestion. The other techniques involve better construction management and improved construction materials. These techniques also have the potential to reduce nonrecurrent congestion, but they do not accomplish this through physical changes to the roadway.

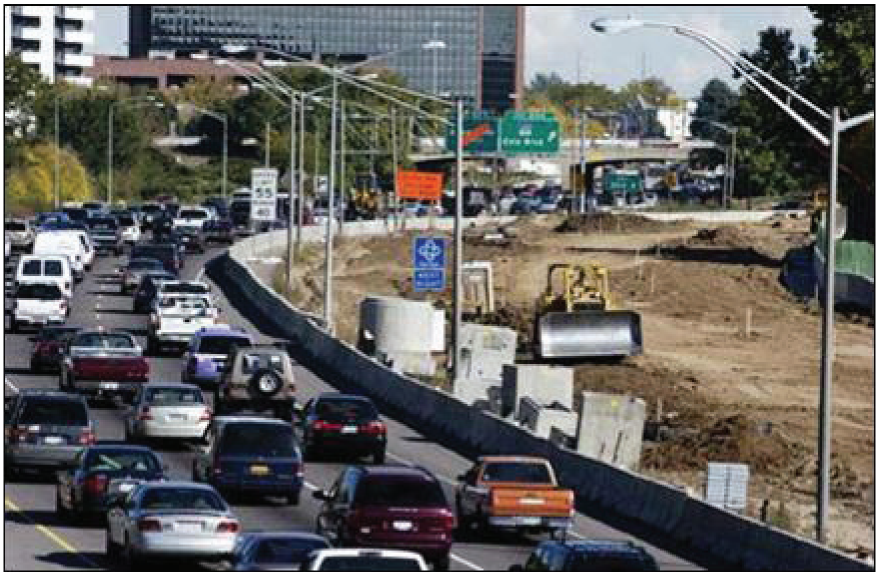


Figure 3.23. *Construction project causing freeway congestion. Source: Knauer et al. (2006).*

How Treatment Reduces Nonrecurrent Congestion

Reduces Duration of Work Zone: Nonpeak Construction

Reducing the duration of a work zone will decrease the lane-blocking time (and therefore the duration of the diminished capacity) associated with that work zone. In addition, if the timing of the work zone is planned such that lane-blocking time during high-demand periods is decreased, operations will improve.

Reduces Duration of Work Zone: Full-Closure Construction

An FHWA study (2003) found that full road closure is a successful tool that reduces the impact of work zones. Of six projects, construction time was reduced by an average of 76% compared with traditional part-width construction.

Reduces Duration of Work Zone: Fast-Track Construction

In research conducted by Konchar (1997), construction speed for design–build projects was, on average, at least 12% faster than design–bid–build projects and 7% faster than construction management at risk. The data used reviewed 351 building projects from the United States. Konchar also found that construction management at-risk projects were at least 5.8% faster than design–bid–build, unit costs were at least 6.1% less, overall project delivery speed was at least 33.5% faster, cost growth was at least 5.2% less, schedule growth was at least 11.4% less, and the quality of work was equal or better.

Factors Influencing Treatment Effectiveness

Factors that may influence the effectiveness of reduced construction duration at reducing nonrecurrent congestion include the following:

- Duration of each work zone
- Construction solutions in regards to timing, sequencing, and management of the project
- Percentage decrease of roadway capacity for each hour of the day while the work zone is in effect

Cost

Factors that may affect the cost of implementing a reduced construction duration plan include the following:

- Type of change to the construction plan (e.g., using more expensive materials that can be placed faster, providing bonuses to contractors for finishing early, working at night only)
- Traffic management plan
- Design time and fees associated with creating a new construction plan
- Contractor bonus for each hour completed ahead of schedule
- Fast-forming materials
- Additional materials or equipment required

Improved Work Site Access and Circulation

Description and Objective

In many construction or maintenance operations, vehicles carrying materials must access the work site from the traveled roadway. Poorly marked or controlled-access points can result in substantial delays when work vehicles enter and leave the work site. Improved access treatments allow work vehicles to enter and leave the work site more quickly and safely.

The objective of providing improved work site access and circulation is to minimize the traffic congestion associated with operations. The negative effect of a work zone on traffic operations is mitigated by minimizing the impact of vehicles entering and leaving the work site.

Typical Applications

Improved work site access and circulation would have application in any work zone where work vehicles are required to enter or leave the work site directly from the traveled way of a higher-volume roadway. Common examples of the need for such worksite access are paving operations (where trucks bring paving materials to the job site) or trenching sites (where trucks haul excavated materials from the job site).

Design Criteria

Adequate acceleration and deceleration areas are needed for trucks to safely enter and leave work spaces. These access points should also be clearly signed or delineated to discourage motorists from inadvertently following trucks into the work area.

Temporary traffic-control zone design should consider work vehicle access to the work site. Graham and Burch (2006) describe the steps in assuring improved access for trucks as follows: "Truck drivers should be briefed on how to access the project site, the path to follow to deliver materials, where to stop for staging, and how the spotter will instruct them once they are near the work operations."

MUTCD (FHWA 2009) specifies that the path of work vehicles should be delineated and that, where possible, the paths of work vehicles should be separated from workers on foot.

How Treatment Reduces Nonrecurrent Congestion

Mitigates Capacity Reduction Caused by Work Zone

In most cases, a work zone will reduce the total capacity of the roadway for the duration of the work zone activity. One of the ways that a work zone diminishes capacity is by large or slow-moving vehicles accessing the work zone from the mainline. When one of these vehicles slows down to safely navigate into the site, the traffic behind the slow-moving vehicle must also slow down. This decrease in speed can cause a dramatic reduction in capacity during the event, and if vehicle demand is heavy enough, the system can reach a d/c ratio greater than one. This may result in the formation of a queue, and traffic operations may remain poor for a long period of time.

Improved work site access and circulation can mitigate this problem by separating the slow-moving vehicles from the main traffic stream. The slow-moving vehicles are provided an area to safely navigate into the work site without blocking traffic or causing significant slowdowns to the traffic behind them. The resulting congestion is thus reduced or eliminated, and the reliability of the roadway improves.

Factors Affecting Treatment Effectiveness

Improved work site access and circulation will be most effective on roadways with high traffic demands, particularly when d/c ratios are high. This treatment will also tend to be most effective when mainline speeds are high, because the speed reductions required for a large vehicle to access the work site will be more dramatic in relation to the average travel speeds of mainline traffic.

Cost

Factors that may affect the cost of improving work zone access or circulation include the following:

- Materials required for improvement (gravel, traffic cones, traffic barrels)
- Additional construction required for improvement (new pavement, restriping)

ANIMAL–VEHICLE COLLISION DESIGN CONSIDERATIONS

Description and Objective

Animal–vehicle collision design considerations include a wide range of design-related features intended to prevent or reduce animal–vehicle collisions. Animal–vehicle collisions are also referred to as wildlife–vehicle collisions (WVCs) because the animals

Figure 3.24. *A bull elk on the roadway. Source: Gray (2009).*

Figure 3.25. *Boulders in the right-of-way (alternative to wildlife fencing). Source: Huijser et al. (2008).*

involved in the crashes are usually wildlife with habitats close to the roadway areas. Although there are a large number of treatments found in the literature, the focus of this section is on design-related treatments as they pertain to nonrecurrent congestion.

The most common objective for the implementation of these design treatments is to reduce the potential for WVCs by preventing animal crossings at undesirable locations and providing means for animals to cross safely at selected desirable locations.

Figures 3.24 through 3.26 illustrate wildlife on the roadway and design treatments to address animal–vehicle collisions, including boulders and animal crossings.

Typical Applications

Animal–vehicle collision design may be considered at locations where there is greatest potential for WVCs. Various data sources can be used to identify these locations, including the roadkill data from the local police department and crash data from the insurance industry.

Common examples of specific WVC mitigation measures include the following:

- Wildlife fencing
- Boulders in the right-of-way

Figure 3.26. *Long tunnels and long bridges physically separate animals from vehicular traffic.*
Source: Huijser et al. (2008).

- Long tunnels and bridges over the landscape
- Wildlife underpasses and overpasses

Wildlife fencing is one of the most commonly applied measures to separate wildlife from motorists (Romin and Bissonette 1996). Wildlife fences in North America typically consist of wire-mesh fence material 2.0 to 2.4 m (6.5 to 8 ft) high. Several types of fence material are used, but page wire or cyclone fence material is most common. Wooden or metal fence posts are typically used; the latter are particularly important when fencing over rock substrates.

Large boulders can be placed in the right-of-way to deter animals from crossing highways at undesirable locations. Large boulders can be difficult for animals, especially ungulates, to traverse, which makes them a desirable alternative to wildlife fencing. The boulders should be placed outside of the clear zone.

Long tunnels and long bridges over the landscape can be used to separate animals from traveling vehicles. For this discussion, long tunnels (or landscape bridges) are defined as tunnels that are at least several hundreds of meters long, sometimes many kilometers. Long tunnels and bridges are primarily constructed because of the nature of the terrain (e.g., through a mountain, across a floodplain), but in some cases they are constructed to avoid areas that are ecologically sensitive and where no alternatives are available. If the nature of the terrain permits, animals can move freely through long tunnels or under long bridges, and because the animals are physically separated from traffic, WVCs are eliminated. Although long tunnels and long bridges may be among the most effective mitigation measures to reduce animal–vehicle collisions, they are rarely specifically designed to reduce WVCs.

Wildlife underpasses and overpasses are used to provide habitat linkages for various species and to allow animals to cross roads safely by separating them from vehicular traffic. Wildlife fencing is sometimes used to funnel animals to these overpasses or underpasses.

Design Criteria

Wildlife fencing is one the most widely used design treatments to prevent or reduce WVCs. One of the most undesirable effects of wildlife fencing is that it creates a barrier between natural habitats of different species and can potentially have harmful ecological consequences. It is therefore necessary to provide gaps in the fencing with animal detection and warning signs, or provide for overpasses and underpasses. Wildlife fencing (and other "absolute barriers") should always be accompanied with escape opportunities for animals that may end up in between the fences. These escape opportunities can be provided using one-way gates or jump-outs. Jump-outs use a sloping mound of soil placed against a backing material approximately 1.5 m (5 ft) in height and constructed on the right-of-way side of the fence to form an "escape ramp" for the animal. The highway fence (2.4 m [8 ft]) is lowered at the ramp site and forms an integral part of the jump-out that allows deer or other species to jump to the safe side of the fence. The vertical drop-off on the back side of escape ramps is designed to be of sufficient height to preclude deer from gaining access to the right-of-way from the nonhighway side of the fence.

How Treatment Reduces Nonrecurrent Congestion

Reduces Frequency of Incidents

A WVC treatment can reduce the number of WVC crashes that occur. By eliminating crashes, this treatment reduces the lane-blocking time associated with these crashes. This results in a decrease in nonrecurrent congestion for the roadway and improved reliability.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of animal–vehicle collision design considerations:

- Type of WVC treatment
- Annual number of WVC crashes
- Average duration of a WVC incident
- The species involved in the WVCs, including migration patterns, mating seasons, and population

Several methods can be employed for reducing WVCs, including the following:

- Building a barrier to prevent wildlife from entering the roadway
- Building an alternative route for wildlife to avoid the roadway, such as an overpass or underpass
- Controlling wildlife population to minimize vehicle exposure to wildlife
- Making drivers aware of approaching wildlife through warning systems
- Making drivers aware of the likelihood of wildlife presence through static or dynamic signing

Each method will provide a different level of WVC reduction. Treatments that keep most wildlife off the roadway will result in a very large reduction in WVCs; treatments that attempt to make drivers aware of the potential for WVCs may have a smaller impact. However, the former treatment types tend to be significantly more expensive that the latter types.

Treatments will have the greatest safety and operational benefits in areas where WVC rates are high and where the crashes that do occur are severe and result in significant lane-blocking time. Although the safety benefits of WVC treatments will be realized at all locations with these types of crashes, the congestion-reducing benefits will be seen on roadways with higher volumes or where passing an incident may be difficult (e.g., mountainous two-lane roads). These conditions are likely to result in nonrecurrent congestion when a WVC occurs.

Cost

To estimate the installation cost of a WVC reduction measure, the treatment type to be installed must be determined. Each treatment type will have its own set of cost considerations. Several common treatment types with their respective cost considerations are listed below:

- Animal overpasses and underpasses
  - Bridge or culvert construction
  - Right-of-way acquisition
  - Traffic control associated with construction of the project
  - Landscaping to rebuild wildlife habitat near the project site
  - Maintenance of the habitat
- Fencing systems
  - Fence material (e.g., barbed wire, woven wire, orange plastic)
  - Grading
  - Right-of-way acquisition

Animal detection systems will have their own costs, depending on the type. Low-cost treatments include vegetation removal to make animals near the roadway more visible to motorists and signs to warn motorists of the likelihood of animal presence.

WEATHER

Snow Fences

Description and Objective

A snow fence is a structure or vegetative planting used to trap and control blowing and drifting snow before it reaches the roadway. There are two types of snow fences: snow fences that trap snow upwind of the area to be protected (collector-type snow fences) and snow fences that deflect snow around the protected area (deflector-type snow fences).

Winter weather can impair motorists' visibility, cause loss of vehicle control, reduce sight distance at curves and intersections, obscure signs, reduce effective roadway width, and render safety barriers ineffective. Snow fences can mitigate the negative impacts of winter weather by improving visibility and providing drier pavement surface conditions on the travel way. This mitigation allows this treatment to reduce the number of snow-related crashes and the congestion associated with these crashes.

Typical Applications

Snow fences may be designed in various ways and constructed with different materials. The traditional wood-slatted fence with horizontal rails works reasonably well, as do lightweight plastic fences with wooden frames. In either case, fences with openings work best. Studies indicate that snow fences with about 50% porosity are most effective in trapping snow.

Living snow fences refer to vegetative plantings used to control blowing snow. Plant materials may include trees, shrubs, grass, or agricultural crops such as corn or sunflowers left standing throughout the winter. For example, shrubs planted at the top of a cut can be used in place of taller barriers placed farther upwind.

Design Criteria

Blowing snow problems are best identified either through discussions with maintenance crews or through analyses of historical crash data. The following information should be considered in the analysis of a problem related to blowing snow:

- Type of problem (snowdrift, poor visibility, slush, ice)
- Effect (crashes, excessive snow removal costs, pavement repair costs)
- Source of blowing snow (within right-of-way, adjacent open field, frozen lake)
- Cause of problem (cross-section geometry, horizontal or vertical alignment, delineation, safety barrier, roadside vegetation or structure, snow removal practices, traffic)

The following questions should be answered to help justify and prioritize the problem and identify appropriate mitigation measures:

- Is the problem drift encroachment, poor visibility, road icing, or a combination of these factors?
- If the problem is snow deposition, what is the safety hazard (e.g., restricted sight distance, poor visibility caused by snow blowing off the drift at windshield level, loss of vehicle control)?
- What is the crash history at the site?
- Does a drift block roadside drainage or otherwise contribute to water infiltration? Is there any evident pavement damage?
- What impact does blowing snow have on crew requirements, duty cycle, and overtime?
- What is the year-to-year variability in problem occurrence and severity?

- What benefits would be derived by solving the problem? Would it improve safety for the traveling public or maintenance crews? Reduce overtime? Free equipment for use at other locations?

The Minnesota Department of Transportation and the University of Minnesota have developed an interactive internet site to help design a snow fence for a problem location: http://climate.umn.edu/snow_fence/Components/Design/locationb.asp. Tools on this site allow the user to determine the required height, setback, and overlap of snow fence systems for any location in Minnesota, and they can be used to design snow fences for places outside the state by finding a Minnesota location with similar snowfall and snow relocation coefficients. The website is an excellent tutorial of the guidelines for designing snow fences.

How Treatment Reduces Nonrecurrent Congestion

Reduces Frequency of Incidents

Snow fences can reduce the number of snow-related crashes that occur. By eliminating crashes, this treatment reduces the lane-blocking time associated with these crashes. This reduction results in a decrease in nonrecurrent congestion for the roadway and improved reliability.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of snow fences at reducing nonrecurrent congestion:

- Annual number of snow-related crashes
- Average duration of a snow-related crash
- Effectiveness of a snow fence at eliminating snow-related crashes

Snow fences will be most effective on roadways that have a significant number of snow-related crashes each year and long average lane-blocking durations.

A 34-year study of I80 in Wyoming found that snow fences reduced crashes in blowing snow conditions by approximately 75% (Tabler and Meena 2006). The study evaluated the effectiveness of snow fences in reducing crashes and road closures on a 50-mi section of I-80 in southeastern Wyoming. When the highway was first opened to traffic in 1970, no snow fences were in place. However, due to substantial snow-drifting problems, nearly 73% of the roadway was protected by snow fences between 1971 and 1990. In addition to the resulting benefit of crash reduction, reduced traffic delay is another benefit of the snow fence protection: the present snow fence system reduces road closure time by an average of 8.3 days each year.

Cost

Factors that may affect the cost of installing snow fences along a roadway section include the following:

- Type of fence (wood slat, polyethylene, polymer, vegetation)
- Fence height

- Length of fence
- Leasing agreements or land purchase for fences placed on private property

Snow fences can significantly reduce the cost of snow removal. Blowing and drifting snow can add substantially to the cost of snow and ice removal for maintenance crews. Snow fences can also increase the pavement life of the roadway surface by reducing potential drainage issues and reducing exposure of the road surface to winter maintenance equipment. Snow drifts directly contribute to pavement damage by blocking ditches, drains, and culverts and by serving as a source of water infiltration under the pavement. Winter maintenance equipment can also damage the roadway surface.

Blowing Sand Mitigation

Description and Objective

Blowing sand can have significant negative effects on highway operations. Sand can pile up on the roadway and create dangerous conditions for drivers by causing vehicles to turn unexpectedly when crossing uneven mounds of sand. In addition, drivers can be adversely affected by the reduced visibility caused by blowing sand. These unsafe conditions can lead to vehicle crashes.

The objective of these treatments is to reduce the amount of blowing sand on or around a roadway, thus increasing visibility and maneuverability on the highway and reducing the frequency of sand-related crashes. Major treatment types include the following:

- Structures that trap sand and dirt
  - Berms
  - Fences
- Treatments that help hold soil in place during high winds
  - Plantings
  - Irrigation systems
- Blowing sand warning systems

The first two treatment types listed above reduce the amount of sand blowing across or coming to rest on the roadway. The third type does not reduce the amount of blowing sand, but rather is intended to make motorists aware of adverse conditions and encourage them to slow down, be more cautious, or choose an alternative route. All three treatment types can effectively reduce the frequency of blowing sand–related incidents.

Blowing sand can also interfere with the ability of emergency responders to reach a crash site and provide services. On June 16, 2011, television station KESQ reported on a five-vehicle collision on Highway 86 and Avenue 52 in Coachella, California. Emergency personnel reported difficulty in responding to this incident due to poor visibility caused by blowing sand. The highway was closed to traffic in both directions the night

Figure 3.27. *Example of how blowing sand can reduce visibility.*
Source: Goodwin (2003).

after the incident. Types of treatments that reduce the amount of blowing sand on the roadway could be effective in improving emergency personnel response time.

Figure 3.27 illustrates how blowing sand can substantially reduce visibility.

Typical Applications

Many areas in the southwest United States are subject to blowing sand and dust. Some of the major causes of blowing sand include droughts, high winds, soil erosion, and any other process that results in minimal soil cover. In many cases, undisturbed desert areas are not a source of blowing sand and dust. Rather, it is the disturbing of the natural conditions that leads to problems with blowing sand and dust. Therefore, in areas that experience blowing sand problems, care should be taken with any construction or roadwork activity that will disturb the natural soil conditions. By planning to stabilize the soil over the course of an entire construction project, blowing sand can be eliminated directly at the source.

Some typical methods for stabilizing disturbed soil include the following:

- Covering the disturbed soil with wind-resistant material
- Planting small vegetation and grasses (avoid planting when winds are high [typically spring])
- Building wind breaks
- Building wind barriers

Wind barriers are structures that provide total wind blockage. Examples of wind barriers include the following:

- Berms made from wood chips or soil
- Solid fences
- Stacks of hay bales
- Walls of concrete blocks or other structural materials

Wind breaks provide partial wind blockage, as they are less solid and continuous than wind barriers. Examples of wind breaks include the following:

- Porous fences (such as standard orange construction fence)
- Rows of large vegetation (trees and shrubs)

Design Criteria

Some of the most common practices for protecting a facility from blowing sand can be summarized in the following categories:

- Direct shielding
  - Wind barriers
  - Wind breaks
- Stabilization of nearby planted areas
  - Soil stabilizers (e.g., salts, surfactants, wood byproducts)
  - Straw crimping
  - Straw blankets
  - Irrigation to provide dust control and to optimize plant growth

In the *Large Area Land Managers Guide to Controlling Windblown Sand and Dust*, the Dustbusters Research Group (2011) recommends the following multistep strategy for controlling dust:

1. Protect existing vegetation and structures that serve as wind barriers as long as possible before the necessary clearing or demolition.
2. Construct wood chip and earthen berms at critical points along property boundaries. These berms will stop encroaching sand and provide protected areas for possible development of new vegetative wind breaks.
3. Plant and irrigate permanent tree and shrub wind breaks in the protected downwind area of berms as part of the overall site landscaping plan.
4. Place a thin wood chip layer on loose blowing sand areas within the property.
5. Stabilize large areas of disturbed soil with temporary vegetation or furrows, especially where land development activities will not begin immediately on previously cleared land. Temporary vegetation such as mustard, barley, or cereal grains will require irrigation for quick and effective germination during cool weather conditions.
6. Construct wood chip and earthen berms at critical points within the property to

stop the blowing sand and to provide protected areas for possible development of new vegetative wind breaks.

7. Reduce the length of unobstructed terrain over which the wind flows, including straight stretches of unpaved roads that run parallel to the direction of prevailing high winds.
8. Develop a plan and work schedule that minimize the time during which each parcel of a new development remains in a disturbed condition.

Blowing sand problems are best identified either through discussions with local maintenance crews or through analyses of historical crash data. The following information should be considered in the analysis of a problem related to blowing sand or dirt:

- Type of problem (visibility reduction or sand drifting onto the roadway that either reduces friction or causes an irregular surface texture that can lead to loss of control of the vehicle)
- Effect of problem (crashes, excessive sand removal costs, pavement repair costs)
- Source of blowing sand or dirt
- Cause of problem (nearby construction projects, abandoned farmland, recent drought)

How Treatment Reduces Nonrecurrent Congestion

Reduces Frequency of Incidents

Blowing sand mitigation can reduce the number of blowing sand–related crashes that occur. By eliminating crashes, this treatment reduces the lane-blocking time associated with these crashes, which results in a decrease in nonrecurrent congestion for the roadway and improved reliability.

Reduces Incident Response Time

Berms or fences can reduce the amount of blowing sand on the roadway. By reducing the amount of blowing sand, emergency responders may be able to identify and reach an incident site more quickly. This results in faster response and clearance times, thus reducing congestion and improving reliability.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of blowing sand mitigation at reducing nonrecurrent congestion:

- Annual number of blowing sand–related crashes (caused by either diminished visibility or sand drifts on the roadway)
- Average duration of a blowing sand–related crash
- Effectiveness of treatment at eliminating sand-related crashes (different treatments will have different expected levels of effectiveness at preventing and trapping blowing sand)

This treatment will be most effective on roadways that have a significant number of blowing sand–related crashes each year and long average lane-blocking durations. The vehicle demand volume is also an important consideration, as the delay associated with a lane-blocking event on a roadway with a high d/c ratio will be greater than that of a roadway with a lower demand volume.

Cost

The costs for installing this treatment will vary depending on which specific mitigation measure is selected and the length of roadway to be protected. For example, installing a construction fence would generally be very inexpensive. However, the installation of an irrigation system to encourage vegetation growth and increase soil moisture content could be quite expensive or complicated, especially if the treatment is needed throughout areas not within the roadway right-of-way. Building berms or barriers might have moderate expenses, even if the barrier material is inexpensive, after construction costs have been accounted for.

Each treatment will also have associated maintenance costs. Barriers will collect sand and dirt on the upwind side of the structure that will have to be occasionally removed for the barrier to maintain effectiveness. Vegetation may have to be fertilized, watered, or periodically replanted. In addition, new plantings may not be effective at retaining the soil or blocking blowing sand and dirt until a few years of growth have been achieved. Each treatment will also have a different life expectancy and will require the consideration of replacement costs.

Anti-Icing Systems

Description and Objective

Anti-icing involves the proactive application of chemicals to a roadway surface before a winter storm. Anti-icing helps prevent snow and ice from bonding to the pavement (in contrast to deicing, which involves the reactive application of chemicals to a roadway surface during or after a storm, when snow and ice may have already formed). The objective of anti-icing systems is to reduce the number of snow- and ice-related crashes that occur on a roadway by reducing or eliminating the time during which the pavement surface is covered in ice. Figure 3.28 presents a schematic of a bridge anti-icing system in Minnesota.

Typical Applications

Anti-icing systems may be fully automated, semiautomated, or manually activated. Fully automated systems rely on sensors to determine the need for application of anti-icing chemicals and automatically activate anti-icing measures. Semiautomated systems can be activated by someone from a remote location in response to a sensor indication. Manually activated systems do not include roadway sensors and must be activated directly at the site.

Automated anti-icing systems are composed of roadway sensors and electrical and mechanical systems that disperse anti-icing chemicals onto the roadway surface to help prevent the formation of ice. The most common automated anti-icing systems use a series of spray nozzles connected to a chemical storage tank. Using a pump system,

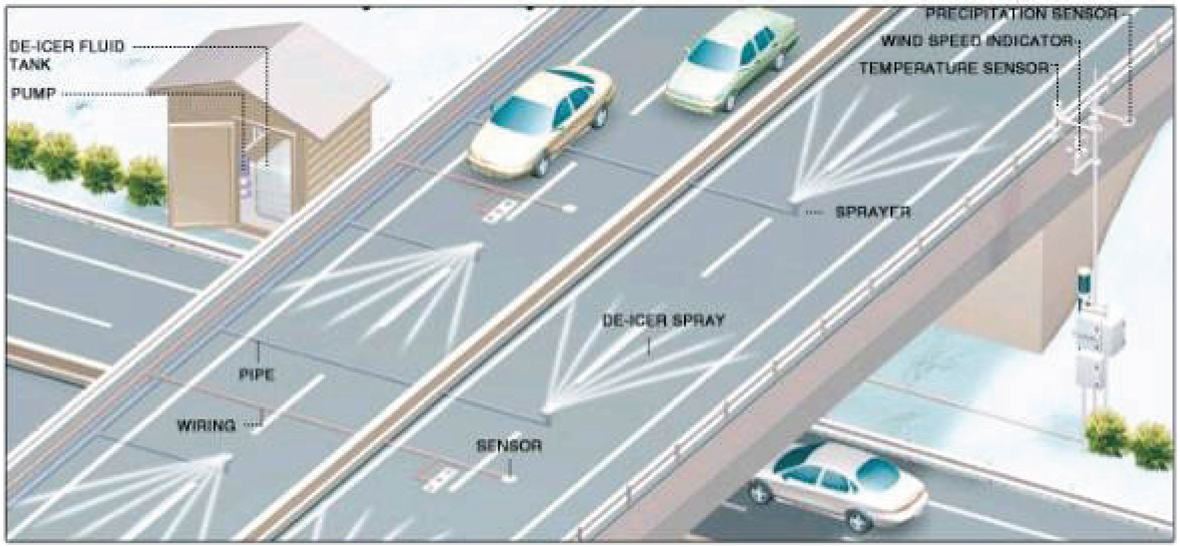


Figure 3.28. *Bridge anti-icing system in Minnesota.*
Source: Goodwin (2003).

the chemicals are dispersed along a roadway segment through nozzles, which can be embedded into the pavement or placed along the edges of the roadway.

Anti-icing systems are commonly applied on bridge decks, which tend to freeze more quickly than other parts of the roadway, and horizontal curves, where traction is critical. Application criteria for where to apply anti-icing systems are generally not available, and the decision to use anti-icing is left to the discretion of the highway agency. Factors to consider include past ice-related accident history, benefit–cost analysis, and the potential harmful effects of the chemicals on the roadway structures and environment.

Design Criteria

Anti-icing technology systems have been installed in California, Kentucky, and Minnesota. Several systems combine road weather information system technology with the automated anti-icing technology. These systems have not been widely implemented because of their initial and operating costs.

How Treatment Reduces Nonrecurrent Congestion

Reduces Frequency of Incidents

Anti-icing systems can reduce the number of ice-related crashes that occur. By eliminating crashes, this treatment reduces the lane-blocking time associated with these crashes, which results in a decrease in nonrecurrent congestion for the roadway and improved reliability.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of anti-icing systems at reducing nonrecurrent congestion:

- Annual number of ice-related crashes
- Number of hours per year when ice covers the roadway (if no anti-icing system were used)
- Number of hours per year during which the melting capacity of the system is exceeded, making the system ineffective

Several studies have shown reductions in the frequency of wintertime accidents from 25% to 100% due to the installation of anti-icing technologies.

Cost

Factors that may affect the cost of installing an anti-icing system along a roadway section include the following:

- Type of system to be installed (automated, semiautomated, manually activated)
- Area of roadway to be covered by treatment (considering both length of segment or bridge and pavement width)
- Ongoing material costs (based on expected frequency of use of the system)
  - Deicer fluid
  - Electricity
  - Personnel to operate system
- Maintenance of the system

4 CATALOG OF SECONDARY TREATMENTS

This chapter presents a catalog of secondary treatments that can be considered for use in addressing nonrecurrent congestion. A detailed summary of each of the secondary treatments is provided that includes the following information:

- Description and objective
- Typical applications
- Design criteria
- How treatment reduces nonrecurrent congestion
- Factors influencing treatment effectiveness
- Cost

The secondary treatments are classified based on similarities with respect to function or location on the roadway. Chapter 3 presents a catalog of the nonrecurrent congestion design treatments.

LANE TYPES AND USES

Contraflow Lanes for Emergency Evacuations

Description and Objective

A contraflow lane is a lane that has been "borrowed" from one direction of travel to add capacity to the other direction of travel. This borrowing can be accomplished using overhead lane designations, static and dynamic signing, police traffic control, interchange gates or barriers, or by other means. Contraflow lanes can be used to accommodate emergency evacuations, most commonly in anticipation of hurricanes (as illustrated in Figure 4.1), although sometimes in cases of other natural or humanmade

Figure 4.1. *Contraflow operations used in South Carolina after a hurricane. Source: Goodwin (2003).*

disasters. During evacuations, nearly all motorists using the facility want to travel in one direction—away from the threat of danger. In such situations, nearly all opposing (i.e., minor-flow) lanes are converted to contraflow lanes, which essentially doubles the number of lanes available for evacuation traffic. Sometimes, one of the inbound lanes remains open for inbound travel by emergency or military vehicles.

Typical Applications

Contraflow lanes are most often used in situations when either an increase in demand or decrease in capacity necessitates finding additional capacity to serve vehicles in that direction. Common applications are during peak hours when demand is highly directional, during emergency evacuations, and during work zones. The first application is used in circumstances of recurrent congestion due to daily demand fluctuations and is outside the scope of this research.

Contraflow lanes as a nonrecurrent congestion treatment during work zones are discussed in the next section. Contraflow lanes in emergency evacuations are considered here.

Applications of emergency contraflow lanes are typically found near coastal regions that experience hurricane (and therefore evacuation) risk. In addition, emergency contraflow may be used to evacuate residents from the path of a wildfire or flood or away from a terrorist attack.

Design Criteria

Many states within the United States have developed emergency evacuation plans for a variety of disasters, such as hurricanes. Several of these evacuation plans include contraflow lane systems to increase outbound roadway capacity.

Emergency contraflow design plans include designating the contraflow routes and developing and installing appropriate emergency traffic control plans that include signing, signal control, and expected levels of police (or other emergency worker) traffic control. In addition, ramps may be retrofitted with gates and devices to implement reversed traffic flow so that interchanges can effectively operate "backwards." The most critical part of the plan is designing how the contraflow will terminate.

Safety concerns in emergency evacuations are likely to be found at the terminal points (i.e., where the contraflow begins and ends) and at interchange ramps (where traffic in the wrong direction intersects with the arterial roadway network).

Generally, a significant number of police officers or other officials are needed to manually direct traffic during lane reversals, especially at interchanges.

It is important to remember that driver behavior will be different in emergency evacuations than under normal travel conditions, and therefore, the effective capacity of highway lanes may be reduced. In addition, the highway cross section may be used differently in an attempt to increase capacity, such as by allowing travel on the shoulder or ignoring lane lines to facilitate an additional, narrower lane on the roadway segment. Finally, consideration should be given to the likelihood of additional traffic demand from nearby jurisdictions that are evacuating through the area being considered.

How Treatment Reduces Nonrecurrent Congestion

Increases Roadway Capacity During an Incident

Using contraflow lanes during an emergency event increases the roadway capacity in the primary direction of travel. It is expected that in emergency evacuations, demand on outbound freeway segments will more than double and that even with full contraflow plans in effect, evacuation routes will be operating with significant congestion. However, the increase in roadway capacity will reduce the overall evacuation time, ensuring that more people can evacuate areas of risk before harm comes.

Although contraflow lanes will reduce congestion during an emergency evacuation, this reduction in congestion cannot be easily translated into an improvement in reliability.

Factors Influencing Treatment Effectiveness

Factors that may influence the effectiveness of contraflow lanes at reducing nonrecurrent congestion due to evacuations include the following:

- Evacuation frequency
- Treatment deployment frequency
- Capacity available for contraflow during evacuation (may include shoulder use, if full-width, full-depth shoulders are available, and may exclude lanes reserved for emergency vehicles)
- Expected demand during evacuation on the segment of interest (on the basis of availability of alternative routes and the desirability of the destinations served by the segment)

Contraflow lanes for emergency evacuations will be most effective when demand volumes are high relative to the available roadway capacity.

Cost

Several factors may affect the cost of installing a contraflow lane for emergency evacuations along a roadway section:

- Construction costs
    - Gate purchase and installation costs
    - Cost for tying into existing intelligent transportation system (ITS) infrastructure
    - Purchase of temporary or portable signs to be used during evacuation
    - Purchase of temporary barricades to be used during evacuation
    - Construction of permanent dynamic signing to be used during evacuation

    - Installation of permanent signs for use during evacuation
    - Installation of permanent fold-out–type signs
- Ongoing costs
    - Police officers to direct traffic
    - Implementation of temporary message boards to be used during evacuation
    - Implementation of gates or barricades
    - Implementation of temporary or portable signing
    - Service and maintenance for gates, ITS, and other devices

Contraflow Lanes for Work Zones

Description and Objective

A contraflow lane is a lane that has been "borrowed" from one direction of travel to add capacity to the other direction of travel. Contraflow lanes are most often used when either an increase in demand or decrease in capacity necessitates finding additional capacity to serve vehicles in that direction. Common applications are during peak hours when demand is highly directional, during emergency evacuations, and during work zones. The first application is used in circumstances of recurrent congestion due to daily demand fluctuations and is outside the scope of this research. Contraflow lanes in emergency evacuations are discussed in the previous section. Contraflow lanes as a nonrecurrent congestion treatment during work zones are considered here.

Contraflow lanes can improve roadway operations during work zone and maintenance activities, as illustrated in Figures 4.2 and 4.3, by providing additional capacity for the direction of travel with reduced capacity due to a closed shoulder or lane. However, consideration must be given to capacity and demand in the opposing direction of traffic before borrowing a lane, because reducing capacity in the opposite direction may have significant negative effects if demand levels are sufficiently high.

Typical Applications

Contraflow lanes may be used for routine temporary work zones or nonroutine semipermanent work zones. Contraflow lanes are frequently used on both arterials and freeways. On freeways, vehicles in one direction of travel are often routed through a median or barrier to a lane on the other side. This lane is separated from the adjacent lanes, which are still accommodating traffic flowing in the opposite direction, by some combination of double yellow striping, delineators, or a barrier. On arterials, contraflow lanes may be temporary in nature, perhaps to be used only during certain hours of the day, and are frequently delineated with only cones and signing.

On freeways, contraflow lanes are often used in extended, long-term work zones on divided facilities, when one direction of travel is closed for construction or maintenance (see Figure 4.4). In these applications, traffic is rerouted from the original travel lanes across temporary median crossovers to lanes in the opposite direction of travel. Depending on the number of lanes, lane width, facility speed, and duration of the work zone, traffic in the contraflow lane may be separated from adjacent opposing traffic

Figure 4.2. *Traffic diverted across median. Source: Federal Highway Administration website.*

with striping changes, concrete barriers, or flexible delineators. Additional pavement may be required to route traffic through the median to the contraflow lane. Figure 4.4 illustrates a typical median crossover.

On arterials without a median or barrier, signing and cones are often used to temporarily shift traffic in one direction around the work zone and over one lane. For longer-term work zones, the treatment may include changes in striping.

Design Criteria

The following are criteria for closing one side of a divided roadway and operating two-way traffic on the opposite side:

- On a four-lane divided highway, traffic volumes in both directions must each be accommodated in one lane. On freeways with six lanes or more, the number of lanes available for each direction of traffic after the contraflow lane is implemented must adequately accommodate the demand. This would imply that volumes should be below 1,600 vehicles per hour per available lane.
- No more than one or two interchanges should be included in the work area.
- Work operations are difficult to accomplish in a manner that allows some traffic to continue using the direction of freeway where the work zone will be located. That is, consideration should first be given to staging the work zone in a way that keeps one or more lanes open in the primary direction.

The primary advantages of using contraflow lanes include the following:

- Work zone duration may be shortened by allowing full lane closures and routing traffic to lanes typically used for the other direction of travel.
- Traffic can be shifted away from work zones that are very near or encroach on travel lanes so that drivers are not exposed to drop-offs or other hazards created by the construction operations.

Traffic can be shifted away from work zones to provide highway workers with more clearance from traffic.

The basic disadvantages of the contraflow strategy are as follows:

- There is an increased risk of serious head-on collisions when traffic normally separated by a barrier or median is now flowing in adjacent lanes. Positive separation of the two directions must be considered, especially on high-speed roadways.
- On freeway applications with unpaved medians, crossovers must be constructed at the start and end of the contraflow lane and additional treatments may be needed to handle traffic at interchanges.
- Shoulders may need to be improved to accommodate crossover traffic, especially if shoulder width is used as part of the contraflow lane. Temporary attenuators may be needed where there are bridge rail or guardrail ends exposed to traffic.

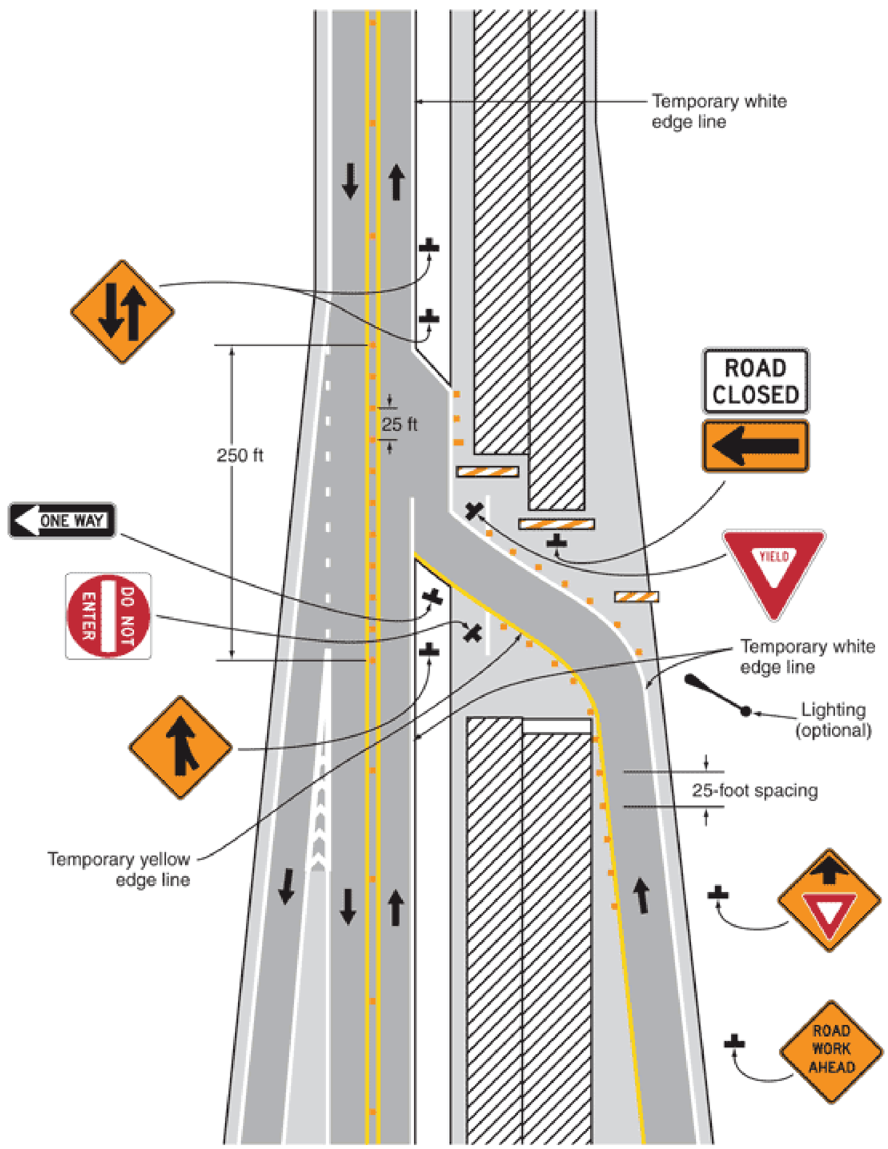


Figure 4.3. *Median crossover at a ramp for use in contraflow lane for a work zone.*
Source: Manual on Uniform Traffic Control Devices *(FHWA 2009).*

How Treatment Reduces Nonrecurrent Congestion

Reduces Impact of Work Zone

A contraflow lane may be used during a work zone to offset the reduction of available lanes in the direction affected by the work zone. For example, if a work zone is planned that will block two lanes, the contraflow lane may borrow one lane from the opposing direction for the duration of the work zone, thereby offsetting the negative impact of the work zone by 50%. Attention must be paid to the demands and capacities of both directions of travel to ensure that operations in the direction from which lanes are borrowed are not extensively degraded.

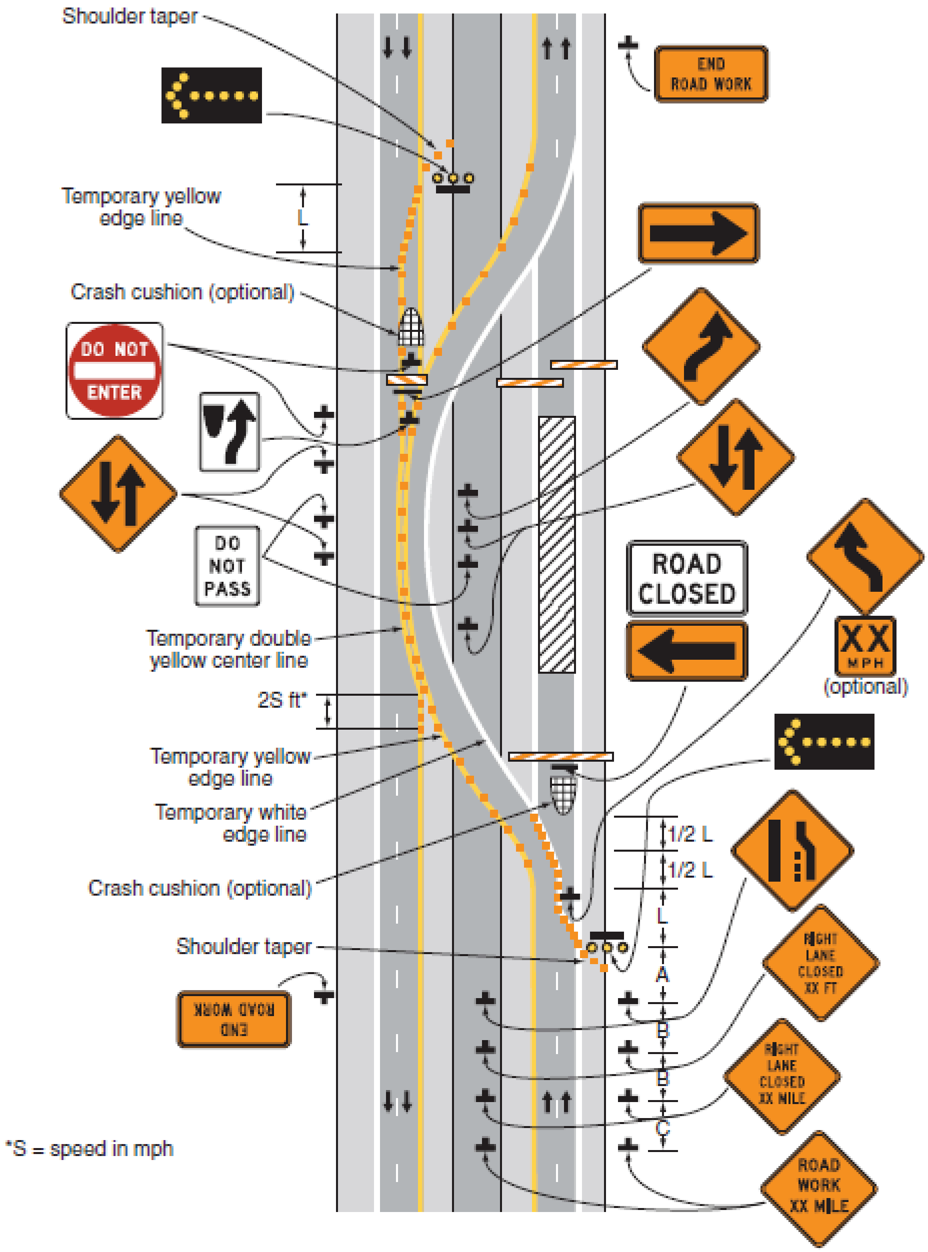


Figure 4.4. *Typical median crossover on a divided highway. Source:* Manual on Uniform Traffic Control Devices *(FHWA 2009).*

By providing additional capacity during a work zone event, contraflow lanes can improve roadway operations by reducing delay and improving reliability.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of contraflow lanes at reducing nonrecurrent congestion due to work zones:

- The number of lanes to be shifted
- Traffic volume in the direction of the proposed contraflow lane
- Roadway capacity in the direction of the proposed contraflow lane
- Traffic volume in the opposing direction of the proposed contraflow lane
- Roadway capacity in the opposing direction of the proposed contraflow lane

Contraflow lanes for short-term work zones will be the most cost-effective when volume-to-capacity ratios are high in the direction of the proposed contraflow lane and low in the opposing direction. For long-term work zones, the direction of peak flow is expected to change throughout the day, and this consideration may not be relevant.

Cost

Factors that may affect the cost of a contraflow lane for use in a work zone include the following:

- Length of proposed contraflow lane
- Need for modular concrete barriers to separate opposing directions of travel
- Availability of temporary concrete barriers (i.e., will barriers be required for the construction project anyway, and therefore on site regardless of whether contraflow lanes are used?)
- Need for temporary pavement (e.g., to allow vehicles to move from one side of a divided highway to the other for contraflow operation)
- Contraflow signing
- Temporary barricades
- Temporary pavement construction
- Temporary pavement marking (on existing and temporary pavement)

HOV Lanes and HOT Lanes

Description and Objective

A high-occupancy vehicle (HOV) lane, often referred to as a carpool lane, is a lane dedicated to those traveling with at least one passenger in addition to the driver in the vehicle; HOV lanes are also often used by buses. HOV lanes are designated with signing and pavement marking or, in some cases, a physical barrier. They may operate as HOVs permanently or only during peak hours. Typically, HOV lanes are patrolled by law enforcement, and violators are ticketed.

High-occupancy toll (HOT) lanes are similar to HOV lanes, but instead of being exclusively for vehicles with passengers, they are also open to motorists without passengers but who are willing to pay a toll to use them. Hours of tolling operation may be based on the level of congestion or prevailing speed in the HOT lane or in the adjacent single-occupant vehicle lanes, or on time of day.

The objective of this treatment is to reduce nonrecurrent congestion by temporarily opening an HOV (or HOT) lane to all traffic. During an incident that causes one or more lanes to be blocked, the HOV lane is opened to all traffic, increasing the roadway capacity and allowing the queue to dissipate. Once the incident is cleared and traffic flow returns to normal, the HOV lane can resume normal operation, as illustrated in Figures 4.5 and 4.6.

Figure 4.5. *HOV lane.*
Source: Neudorff et al. (2003).

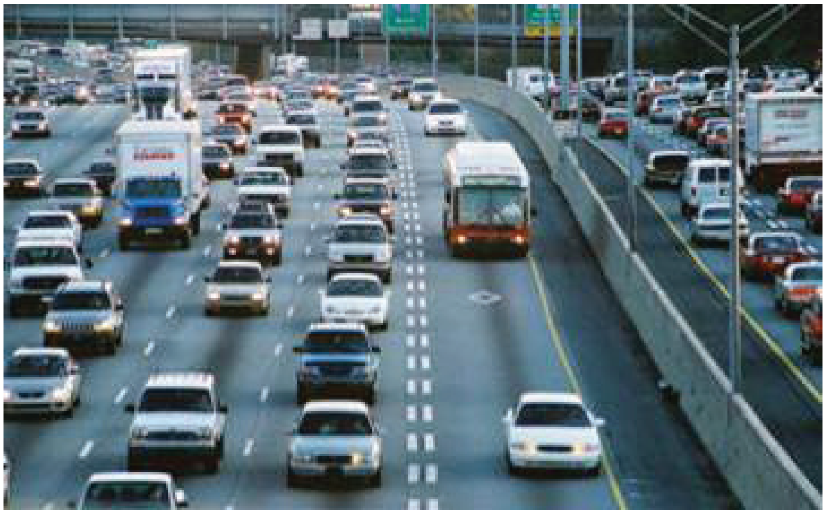


Figure 4.6. *HOV lane in Atlanta, Georgia.*
Source: Transportation Conformity Brochure *(FHWA 2010).*

Typical Applications

HOV–HOT lanes are widely used around the country to encourage carpooling and transit ridership along heavy commuter routes. They are often retrofitted on existing roadway cross sections by using some or all of the shoulder and striping narrower general-purpose lanes. In circumstances of strong directional traffic, a contraflow lane may be used as an HOV or bus lane. This lane may be separated from opposing traffic by a movable barrier or flexible delineators that are removed during those times of day when the contraflow lane is not in use. Additional lanes are sometimes built in the median of a divided freeway as dedicated HOV or HOT lanes. These lanes may be reversible, operating in the peak direction by time of day, or they may serve both directions in two-way operation. HOV–HOT lanes may be separated from general-purpose lanes with concrete barriers, double-line striping, single-line solid striping, a buffer area or shoulder, or other special delineation. HOV lanes may have restricted ingress and egress or may allow vehicles to enter and exit at any point along the lane. Most HOT lanes have restricted access so that single-occupant vehicles that are required to pay the toll for using the lane can be accounted for at tolling locations. In some applications, HOV–HOT lanes have dedicated ramps and fly-overs to connect the HOV–HOT lane on one route to the HOV–HOT lane on another route, eliminating the need for HOV–HOT lane users to merge with general traffic to exit and enter.

Design Criteria

Four distinct facility types can be used in the design of HOV lanes:

- Concurrent-flow HOV lanes
- Contraflow HOV lanes
- Two-way barrier-separated HOV facilities
- HOV lanes in separate rights-of-way

A concurrent-flow HOV lane may be separated from adjacent traffic by a narrow buffer area. The buffer area is delineated by a solid white edgeline on the inside and a solid double yellow line on the outside. Both pavement markings and static signs are used to inform motorists of the intent of the inside lane.

A contraflow HOV lane uses the leftmost lane in the low-volume direction to accommodate HOV traffic in the opposing direction. The lane can be separated from the rest of the facility by removable flexible delineators. Limiting a contraflow lane to buses and vanpools ensures that the drivers are trained to safely navigate while traveling in the opposing direction of adjacent traffic. Removable delineators allow the lane to be switched from normal operation to contraflow and back by time of day.

In some cases, a separate HOV facility is constructed between the opposing lanes of freeway traffic. The HOV lanes operate in one direction during a.m. peak periods and the opposite direction during p.m. periods. The HOV facility is separated from general traffic by permanent concrete barriers or by shoulders and grass medians.

The fourth type of HOV facility, in which the lanes are in separate rights-of-way from the general traffic, is often for dedicated bus routes or other rapid transit lines. Because these facilities do not interact with the freeway in the same way as the other three types of facilities (i.e., they are not designed to facilitate vehicles moving back and forth between the general-purpose lanes and the HOV lanes), they probably have less potential to reduce nonrecurrent congestion.

Each highway agency may have its own design standards for each of the four types of HOV facilities, but the American Association of State Highway and Transportation Officials' *Guide for High-Occupancy Vehicle Facilities* (AASHTO 2004) provides desired and minimum cross-section designs, as well as design guidance for ramps, flyovers, tapers, enforcement areas, transitions, and bus stops.

When choosing an HOV facility design, thought should be given to the ease with which reversible lanes can be flushed and redirected, the frequency of ingress and egress points along barrier-separated facilities, the ease with which barriers or delineators can be moved, the width of shoulders and how easily they could be used as lanes, and other factors that may allow HOV lanes to be converted to general-purpose lanes in the event of severe nonrecurrent congestion.

How Treatment Reduces Nonrecurrent Congestion

Increases Capacity of Segment During an Incident

In many cases, there is not sufficient HOV demand for an HOV lane to operate at capacity. Even when traffic operations break down and speeds decrease in the normal lanes, the HOV lanes may continue to operate well below capacity.

When a major incident takes place and leads to significant queuing on the freeway, the HOV lane may be opened to all traffic. Vehicles will then spread over all lanes equally, resulting in an increase in capacity of the roadway segment. After the incident is cleared and the queue dissipates, the HOV lane may again be closed to non-HOV traffic.

Opening an HOV lane to all traffic has a negative impact on the HOV traffic, because the advantage of carpooling or riding the bus is eliminated during the period when the lane is open to all traffic. For this reason, such action is recommended in response to major incidents only.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of HOV–HOT lanes at reducing nonrecurrent congestion:

- Demand-to-capacity (d/c) ratio of the HOV lane
- Type of separation between the HOV lane and normal lanes (pavement marking only or barrier)
- Infrastructure for notifying drivers of lane opening (e.g., dynamic message boards)

Cost

Factors that may affect the cost of opening an HOV lane to general traffic include the following:

- Improvements to infrastructure for notifying drivers of lane opening
- Loss of toll revenue during period when HOT lane is open to all traffic for free

- Dynamic message board construction and operation costs
- Costs of additional staff to monitor roadway conditions and initiate opening of HOV lane to all traffic

In some cases, this treatment may be implemented for a negligible cost, particularly along freeways with existing traffic management centers. If infrastructure improvements are needed, costs may range from thousands to tens of thousands of dollars.

Dual Facilities

Description and Objective

Dual facilities provide additional freeway managed lanes, not simply set aside by striping or barriers, but a second set of mainline facilities that are separate, parallel, and adjacent to the primary freeway. A dual–dual configuration may allow trucks and passenger cars to use separate facilities within the same freeway envelope. The inner roadway may be dedicated to passenger cars and light vehicles, while the outer roadway is available to all vehicles, including heavier trucks and buses. Each separate roadway has its own entrance and exit ramps.

The purpose of a dual facility is to separate the traffic streams between disparate types of vehicles that would normally be combined in mixed-flow lanes. Objectives for this separation include enhanced traffic safety, opportunities for alternative treatments of different user types, and reduced congestion.

Typical Applications

The New Jersey Turnpike is the primary example of a dual facility freeway. It has over 30 mi of inner lanes (for passenger cars) and outer lanes (for truck, bus, and car traffic) within the same right-of-way. For most of this length (23 mi), the inner and outer roadways have three lanes in each direction. On one 10-mi section, the outer roadway has two lanes per direction, and the inner roadway has three lanes per direction. Each roadway has 12-ft lanes and shoulders, and the inner and outer roadways are barrier separated. Figure 4.7 presents a photo of interchange bypass lanes in Los Angeles, California.

By using gates or signage, operators can limit access to a particular roadway as needed to manage typical demand peaks, as well as to respond to incidents and other nonrecurring events. The result is a roadway that operates efficiently because turbulence in the traffic flow is minimized.

When the New Jersey Turnpike experiences an incident that closes the outer roadway and traffic is diverted into the inner roadway, lane restrictions are employed on the inner roadway. Regulatory signs reading “NO TRUCKS OR BUSES IN LEFT LANE” are displayed. Passenger cars are also restricted by the following regulatory sign message: “CARS USE LEFT LANE FOR PASSING ONLY.”

Figure 4.7. *Interchange bypass lanes in Los Angeles, California.*
Source: Neudorff et al. (2003).

Design Criteria

When evaluating a route to determine whether a dual facility will be good fit, the following items should be considered:

- Merging zones
- Exit and entrance ramps
- Interchange ramps
- Access to local interchanges
- Results of heavy-truck flow survey
- Results of toll analysis
- Results of demand analysis
- Overcoming problematic use of current ramps (may not be suitable for heavy trucks)

Dual facilities offer a unique opportunity for handling nonrecurrent congestion. The major benefit to motorists is having a supplemental adjacent freeway available on which to divert. On a typical freeway, when nonrecurrent congestion occurs as the result of an incident that blocks a lane, the impact to delay can be significant, with some of the affected traffic diverting onto the surface street network. However, when this type of incident occurs on a dual-facility freeway, the first alternative route available is the adjacent, parallel, controlled-access roadway. For many motorists, this is a more favorable alternative than the surface street network. This is particularly true during hours when the freeway is not operating at capacity. In the case of a full road closure, when all lanes in one direction on either the inner or outer roadways are closed, the value of a dual facility as a diversion route is significant.

How Treatment Reduces Nonrecurrent Congestion

Reduces Frequency of Incidents

The safety benefits of separating auto and truck traffic may be one of the most important benefits of truck lanes (Fischer et al. 2003). By reducing the frequency of crashes, this treatment also reduces the nonrecurrent congestion associated with these crashes. Reducing the number of times that a lane is blocked by a crash-involved vehicle reduces congestion and improves reliability.

Increases Base Capacity of a Segment

The operational benefits of dual facilities are expected to result from separating small vehicles from large vehicles. These different vehicle fleets have different operating characteristics, such as acceleration–deceleration rates, visibility, and conspicuity. Separating these vehicle classes into separate facilities enhances the uniformity of operations within each roadway and thus improves traffic operations.

This increase in base capacity causes a reduction in the d/c ratio, a key factor in nonrecurrent congestion. The lower the d/c, the less negative impact a lane-blocking incident has on roadway operations, and the greater the reliability of the roadway segment.

Factors Influencing Treatment Effectiveness

Factors that may influence the effectiveness of dual facilities in reducing nonrecurrent congestion include the following:

- Demand volumes (all traffic)
- Proportion of all traffic made up of heavy vehicles
- Crash frequency
- Capability of warning motorists of congested conditions in advance so they can divert onto the noncongested facility

Dual facilities will be most effective at reducing nonrecurrent congestion along freeways with high-demand volumes, a high proportion of heavy-vehicle traffic, and high crash rates.

Cost

Construction of dual facilities is generally very expensive, potentially including the purchase of right-of-way, extensive design work, as well as roadway and bridge construction costs.

Reversible Lanes

Description and Objective

Reversible lanes are lanes on which traffic flows in one direction during certain times of day and in the opposite direction during other times of day. Reversible lanes can be used to add capacity in the direction of the dominant flow for general-purpose traffic or for limited traffic such as buses or HOVs.

The objective of reversible lanes is to address unbalanced flow, which typically occurs during the morning and evening peak travel times on routes heavily traveled by metropolitan commuters. The purpose is to match directional lane capacity to the proportion of directional traffic flow. Rather than adding capacity to both directions of travel, which do not require the additional capacity at the same time, fewer lanes can be constructed and shared between the two directions, accommodating each direction as needed. Because reversible lanes may be opened to a given direction of travel in response to nonrecurrent events (e.g., lane-blocking crash, work zone), they are a useful treatment for reducing nonrecurrent congestion.

Typical Applications

Reversible lanes are used on both freeways and arterials. On freeways, the most common application is one or more lanes located in the median. These lanes may be separated from the general-purpose lanes by a barrier or median. They have limited ingress and egress points that can be directionally switched by time of day, so that the lanes are open to one direction of traffic during the morning peak and another in the evening peak.

On arterials, these lanes are often not separated from the adjacent lanes but are indicated by special striping and signs. Changeable lane-use signs may be placed overhead at certain locations along the reversible lanes to indicate the direction in which the lanes are operating at any given time. Arterial reversible lanes are sometimes used to handle daily recurrent congestion, but they are also often used to accommodate traffic for special events near sports stadiums (see Figure 4.8), arenas, and other venues.

Figure 4.8. *Reversible lane used for clearing stadium traffic in Baltimore, Maryland.*

Design Criteria

The AASHTO *Green Book* (2011) provides design guidance for HOV reversible configurations. These elements include transition areas (between the general-purpose lanes and the reversible lanes), entry and exit points at ramps and midsegment, and cross-section width.

NCHRP Synthesis of Highway Practice 340: Convertible Roadways and Lanes: A Synthesis of Highway Practice (Wolshon and Lambert 2004) suggests that the design criteria for many characteristics of reversible roadways are identical to the standards set forth in the Federal Highway Administration's (FHWA) *Manual on Uniform Traffic Control Devices* (MUTCD) (2009) and the *Green Book* (AASHTO 2011). This overlap in standards may have occurred because many reversible lanes in use were originally designed for conventional use and have since been retrofitted as reversible lanes. However, the report notes that on newer facilities that are being constructed as reversible lanes, and on freeways where physical lane separation is necessary, special design treatments may be necessary.

How Treatment Reduces Nonrecurrent Congestion

Increases Capacity of Segment During an Incident

Reversible lanes can be opened during nonpeak periods in response to nonrecurrent lane-blocking events such as a major crash or a temporary work zone. In these cases, the decreased capacity caused by the nonrecurrent event is mitigated by the additional capacity provided by the reversible lane. By increasing capacity at these times, this treatment can reduce nonrecurrent congestion and improve reliability.

Factors Influencing Treatment Effectiveness

Very few evaluations have measured the operational or safety effectiveness of reversible lane facilities. Those studies that have addressed operational effectiveness typically measured operational effectiveness either in terms of traffic volume, travel time, and/or travel speed increases after the implementation of the reversible lanes. For example, an evaluation of a reversible lane installed in Dearborn, Michigan, reported increases in total traffic volumes between 3% and 7% (Wolshon and Lambert 2004). On the same facility, travel time was reduced by approximately 16%, and travel speeds increased approximately 21%.

The effectiveness of reversible lanes at reducing nonrecurrent congestion will be based on the following:

- Number of times that a reversible lane will be deployed in response to a congestion-causing incident
- Traffic demand levels during nonpeak times (because, presumably, the reversible lane will already be open in the given direction during peak times and cannot be deployed in response to a congestion-causing event)
- Percentage capacity added to the roadway by the opening of the reversible lane
- Duration of time that passes between a congestion-causing event occurring and the opening of the reversible lane

Cost

Implementation of reversible lanes is widely considered one of the most cost-effective methods of increasing peak period capacity along existing streets. Several direct costs are associated with the maintenance and operations of reversible lanes:

- Pavement construction (if applicable)
- Median reconstruction
- Law enforcement to prevent violations of lane-use restrictions
- Personnel to set up and remove traffic control devices
- Staff to operate and strategically manage the system

Work-Zone Express Lanes

Description and Objective

This treatment involves the construction of express lanes that bypass a freeway work zone without any additional entry or exit points. The targeted application of this treatment is in freeway environments in which entire directions of travel must be closed to allow for new roadway construction and improvements. Because of the limited access of this treatment, it is naturally complemented with exterior frontage roads to handle traffic that has entry or exit needs within the work zone area.

The objective of work-zone express lanes is to allow traffic to move through a work zone area without being inhibited by an arterial street environment. When extensive construction exists along a freeway, traffic must either be diverted to local streets or directed along specially designated express lanes. For vehicles that have no local demand within the work zone area, an express lane provides a safe and efficient route through what might otherwise become a congested area. This congestion can be due, in part, to turbulence resulting from excessive weaving and turning maneuvers under high volumes.

How Treatment Reduces Nonrecurrent Congestion

Increases Capacity of Segment During a Work Zone

Work-zone express lanes increase the capacity of a segment by eliminating the weaving and turbulence created by entering and exiting vehicles. The work zone will likely cause reduced capacity for the duration of the construction project, and work-zone express lanes can be an effective tool in mitigating the capacity decrease caused by the work zone. By increasing capacity during the period of the work zone, this treatment can reduce the amount of nonrecurrent congestion caused by the work zone, thus improving reliability.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of work-zone express lanes at reducing nonrecurrent congestion:

- Demand volumes
- Duration of work zone

- Capacity decrease expected due to the work zone (e.g., one lane of a three-lane cross section is closed)
- Capacity of the express lanes

Cost

The cost of installing a work-zone express lane will vary based on the length of roadway to be constructed, the availability of right-of-way, and the extent of traffic control needed.

TRAFFIC SIGNALS AND TRAFFIC CONTROL

Traffic Signal Preemption

Description and Objective

Traffic signal preemption is a system that allows the normal operation of traffic signals to be interrupted. Typically, traffic signal preemption systems give priority to emergency vehicles by changing traffic signals in the path of the approaching emergency vehicles to green (or in some cases, flashing green) and stopping cross traffic. The objective of traffic signal preemption systems is to reduce the response time of emergency vehicles. Preemption systems also reduce the likelihood of a secondary incident involving an emergency vehicle en route to an incident.

Traffic signal preemption technologies employed today include light-, infrared-, sound-, and radio-based emitter–detector systems. Stakeholders need to gather information and consider key operational features and interoperability requirements as they plan deployments of such systems. The FHWA *Traffic Signal Timing Manual* (Koonce et al. 2008) outlines several types of technologies available to vehicles requesting preemption, including light (strobe), sound (siren), pavement loops, radio transmission, and push buttons. Table 4.1 summarizes technical considerations for the various preemption technologies.

TABLE 4.1. SUMMARY OF TECHNICAL CONSIDERATIONS OF VARIOUS TRAFFIC SIGNAL PREEMPTION OPTIONS

Technology Consideration	Strobe Activated	Siren Activated	Radio Activated
Dedicated vehicle emitter required	Yes	No	Yes
Susceptible to electronic noise interference	No	No	Yes
Clear line of sight required	Yes	No	No
Affected by weather	Yes	No	No
Possible preemption of other approaches	No	Yes	Yes

Source: FHWA (2005).

A recent FHWA report, *Traffic Signal Preemption for Emergency Vehicles: A Cross-Cutting Study* (2005), identifies issues associated with emergency vehicle preemption. By using data from three jurisdictions that operate traffic signal preemption systems, the report identifies the following benefits of the systems:

- Reduction in response times.
- Reduction in the number of emergency vehicle crashes.
- Ability to achieve the same response times with fewer fire and rescue and emergency medical services stations than would normally be required as a result of the traffic signal preemption system (this benefit provides significant cost savings).

How Treatment Reduces Nonrecurrent Congestion

Reduces Emergency Response Time

Emergency vehicle signal preemption systems allow emergency personnel to navigate through an intersection more quickly, thus reducing their response time to an incident scene. This reduces the period of time during which disabled vehicles remain in the roadway or on the roadway shoulder. By reducing the lane-blocking time of an incident, the nonrecurrent congestion associated with that incident is reduced, and reliability is improved.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of signal preemption systems at reducing nonrecurrent congestion:

- Frequency of system use
- Average travel time savings for emergency personnel using the system
- Frequency of crashes involving emergency personnel en route to another incident scene

Cost

Factors that may affect the cost of constructing and operating a traffic preemption system include the following:

- Technology type (light or sound based)
- Number of units purchased
- Intersection cost variables
    - Availability of power on the mast arm
    - The need to run new power or communication cables (or both) through existing conduits
    - Availability of suitable detector placement locations
- Existing emergency vehicle provisions for housing the power supply and emitter

Queue-Jump and Bypass Lanes

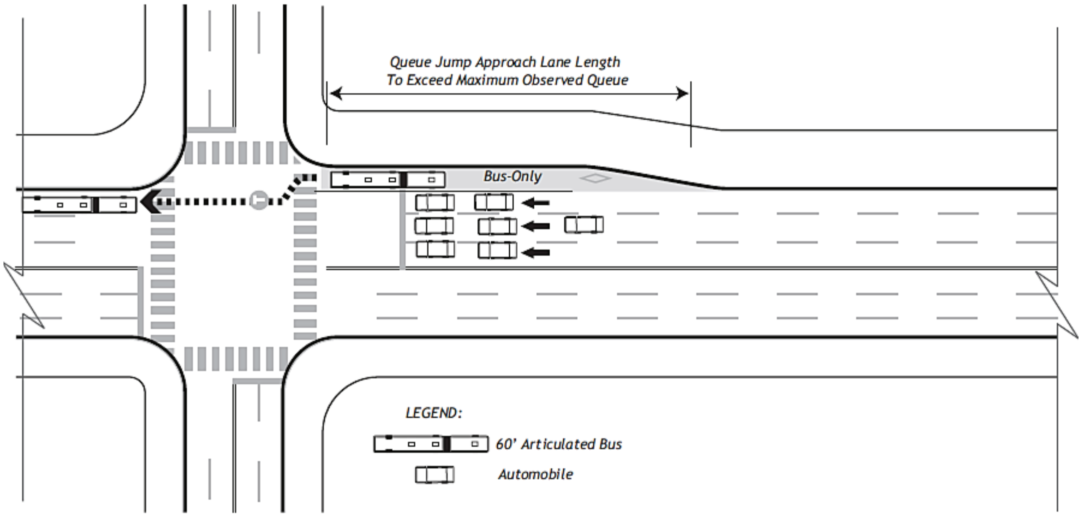
Description and Objective

Queue-jump lanes are built at congested intersections or ramps to allow transit vehicles, HOVs, or toll-paying vehicles to bypass the queue at the signal or ramp meter. One example of a queue-jump lane is a short lane provided at the signal approach and continued for a short distance beyond the signal. Typically, this lane is dedicated to transit or HOVs, and the lane is controlled by a dedicated signal that allows the lane to clear before releasing adjacent traffic. The working mechanisms of queue-jump lanes are traffic signal priority devices, which connect the traffic signal with the bus presence.

Bus bypass lanes are built on roadways where considerable bus traffic and considerable mixed traffic exists. These lanes are used to bypass the congestion of mixed traffic and minimize the mixed traffic and bus interaction.

The primary objective of queue-jump lanes and bypass lanes is to allow higher-capacity vehicles to advance to the front of the queue at a signal, reducing the delay caused by the signal and improving the operational efficiency of the transit system. However, this objective relates exclusively to recurrent congestion. The objectives of a queue-jump or bypass lane at reducing nonrecurrent congestion include (1) reducing emergency response time and (2) providing a path for traffic around a lane-blocking incident. Figures 4.9 and 4.10 present examples of queue-jump lanes.

Figure 4.9. *Queue-jump lane on a metered ramp in Minnesota.*



Notes:
1.) Right-turn movements are prohibited in this scenario.
2.) This type of queue jump lane may also be employed with a curbside bus-only lane.
3.) Effectiveness will be improved if the queue jump lane is integrated with transit signal priority.

Figure 4.10. *Queue-jump lane with advance stop bar.*
Source: Levinson et al. (2003).

Typical Applications

Queue-jump lanes are installed at intersections. The queue-jump lane can be a right-turn-only lane that permits through movements for buses only. They can also be installed between right-turn and through lanes. In Minneapolis–St. Paul, Minnesota, queue-jump lanes are provided at several metered ramps to allow carpools, buses, and motorcycles to bypass any queues formed at the ramp meter.

Bus bypass lanes are roadway lanes that are dedicated to bus and metro use only. Bus bypass lanes could be installed on the rightmost lane or shoulder of high-volume arterials and freeways. In Kansas City, Missouri, bus bypass lanes are installed along the curbside edge. This arrangement eliminates roadside parking, but it allows passenger embarking and disembarking to continue without affecting roadway traffic.

Design Criteria

Installations of queue-jump lanes typically involve modifying signal timing plans at the intersections. Design considerations include signing, lane and shoulder widths, merging area (where queued vehicles and bypassing vehicles have to merge), and sight distance. Three types of systems are used for traffic signal priority: optical, wayside reader, and “smart loop.”

TCRP Report 19 (Fitzpatrick et al. 1996) indicates that queue-jumper bus bays may be considered on arterial street intersections when the following factors are present:

- High-frequency bus routes have an average headway of 15 min or less.
- Traffic volumes exceed 250 vehicles per hour in the curb lane during the peak hour.

- The intersection operates at Level of Service D or worse.
- Lane acquisitions are feasible and costs are affordable.
- An exclusive bus lane, in addition to the right-turn lane, should be considered when right-turn volumes exceed 400 vehicles per hour during the peak hour.

Multiple variations of bus bypass lanes are found on mainline freeways and ramps. One variation is the use of a shoulder or added constructed lane on the right side of the road that is only used by buses. This lane ends with a lane drop where the bus bypass lane merges with the rightmost lane of roadway. The lane is divided into three sections. The initial section is the entrance merge, where buses can enter the bus bypass lane. The second section is a normal queue length, a length of roadway where the bus lane is a uniform width running in alignment with the roadway. The third section of the bus bypass lane is the drop section, where the roadway merges left into the rightmost lane over a distance. Ample markings and signage should occur just before and within this section of roadway to notify both mainline traffic and bus traffic of the lane merge.

The second type of bus bypass lane is a convergence ramp. The convergence ramp allows buses to bypass congested traffic by using an additional travel lane on the entrance ramp. The convergence ramp is composed of three sections. The initial section is the entrance merge, where buses can enter the bus bypass lane. The second section is a normal queue length, a length of roadway where the bus lane is a uniform width running in alignment with the roadway. The third section of the convergence ramp is the convergence section, where the roadway expands into an additional lane with the ramp lane and bus lane. Ample markings and signage should occur just before and within this section of roadway to notify both mainline traffic and bus traffic of the lane merge.

How Treatment Reduces Nonrecurrent Congestion

Reduces Emergency Response Time

Queue-jump or bypass lanes can be used by emergency personnel to bypass queued vehicles while en route to an incident scene. Reducing emergency response time reduces the amount of time that an incident-involved vehicle remains on the roadway blocking a lane. Reducing this lane-blocking time reduces the congestion associated with these incidents, leading to improved reliability.

Increases Capacity of Segment During an Incident

In the event that an incident occurs on an intersection approach and does not block access to the queue-jump (or bypass) lane, the lane may provide traffic access around the incident until the incident can be cleared. By increasing capacity during a lane-blocking incident, this treatment can reduce nonrecurrent congestion and improve reliability.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of queue-jump and bypass lanes at reducing nonrecurrent congestion:

- Length of queue-jump or bypass lane (longer lanes will be easier for emergency response personnel to access when queues exist)
- Traffic demand levels
- Incident frequency
- Local policies encouraging or discouraging general traffic to bypass an incident by using the queue-jump lane

Roadways with high frequencies of lane-blocking incidents, high-demand levels, and local policies encouraging general traffic to bypass an incident using the queue-jump lane will be most positively affected by this treatment. Queue-jump and bypass lane treatments are also more effective when the bypass lane is sufficiently long to bypass the general traffic queue and the right-turn volume in the bypass lane is relatively low.

Cost

Factors that may affect the cost of constructing queue-jump or bypass lanes include the following:

- Need for additional right-of-way
- New pavement construction costs
- Traffic signal hardware and materials needed
- Modification of signal timing
- New signing
- Pavement markings
- Adjustments to roadway lighting or other utilities

Traffic Signal Improvements

Description and Objective

Traffic signal improvements encompass a wide range of specific actions or treatments at signalized intersections. These include improvements to the physical signal system itself, such as the following:

- Installing new signals
- Upgrading span-wire signals to permanent signals on poles and mast arms
- Adding supplementary signal heads to increase signal head visibility
- Increasing signal head size from 8 to 12 in.
- Changing a three-head signal to a four- or five-head signal to allow for protected left turns
- Moving signal poles farther from the roadway to minimize the likelihood of vehicles knocking them down

- Upgrading to signal controllers that can handle closed loop, responsive, or adaptive signal timing plans
- Installing or upgrading vehicle detection at intersections (inductor loops or cameras)

Treatments may also include improvements to the signal timing plan, such as the following:

- Improving clearance intervals to maximize efficiency while taking safety concerns into consideration
- Changing phasing to add or remove protected left turns
- Implementing or improving coordination plans along a corridor
- Implementing responsive or adaptive signal timing systems
- Adjusting timing elements such as minimum green, maximum green, gap time, and overlaps
- Providing pedestrian phases with pedestrian push buttons and signal heads

In addition, automated enforcement for red light running or speed violations are signal-related improvements that may be implemented to reduce incidents caused or related to these violations.

The primary objective of any signal timing plan is to minimize conflicts at an intersection. Signal timing improvements and improvements to the signal hardware and infrastructure are often aimed at either improving the efficiency of the intersection (or corridor) or improving safety for vehicles, bicyclists, and pedestrians at the intersection. Figure 4.11 presents an example of a signal improvement.

Figure 4.11. *Lane-aligned signal heads. Source: Rodegerdts et al. (2004).*

How Treatment Reduces Nonrecurrent Congestion

Reduces Crash Frequency

Improvements to traffic signals may lead to a reduction in total crashes. By eliminating crashes, this treatment eliminates the congestion associated with these crashes, thereby improving reliability.

FHWA and the Institute of Transportation Engineers published a document in September 2007 related to traffic signal timing and safety. The authors of this document found that "[t]he following changes may decrease crashes:

- Signal retiming, phasing, and cycle improvements;
- Review and assurance of adequacy of yellow change interval/all-red clearance; interval for safer travel through the intersection;
- Use of longer visors, louvers, backplates, and reflective borders;
- Installation of 12-in. signal lenses;
- Installation of additional signal heads for increased visibility;
- Provision of advance detection on the approaches so that vehicles are not in the dilemma zone when the signal turns yellow;
- Repositioning of signals to overhead (mast arm) instead of pedestal-mounted;
- Use of double red signal displays; and
- Removal of signals from late-night/early-morning programmed flash."

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of traffic signalization improvements at reducing nonrecurrent congestion:

- Signal-related intersection delay before improvements
- Signal spacing through the corridor
- Vehicle detection before improvements
- Number of pedestrians using the intersection
- Number of special users near the intersection (children, bicyclists, senior citizens)
- Traffic demand volumes
- Intersection geometry and lane configuration
- Crash pattern and frequency before improvement
- Existing clearance intervals
- Visibility of signal heads

Traffic signalization improvements will provide the most benefit in locations with high crash rates and where demand levels are often near capacity.

Cost

Signal timing improvements often have high benefit–cost ratios because the cost may be little more than a few hours of staff time to develop and implement an improved plan, although the benefit could be the reduction of several severe crashes. Improvements to vehicle detection (cameras or induction loops); signal controller upgrades; and replacement or addition of signal heads, backplates, and other infrastructure can cost from hundreds of dollars to tens of thousands of dollars per intersection.

Signal Timing Systems

Description and Objective

Certain signal timing systems are capable of changing timing plans at an intersection or along a corridor as traffic conditions change. These systems require top bar detection, and in many cases, upstream and midblock detection, as well. Induction loops in the pavement, cameras, or radar may be used to detect vehicle presence, density, speed, and/or travel time, and this information can be conveyed to the signal controller, which determines the most appropriate signal timing.

Responsive signal timing systems such as closed loop systems use information from the detectors along a signalized corridor to choose the most appropriate signal timing plan from a library of plans. A traffic engineer develops a library of plans before the system is implemented, and each plan in the library is assigned certain threshold limits in the traffic characteristics. These thresholds are determined by observing the traffic flow under various conditions (e.g., off peak, evening peak, at the release of a sporting event) and by the engineer's judgment. For example, the engineer may observe that during the holiday shopping season, the ramps at the interchange near the shopping mall back up onto the highway because the signal timing at the ramp does not permit enough vehicles to move off the ramp during each cycle. A loop detector near the end of the ramp can be used to detect the presence of vehicles being stored there, and when the presence reaches a certain threshold (perhaps cars are detected for 50% of the time or more), the controller will chose a plan that allows more green time to the phases that serve the ramp. This new timing plan will run until the detectors indicate that vehicle presence has fallen below the assigned threshold.

In most closed loop systems, the information gathered from the detectors is fed to a master controller that chooses the timing plan that will be run. The master then tells all the other controllers in the corridor which plan to implement locally and provides the proper offset to each controller so that the corridor will continue to operate in coordination no matter which plan is chosen.

Adaptive signal timing systems use vehicle detection at the intersection approach to assess real-time demand at each leg of the intersection. They then use an algorithm to assign priority to each signal phase according to the number of cars that are queued. The order of signal phases and the green time allocated to each phase are based on the priority assignment given by the algorithm. In an adaptive signal timing system, real-time data at the intersection and along the corridor are used to determine the most efficient signal timing plan, and this plan changes with changing conditions.

Adaptive systems do not necessarily have defined signal timing plans with a set cycle length or offsets. They do not have to move sequentially through a set of phases, because the controller can skip phases, or move back to a previous phase, to best minimize delay.

The objective of responsive and adaptive signal systems is to make each intersection, and the corridor as a whole, more efficient by using real-time information about vehicle demand and traffic flow. As green time is allocated more efficiently, vehicle delay and congestion are reduced. Figure 4.12 illustrates an example of a signal timing system.

Figure 4.12. *A series of traffic signals controlled by a signal timing system. Source: FHWA (2011).*

How Treatment Reduces Nonrecurrent Congestion

Increases Capacity During an Incident

Responsive and adaptive signal timings can adjust green time allocation in response to an incident. For example, if a westbound through lane is blocked by a crash-involved vehicle, the westbound through movement capacity will be greatly diminished. Responsive or adaptive signal timing can react to this event by providing a longer green time, effectively increasing capacity for this movement. This capacity increase results in reduced congestion and delay along this segment. Providing additional green time to one phase necessarily takes time from another phase, leading to increased delay in the latter direction. Overall, however, the system should see a net benefit despite the increased congestion in the nonincident direction.

Factors Influencing Treatment Effectiveness

The following factors are important in determining the effectiveness of signal timing systems for reducing nonrecurrent congestion:

- Type of signal control (responsive or adaptive)
- Demand volumes for all movements
- Quality of vehicle detection system
- Number of crashes

Signal timing improvements will provide the most benefit in locations with high crash rates and where demand levels are often near capacity.

Cost

The cost of implementing signal timing improvements varies considerably; it is most dependent on the type of controller and detection already present at the intersection. When these are already sufficient, closed loop responsive systems may be implemented for only the cost of the staff time required to develop timing plans and threshold criteria. When controllers and cabinets must be replaced or upgraded, and detection must be installed or upgraded, the cost is substantially higher.

Ramp Metering and Flow Signals

Description and Objective

Ramp metering uses traffic control devices to control or meter the flow of vehicles from a freeway ramp onto a freeway mainline. Ramp meters help reduce the potentially disruptive impact of the ramp traffic on the heavier mainline freeway traffic. Vehicles are released from the on-ramp at a regular interval, one or two at a time.

Ramp meters typically consist of one or more traffic signal heads, as well as associated signs and pavement markings. Geometric considerations on the ramp and approach roadways include ramp width, queue storage space, and turn lanes. Signal timing at a ramp metering location can be either pretimed or traffic responsive. Timing plans can also be based on localized or systemwide factors. When traffic-responsive operations are employed, vehicle detection and communication equipment are needed. For systemwide traffic-responsive installations, the detection and communication equipment can be extensive, collecting traffic flow rate and speed data throughout the system. This information can be input into a ramp metering algorithm to adjust the flow of vehicles entering the mainline from each on-ramp with the goal of providing smooth flow from the ramp without vehicle platooning. As the mainline volumes increase, the ramp flows may be decreased to maintain higher system speeds and capacities. If necessary, the ramp flows can also be adjusted to prevent back-ups onto nearby arterials. Ramp metering is used in several major metropolitan areas in the United States, as well as in Europe, Japan, South Africa, New Zealand, and Australia.

The objective of ramp metering is to increase the capacity of a freeway segment at an on-ramp junction by introducing on-ramp traffic into the mainline in a steady pattern. Typically, this is done during peak periods when additional capacity is most needed, though ramp meters could also be activated in response to a crash or special event. Photos of ramp meters are shown in Figures 4.13 and 4.14.

How Treatment Reduces Nonrecurrent Congestion

Increases Capacity During an Incident

Ramp meters usually operate during defined peak periods to reduce recurrent congestion. However, they can also be used to reduce nonrecurrent congestion if they are activated during a nonrecurrent congestion event. For example, a serious crash may block multiple lanes during a nonpeak period when the ramp meters do not generally run. If the ramp meters are activated, the roadway capacity will be increased, helping to offset the negative effects of the lane block. Once the crash is cleared and traffic normalizes, the ramp meter can be turned back off and normal operations resumed.

Figure 4.13. *Ramp metering installation (right-lane signal).*

Figure 4.14. *Ramp meter.*
Source: FHWA (2004).

Reduces Frequency of Incidents

Several sources indicate that ramp metering systems can reduce the number of crashes on a freeway segment (Minnesota Department of Transportation 2006). This reduction is accomplished by smoothing operations at the on-ramp–mainline junction and eliminating platoons of vehicles entering the freeway in rapid succession. By reducing the number of crashes, lane-blocking time is reduced, nonrecurrent congestion is reduced, and reliability is improved.

Factors Influencing Treatment Effectiveness

The following factors are important in determining the effectiveness of ramp meters at reducing nonrecurrent congestion:

- Percentage capacity increase provided by ramp metering system, which is affected by
  - Weaving segment length
  - Platooning of on-ramp traffic when ramp meter is off
  - Driver behavior
- Capability of ITS to recognize a lane-blocking event and activate the ramp meter

Cost

Factors that may influence the cost of installing a ramp metering system include the following:

- Required roadway ramp improvements
- Type of system deployed (fixed, local, or system)

- Required improvements to facilitate communication between system parts
- Construction costs such as the following
  - Controller
  - Signal heads
  - Detectors
  - Signing
  - Pavement markings
  - Communication infrastructure
  - Power source

Temporary Traffic Signals

Description and Objective

Temporary traffic signals are provided at intersections for a limited period of time. Often, temporary span-wire signals are installed and used for the duration of a construction project. Alternatively, portable traffic signals can be set up on site to be used during a construction project or during an emergency such as a power outage or a damaged controller cabinet.

The objective of temporary traffic signals is to increase intersection capacity during a work zone or an emergency. Without this treatment the intersection would operate as stop-controlled, with greatly reduced capacity.

Portable traffic signals can be used in a variety of situations. As with fixed temporary signals, portable temporary signals can be used in construction zones. For example, if a section of road is reduced to one lane, with two-way traffic alternating use of that lane, a portable traffic signal could be used (rather than a flagger) to direct oncoming traffic either to stop or to continue through the roadway section.

The design of a properly installed temporary traffic control signal system is based on many factors. The Minnesota Department of Transportation's *Guidelines for the Selection of Temporary Lane Control Systems in Work Zones* (2006) provides key considerations for the design of a temporary traffic signal:

- ***Type of signal system***. Selecting wood pole with span wire, trailer-mounted with overhead signal heads, or portable pedestal ground-mounted systems as appropriate
- ***Location of signal***. Considering the visibility of the signal heads and queues that might result from the installation of the signal
- ***Signal timing parameters***. Providing signal timing parameters that minimize delay through work zones while maintaining safe clearance intervals
- ***Monitoring and maintenance***. Performing routine quality checks to monitor the operations (such as timing parameters, signal head alignment, and power supply) of temporary traffic signals

Temporary signals for bridge construction are necessary for one-lane operations. The use of temporary signals on bridges allows road construction teams to remove flaggers from the field and dedicate synchronized signal timing between signal units. In addition, temporary signals give extra notice to drivers during nighttime operations.

How Treatment Reduces Nonrecurrent Congestion

Increases Capacity During an Incident

Temporary traffic signals increase the capacity of an intersection during a work zone or emergency event that results in reduced congestion and delay along the affected segment. The negative impact of the work zone or emergency is mitigated by the use of the temporary signal, which results in reduced nonrecurrent congestion and improved reliability.

Factors Influencing Treatment Effectiveness

The following factors are important in determining the effectiveness of temporary signals for reducing nonrecurrent congestion:

- Type of use (during work zone or to respond to emergency situations)
- Duration of work zone (if applicable)
- Number of expected signal-disabling incidents (if applicable)
- Demand volumes

Temporary signals will be most beneficial at intersections with high-demand volumes during extended work zones or in locations with high numbers of signal-disabling incidents.

Cost

The cost of conventional temporary traffic signals with wood poles and span wires varies greatly depending on the length of the work zone, intersection geometry, and other work zone characteristics.

Variable Speed Limits and Speed Limit Reduction

Description and Objective

Variable speed limit (VSL) systems, also known as variable speed reduction systems, use sensors to monitor prevailing traffic or weather conditions (or both) and post appropriate, enforceable speed limits on dynamic message signs. VSL deployments can be constructed as permanent installations or as temporary work zone installations. They are generally classified as either a lane management or a speed management system. They can be applied to freeways and arterials in both rural and urban contexts.

The primary objectives of a VSL system are to manage current and future traffic flows, minimize congestion, and improve highway safety. Temporary work zone VSLs are used to adjust vehicular speeds so that uniform traffic flow and safe travel speeds can be achieved through the work zone area. Permanent deployments are often designed to address safety and traffic congestion issues in specific corridors or locations. They tend

Figure 4.15. *Variable speed limit sign in Missouri.*

Figure 4.16. *Variable speed limits on M42 in Manchester, United Kingdom.*
Source: Neudorff et al. (2003).

to be used to address weather issues, grade and roadway condition issues, or heavy traffic congestion (both recurrent and nonrecurrent).

In congested conditions, VSLs help smooth traffic flows, allowing motorists to pass through the area more quickly and in a uniform manner. This smoothing results from a greater number of drivers traveling in a tighter speed range and a slowing or metering of vehicles entering the congested area. For example, with VSL deployed, drivers both approaching and traveling through a congested area posted at 35 mph may all travel at speeds between 30 and 40 mph, but stop-and-go conditions would have existed with a posted speed of 55 mph. In some situations, VSL also reduces speed differentials and moderates travel speeds, which can prevent incidents that might cause nonrecurrent congestion. Figures 4.15 and 4.16 illustrate examples of VSL implementations.

The temporary deployment of VSL in a work zone often consists of trailers with dynamic message signs. The trailers typically contain various communication equipment components, as well as vehicle detection and power generation equipment.

How Treatment Reduces Nonrecurrent Congestion

Increases Capacity of Segment During an Incident

VSLs can be activated during nonpeak periods in response to lane-blocking events such as disablements, crashes, and temporary work zones. In these cases, the decreased capacity caused by the lane-blocking event is mitigated by the additional capacity provided by the VSL. By increasing capacity at these times, this treatment can reduce nonrecurrent congestion and improve reliability.

Reduces Crash Frequency

VSLs help smooth traffic speeds, decreasing the speed differential between fast-moving and slow-moving vehicles. This increase in speed uniformity may lead to a decrease in crash frequency. By eliminating crashes, this treatment eliminates the congestion associated with these crashes, thereby improving reliability.

Factors Influencing Treatment Effectiveness

Factors that may influence the effectiveness of VSL systems at reducing nonrecurrent congestion include the following:

- Traffic demand volumes
- Crash frequency before VSL implementation
- Type of VSL system (permanent or temporary)
- Sophistication of VSL system (automated with internal algorithms for determining speed limit or requiring manual speed limit management)
- Traffic management center capability (to activate VSL in response to incidents)

VSL systems will provide the most benefit along roadways with high-demand volumes during off-peak time periods, when crashes are relatively frequent.

Cost

The cost of VSL implementations depends on the length of the corridor to which they are applied, the number of signs needed, the type of sign supports needed, and the sophistication of the detectors and algorithms used.

TECHNOLOGY

Electronic Toll Collection

Description and Objective

Originally developed as a solution to systematic recurrent congestion on tolled highways, electronic toll collection has also proved useful in reducing nonrecurrent congestion in multiple ways. This technology uses communications equipment installed in vehicles and along a roadway segment to collect tolls instantaneously and automatically, thus removing the need for toll booth facilities and operators and allowing tolls to be collected while vehicles are operating at highway speeds. Electronic toll collection has been implemented in many cities across the United States and worldwide as a convenient means of collecting tolls without disrupting the flow of traffic.

The main objective of electronic toll collection is to allow roadway user fees to be collected instantaneously from the road user at high speeds. Electronic toll collection allows more than double the vehicle throughput of manually operated toll booths and reduces vehicle delay at toll plazas. The increased per lane capacity of electronic toll collection requires fewer lanes. The operating expenses incurred from electronic toll collection equipment are typically offset by the reduction in staff required to operate the facility.

How Treatment Reduces Nonrecurrent Congestion

Shifts Demand to Other Time Periods

Electronic toll collection provides a means for counting the number of vehicles traveling along a given segment of roadway. This information can be used in conjunction with ITS to notify the traveling public of congested conditions. On receiving information that a certain freeway segment is experiencing congestion, potential users may divert to other routes or plan their trip during a different period, thereby reducing demand on the roadway during peak times and reducing the associated nonrecurrent congestion.

This effect can be magnified through the use of variable toll pricing schemes, which have been used in many locations. By charging road users a premium to access the roadway during times of peak demand, motorists are encouraged to shift their trip to other facilities or time periods. When variable tolls are used, drivers should be notified of the premium pricing as far in advance as possible so they may have the greatest number of alternative options possible. Although variable tolling is often used during recurring congestion by increasing prices during daily peak hours, it can also be used to reduce demand during nonrecurrent congestion caused by special events, road construction, or lane-blocking incidents.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of electronic toll collection systems at reducing nonrecurrent congestion:

- Traffic demand
- Traffic demand profile (roadway segments with short periods of very high demand surrounded by periods of moderate demand will tend to be especially improved by this treatment)
- Existing infrastructure for relaying information to the traveling public (ITS, electronic message boards, radio)
- Availability of alternative routes with surplus capacity

Cost

Initial costs for field equipment used in electronic toll collection can be significant. Compared with the costs to build and operate full-scale toll booth plazas, however, electronic toll collection represents a significant reduction in cost. Employing field equipment on existing structures for the purpose of managing nonrecurrent congestion would further reduce the overall cost of implementation.

If electronic tolling already exists, the cost of using the system to reduce nonrecurrent congestion will include any necessary ITS to relay congestion information to travelers, as well as any expense associated with varying the toll price with nonrecurrent congestion.

Overheight Vehicle Detection and Warning Systems

Description and Objective

This treatment is designed to detect overheight vehicles and activate warning devices to alert those vehicles of oncoming overhead height restrictions. An overheight vehicle is any vehicle containing a load whose height (legal, permitted, or illegal) exceeds the height of an approaching overhead facility.

The two primary types of vehicle detection systems are optical systems and laser radar. These systems function similarly, with a transmitter and receiver creating a beam at a desired height. When a tall vehicle passes, the beam is broken, causing the detector to activate a beacon or signal.

The primary objective of an overheight vehicle detection system is to reduce the number of overheight vehicle collisions with overhead facilities such as bridges or tunnels. These overhead facilities may be permanent (e.g., a tunnel) or temporary (e.g., construction areas). A secondary objective is to provide appropriate advance notification so drivers can divert to another route without causing traffic delays.

How Treatment Reduces Nonrecurrent Congestion

Reduces Number of Overheight Vehicle–Related Crashes

Overheight vehicle detection systems are deployed to reduce the annual number of overheight vehicle–related incidents and crashes. By notifying drivers of potential clearance problems in advance of an overhead facility, this treatment can reduce the total number of such crashes. With fewer crashes blocking lanes and negatively affecting traffic flow, nonrecurrent congestion is reduced, and reliability is improved.

Reduces Number of Overheight Vehicle–Related Lane-Blocking and Shoulder-Blocking Events

In some cases, drivers of overheight vehicles may realize that their vehicle is too tall to clear an upcoming obstruction, but this realization comes too late to divert to another route. The driver will stop the vehicle before colliding with the obstruction, but blocks the lane or shoulder, thus impeding other traffic. When overheight vehicle detections systems are employed, such that drivers of overheight vehicles are made aware of upcoming obstructions with enough notice to divert to another route, the number of these lane-blocking and shoulder-blocking events are reduced. This reduction in events results in reduced nonrecurrent congestion and improved reliability.

Factors Influencing Treatment Effectiveness

The following factors are important in determining the effectiveness of overheight vehicle detection systems at reducing nonrecurrent congestion:

- Annual number of overheight vehicle crashes
- Annual number of overheight vehicle lane-blocking events
- System effectiveness at notifying drivers in time to avoid collision
- Available alternate routes for overheight vehicles

Cost

Cost estimates will vary depending on the type of system deployed. A simple, lower-cost system could be an optical system, consisting of an activated flash beacon mounted above a static sign using solar power and wireless communication. A more complex, higher-cost system would be one that has a series optical system, dynamic message signs with activated flashing beacons, cameras, high bandwidth communication, and commercial power.

EMERGENCY RESPONSE NOTIFICATION

Reference Location Signs (Emergency Reference Markers)

Description and Objective

Reference location signs provide precise location information to roadway users, incident management responders, and highway maintenance personnel. The objectives of reference locations signs are as follows:

- Aid roadway users in their trip progress assessments
- Serve as alignment markers on rural routes, especially at night or in other low-visibility conditions
- Facilitate road maintenance activities such as repair operations, clearance of debris, and highway inventories
- Assist in accurate reporting of emergency incident and traffic crash locations to reduce response time and inform other motorists of incidents that may affect routing decisions

The second and third objectives listed above can reduce nonrecurrent congestion by shortening the duration of the incident. Accurate location information allows maintenance crews to quickly remove debris from the roadway that may be blocking the travel way; it also allows emergency responders to arrive at the scene of a crash quickly, so that investigation and vehicle removal can occur quickly. Quicker identification of incidents typically results in faster response and clearance times and allows highway operations to return to normal sooner than they may otherwise have. The benefit of rapid identification and response is considered here.

Reference location signs are typically installed along Interstates and other major highways at mile increments. The marker references the mile post along the roadway, most often numbered from a state line, and correlates with the exit numbers along the route, as illustrated in Figures 4.17 and 4.18. Intermediate reference markers may be used at one-tenth or two-tenths of a mile increments and include both the mile post and a decimal.

Various types of highway reference markers are shown in Figure 4.18.

Figure 4.17. *Highway reference marker on I-470.*

Figure 4.18. *Examples of highway reference markers.*
Source: MUTCD (FHWA 2009).

How Treatment Reduces Nonrecurrent Congestion

Reduces Incident Response Time

Reference location signs allow people involved in or reporting an incident to provide detailed information about the exact location of the incident. This action results in faster response and clearance times, reducing congestion and improving reliability.

Reduces Mainline Demand During an Incident

Reference location signs promote the communication of accurate incident location information that can be relayed to motorists through advanced traveler information systems such as dynamic message signs or local radio stations. When motorists are made aware of congested conditions along their route, they are able to divert to other routes, thereby reducing the mainline demand. This reduced demand helps improve operations while the incident is being cleared, reducing delay and improving reliability.

Reduces Frequency of Incidents

Frequently spaced intermediate reference location signs (such as every tenth of a mile) may serve as roadway delineators, especially at night or during inclement weather. These signs may help keep drivers on the road when the edgeline may be difficult to see, which reduces the frequency of lane-blocking incidents and crashes. With fewer lane-blocking incidents, freeway congestion is reduced and reliability is improved.

Factors Influencing Treatment Effectiveness

Factors that may influence the effectiveness of reference location signs in reducing nonrecurrent congestion include the following:

- Existing emergency response time
- Familiarity of average driver with area (emergency reference markers will have a stronger impact on roadways with a high percentage of drivers unfamiliar with the area)
- Spacing of emergency reference markers (a closer spacing will increase the probability that a driver will be able to determine his position and accurately report to a 911 operator)
- Size of sign
- Reflectivity of sign
- Presence of a traffic management system that can identify crash locations before call is made

Cost

The cost of installing reference location signs will depend significantly on the distance of the roadway and planned spacing. The reference markers will also require periodic inspection and replacement.

Roadside Call Boxes

Description and Objective

Roadside call boxes are telephone stations located in close proximity to a roadway. They are useful in locations with inadequate cell phone reception, such as tunnels. Modern call boxes are capable of informing dispatchers of the location where the call originated, which aids in directing emergency personnel to the scene more quickly.

The objective of roadside call boxes is to notify emergency personnel of an incident quickly, thus decreasing the response time of emergency personnel. The information relayed via a roadside call box may also be used by ITS to notify drivers of adverse conditions ahead (e.g., by using variable message boards or radio announcements).

Typical Applications

Historically, call boxes were placed at regular intervals (usually a mile or less) along major routes by the agencies that use them. But as cell phones have become more prevalent, call boxes may not be needed in as many locations. Emergency call boxes can be most beneficial in locations with poor cellular phone service (such as in tunnels or along mountain passes) and in specific areas where congestion-causing incidents are frequent. Call box phones are typically linked directly to a call center or emergency response organization. The call center staff member takes information from the motorist and dispatches the appropriate services (emergency assistance, tow truck, medical). Location information can either be obtained from the motorist (a sign on the box typically includes a location identification code) or transmitted from an automated identification system located within the call box.

The phones are usually operated by pushing a single button; that is, they do not allow calls to be made to other phone numbers. On some phones, a color button system allows the caller to identify the specific service they need. Some phones are also equipped to handle TTY calls for the hearing impaired.

Roadside call boxes may be powered either by electrical power or solar battery power. Telecommunication is either wireless or provided by wire line. In locations with an ITS traffic management system, information gathered from call box users can be relayed to other motorists through changeable message signs or via local radio stations to indicate the potential for congestion or lane blockage. Such announcements may help reduce demand on the affected highway segment by allowing motorists to choose another route.

How Treatment Reduces Nonrecurrent Congestion

Reduces Incident Response Time

Roadside call boxes can help to notify emergency personnel of incidents relatively quickly and accurately regarding the location of a disabled vehicle. By providing personnel with quicker and more accurate information, this treatment can reduce the emergency response time and allow the incident to be cleared sooner. This reduction in lane-blocking time leads to a reduction in nonrecurrent congestion and improved reliability.

Reduces Mainline Demand During an Incident

Roadside call boxes can be used to communicate to a traffic management center that an incident has occurred. The traffic management center may then notify drivers before they reach the incident by using ITS technology (e.g., variable message boards). Drivers who receive this information may divert to other routes to avoid the incident and subsequent congestion. By reducing the demand during the incident, congestion is reduced and reliability is improved.

Factors Influencing Treatment Effectiveness

The following factors may influence the effectiveness of roadside call boxes at reducing nonrecurrent congestion:

- Cell phone reception (the less reception available, the more useful this treatment will be)
- Efficiency of notification system at relaying information to emergency responders
- Traffic demand volumes
- Presence of ITS
- Capability of informing motorists of lane-blocking incidents through variable message signs or local radio
- Frequency of call boxes and uniformity of identifying signs and locations

Cost

Cost estimates will vary depending on ownership (agency or private) and the type of system (commercial power and communication, commercial power and agency communication, solar battery and commercial communication). Factors that may affect the cost to implement call boxes include the following:

- Hardware costs for phones, stands, cases, and other elements
- Installation of phone cable
- Installation of new power source or connection to existing power source
- Ongoing phone service fees and electricity costs

WEATHER

Fog Detection

Description and Objective

Fog detection systems automatically detect the presence of fog and then post warning messages on dynamic message signs upstream of the fog detector to notify drivers that they are entering a portion of roadway where fog is present.

The objective of fog detection systems is to reduce the number of fog-related incidents and crashes by notifying drivers of reduced visibility ahead and inducing them to reduce speeds and proceed with caution.

How Treatment Reduces Nonrecurrent Congestion

Reduces Number of Incidents

Fog detection systems are deployed to reduce the annual number of fog-related incidents and crashes. By notifying drivers in advance of a roadway section with low visibility, these systems encourage drivers to slow down and proceed with caution, resulting in fewer crashes. With fewer crashes blocking lanes and negatively affecting traffic flow, nonrecurrent congestion is reduced and reliability is improved.

In *Best Practices for Road Weather Management*, Goodwin (2003) describes how, from 1973 to 1994, there were 200 fog-related accidents with 130 injuries and 18 fatalities on I-75 in Tennessee. Accidents were reduced after implementation of the 19-mi Tennessee Low-Visibility Warning System (a fog detection system) on the affected stretch of the Interstate.

Factors Influencing Treatment Effectiveness

Several factors may influence the effectiveness of fog detection systems at reducing fog-related crashes and incidents:

- Expected annual number of fog events affecting roadway operations
- Effectiveness of sensors at recognizing fog and activating warning signs
- Driver behavior (e.g., whether motorists follow instructions to reduce speed)

Cost

The cost of a fog detection system varies depending on the size of the system, the extent of automation, and the means used to notify drivers (e.g., dynamic message signs may need to be constructed).

Roadway Weather Information Systems

Description and Objective

A roadway weather information system (RWIS) gathers meteorological information and relays it to highway agency and maintenance personnel. RWIS is composed of environmental sensor stations in the field; a communication system for data transfer; and central systems to collect field data from numerous environmental sensor stations, which measure atmospheric, pavement, and/or water level conditions. Atmospheric data include air temperature and humidity, visibility distance, wind speed and direction, precipitation type and rate, tornado or waterspout occurrence, lightning, storm cell location and track, and air quality. Pavement data include pavement temperature, pavement freeze point, pavement condition (e.g., wet, icy, flooded), pavement chemical concentration, and subsurface conditions (e.g., soil temperature). Water level data include tide levels (e.g., hurricane storm surge) and stream, river, and lake levels near roads. Central RWIS hardware and software are used to process observations from environmental sensor stations to develop forecasts and display or disseminate road weather information in a format that can be easily interpreted by a manager.

The objective of RWIS is to provide road weather information to highway agency and maintenance personnel to enable them to make more informed decisions. The data collected by RWIS can be used to create computer models of weather patterns and continuously calibrate these models. The model weather predictions can be useful to highway agencies in making a determination to close roadway segments in advance of a major storm. The model forecasts can also help agencies be better prepared to respond to a storm with treatments such as anti-icing or deicing chemicals and snow removal equipment.

Figure 4.19. *Road weather information system at the Turner–Fairbank Highway Research Center.*
Source: Zaccagnino (1996).

Figure 4.19 presents a photo of a RWIS at Turner–Fairbank Highway Research Center.

How Treatment Reduces Nonrecurrent Congestion

Reduces Frequency of Incidents

RWIS information can be used by maintenance crews to prepare for deicing, anti-icing, and snow removal treatments in advance of a winter storm. By helping to improve winter maintenance operations and pavement conditions, RWIS technology may reduce winter-related crashes. By eliminating crashes, this treatment reduces the lane-blocking time associated with these crashes, which results in a decrease in non-recurrent congestion and improved reliability for the roadway.

Factors Influencing Treatment Effectiveness

Factors that may influence the effectiveness of RWIS at reducing nonrecurrent congestion include the following:

- Sophistication of system
  - Numbers and types of sensors
  - Accuracy of prediction models
- Effectiveness of communication system between RWIS and maintenance personnel

Cost

The cost of an RWIS system varies depending on the size of the system, as well as weather-prediction model development and ongoing calibration. If certain infrastructure is already in place (e.g., ITS for managing freeway lanes and dispatching emergency personnel), the cost of a RWIS may be reduced.

Flood Warning Systems

Description and Objective

Flood warning systems automatically warn motorists of potentially hazardous flood conditions on the roadway ahead. There are two types of flood warning systems: active and passive. Passive systems consist of warning signs indicating a location on the roadway that may flood or be susceptible to standing water during heavy rains. Active warning systems consist of a sensor to detect high water levels or water on the roadway and a variable message sign (or flashing lights on a static sign) to warn motorists. Some flood warning systems include the capability of closing the roadway with physical barriers, which consist of either automated railroad crossing–type gates or manually placed barricades.

The following are components of flood warning systems (Boselly 2001):

- Sensors to detect the level of water at various locations, such as streambeds, bridges, and road surfaces
- Data processing technology to store the data of all locations
- Components that provide an automated alert to emergency response personnel
- A monitoring subsystem such as a website database that receives data from the field sensors and provides readily accessible and usable information to emergency managers and motorists
- Automated or manually activated signage
- Automated or manually activated traffic control components, such as gates to physically barricade the roadway

The objective of flood warning systems is to notify motorists that the roadway ahead may be underwater from nearby streams and rivers and to discourage or prohibit motorists from entering that section of the roadway.

How Treatment Reduces Nonrecurrent Congestion

Reduces Number of Incidents

Flood warning systems are designed to reduce the number of incidents related to flooded roadways and to prevent vehicles from driving into a situation in which they are "trapped" by a flooded roadway. Like other weather emergency treatments, such as gates that close freeway ramps during snowstorms and contraflow lanes during hurricane evacuations, this treatment is not designed to reduce trip delay or increase reliability, but rather to minimize incidents and improve safety.

Factors Influencing Treatment Effectiveness

The following factors may influence the effectiveness of flood warning systems at reducing flood-related crashes and incidents:

- Expected annual number of flood events affecting the roadway
- Effectiveness of sensors at recognizing flood conditions and relaying a message to personnel or automated gates
- Response time of personnel to manually set barricades (if applicable)

Cost

The cost of a flood warning system varies depending on the size of the system, the extent of automation, and the means used to notify drivers (e.g., dynamic message signs may need to be constructed).

Wind Warning Systems

Description and Objective

Wind warning systems warn motorists of potentially hazardous wind conditions along the roadway ahead. High winds can cause vehicles to swerve, leave the roadway, collide with other vehicles, or overturn; trucks are particularly susceptible to these problems. Since high winds are often less visible than other inclement weather conditions (e.g., snow or fog), wind warning systems can be very valuable for apprising drivers of dangerous conditions and urging them to drive more slowly and carefully.

The simplest wind warning system would be the installation of static signs at highway entrance ramps in areas prone to high winds. Many static signs are supplemented with wind socks that provide drivers with real-time visual information about current wind conditions. Some static signs are accompanied by flashers that are activated during high winds. More advanced wind warning systems include variable message signs, which automatically show wind advisories based on wind speed sensor data. Some policies prohibit certain vehicles from entering a highway or bridge during high wind conditions, and variable message signs can post these prohibitions.

The objective of wind warning systems is to provide information about potentially hazardous driving conditions to drivers, especially those in vehicles especially susceptible to wind such as trucks, RVs, or vehicles with oversized loads. These warnings discourage drivers from traveling during the windy conditions, or encourage them to find an alternative path or proceed with greater caution.

How Treatment Reduces Nonrecurrent Congestion

Reduces Number of Incidents

Wind warning systems are designed to reduce the number of crashes and incidents caused by high winds. Like other weather emergency treatments, such as avalanche warning systems and gates that close freeway ramps during snowstorms, this treatment is not designed to reduce trip delay or increase reliability, but rather to minimize incidents and improve safety.

Factors Influencing Treatment Effectiveness

Factors that may influence the effectiveness of wind warning systems at reducing wind-related crashes and incidents include the following:

- Frequency of high wind events that potentially cause crashes or incidents
- Effectiveness of sensors at recognizing high winds and relaying message to motorists

Cost

The cost of installing a wind warning system varies depending on the type of detection used, the type and number of signs used, and the extent to which the system is automated. In general, construction of a wind warning system may cost several hundred thousand dollars.

5 EXAMPLES OF DESIGN TREATMENT INSTALLATIONS

Several of the treatments described in Chapters 3 and 4 have been implemented, in varying degrees, by highway agencies. They have not always been implemented for the specific purpose of reducing nonrecurrent congestion; however, lessons can still be learned from the agencies' experiences with design, construction, cost, benefits, and challenges. This chapter presents several examples of treatment implementations that were documented in the literature, described in news articles, or identified in interviews with highway agency staff. Although detailed information was not available for inclusion in this report for many of these implementations, the purpose of this chapter is to provide the reader with enough information to follow up with the agencies who have implemented treatments like those being considered by the reader, or who have attempted to address congestion issues similar to those the reader is addressing.

EMERGENCY CROSSOVERS

The Illinois Department of Transportation (DOT) undertook a project in 1997 to make improvements to I-55 (Stevenson Expressway) in Chicago. The design drawings for this project included a detailed plan for an emergency turnaround opening in the median to be used in conjunction with alternating shoulders. The 20-ft-long median opening is located at a place where the alternating shoulder transitions from a westbound left shoulder to an eastbound left shoulder. A pavement marking line and diagonal hashes have been used to designate the shoulder. "No U-turn" signs have been placed at either end of the median opening to discourage the use of this emergency turnaround by general traffic.

The cross section of the roadway consists of two 11.5-ft westbound lanes, an 8.2-ft left shoulder that alternates between the westbound and eastbound direction of travel, a 2-ft-wide concrete median with a 600-mm glare screen, and two 11.5-ft eastbound lanes. A guardrail is located along the outside edge of the rightmost lane in both directions of travel.

GATED MEDIAN BARRIERS

Texas

In the late 1990s, several gated median barriers were installed near Houston, Texas, on the following roadways:

- IH-45 North (four gates)
- US-59 Eastex (five gates)
- US-59 Southwest (11 gates)
- US-290 Northwest (eight gates)

The Texas DOT prefers the manually operated gates over the automated gates, primarily because of the rather infrequent use of the gates. When left closed for extended periods of time, the automated gates tend to lock up and not function correctly, but the manually operated gates have not experienced these problems.

Because the Houston area freeway system has frequent interchanges and a comprehensive system of frontage roads, the gates were not installed to be used by emergency responders to decrease response time. Rather, their intended main function was to reroute traffic in response to major incidents. However, the gates have rarely been used for this purpose. One complicating reason for this infrequent use is that the gates are along a section of roadway that has a center contraflow lane for carpools and buses only. The contraflow lane allows inbound traffic during the morning peak period and outbound traffic in the evening peak period. Because Texas DOT wants to encourage bussing and carpooling by maintaining good operation in the high-occupancy vehicle (HOV) lane, they are hesitant about opening the gated median barriers and disrupting the center contraflow lane, even during incidents on the mainline. Additional gated median barriers have not been installed since 1999.

Michigan

In 2008, the Michigan DOT installed gated median barriers as part of an improvement project on I-75 between Dixie Highway and Birch Run Road near Bridgeport, Michigan. This project involved widening I-75 and eliminating the existing maintenance crossovers. Because the section between Dixie Highway and Birch Run Road is over 8 mi long, gated median barriers were installed to maintain access for emergency and maintenance personnel. Training courses and instructional literature for the appropriate use of these gates were offered to local fire departments and state, county, and local police departments.

Two semiautomated gates were installed in the concrete median barrier along this section of I-75. These gates can be opened by users who enter a code on an electronic keypad. The gates have a manual override if the electronic control should fail. The purchase and installation of each gate added approximately $125,000 to the cost of the project.

There are few recorded instances of the gates being used by emergency personnel to decrease response time. Part of the reason for the low usage rate is that this section of roadway lies between two law enforcement jurisdictions, making it difficult for dispatchers to determine which direction officers will be coming from. Another challenge is the frequent incorrect reporting of crash direction to emergency personnel. Michigan DOT plans to install cameras along this section of freeway to assist in providing emergency personnel with better information.

These gates have been used by the fire department, although the large turning radius of the fire trucks makes their use difficult. Because fire trucks need additional turning space, traffic must remain clear of the inside lanes in both directions of travel, and accomplishing this without law enforcement on site to close the lanes makes this maneuver even more difficult. For these reasons, the median barrier gates have not often been used to reduce the fire department response time.

Another difficulty with these gates has been the corrosive effect of snow and ice on the moving parts of the gate. Ice, salt, sand, and other debris accumulate on the gate and can damage the gears, motors, and other internal components. Currently, extensive maintenance is required to keep the gates operational, though Michigan DOT is working with manufacturers to improve the resilience of these gates in harsh winter conditions. Energy costs for the operation of these gates are approximately $25 per month per gate.

EXTRA-HEIGHT MEDIAN BARRIERS

A project was completed by the Georgia DOT in 2005 to raise the height of a median barrier along a 7-mi section of I85 in Union City, Georgia. The total project cost was $39.7 million, including 7 mi of road reconstruction of outside lanes with associated patching and rehabilitation, an updated guardrail, updated bridge side barrier, expansion of the shoulder to 12 ft in width, and the addition of a glare screen to the existing center median barrier for the total length of the project.

DRIVABLE SHOULDERS

The Minnesota DOT has retrofitted several existing expressways and freeways to allow buses to drive on the shoulder. These drivable shoulders, known as bus-only shoulders, consist of segments ranging from 0.3 to 9.0 mi in length. The segment lengths vary depending on the location. The bus-only shoulders are operational whenever traffic in the adjacent travel lanes is moving at speeds less than 35 mph. Buses may not travel more than 15 mph faster than the mainline, and the maximum speed allowed on the shoulder is 35 mph.

Bus-only shoulders are typically located on the outside shoulder, and the segment is signed as such. Signs warning of buses on shoulders are placed at intersections within the segment to alert drivers entering the roadway to watch for buses on the shoulder.

TABLE 5.1. COSTS ASSOCIATED WITH IMPLEMENTING BUS-ONLY SHOULDERS

Condition	Cost Plus Signing and Striping
Shoulder width and bituminous depth are adequate. Catch basins do not need adjustment. Signing and striping are only requirements.	$1,500 per freeway mile $2,500 per expressway mile
Shoulder width and bituminous depth are adequate. Minor shoulder repairs and catch basin adjustments are needed.	$5,000 per freeway mile $5,000 per expressway mile
Shoulder width is adequate, but bituminous depth requires a 2-in. overlay. This assumes shoulder and roadway can be overlaid at the same time.	$12,000 per freeway mile $12,000 per expressway mile
Same as above but adjacent roadway is not being overlaid. Shoulder must be removed, granular base adjusted, and increased bituminous depth replaced.	$80,000–$100,000 per mile
Shoulder width and depth replacement are required.	$42,000–$66,000 per mile for both freeway and expressway
Installing a 12-ft shoulder rather than a 10-ft shoulder in a new construction project.	$30,000 per mile for both freeway and expressway

Construction costs for these projects vary depending on whether a shoulder is being converted or is part of a new construction project. Table 5.1 indicates different scenarios and the associated costs for implementation on a freeway or expressway. Operating and maintenance costs include the additional cost of snow and debris removal in these areas. There are also increased costs to repair.

ALTERNATING SHOULDERS

The Illinois DOT undertook a project in 2001 to make improvements to the southbound lanes of I-57. Part of the traffic control plan for this project involved shifting the southbound traffic to the northbound lanes via a median crossover and using the northbound lanes to carry both northbound and southbound traffic.

The Illinois DOT determined that two lanes were needed for each direction of travel. However, because providing a four-lane cross section on the existing roadway did not permit adequate shoulder space in both directions, the decision was made to implement alternating shoulders.

During the project, the cross section of the roadway comprised two 11.5-ft southbound lanes, a 2-ft-wide concrete median with a 600-mm glare screen, a 6.5-ft inside shoulder that alternated from one direction of travel to the other, and two 11.5-ft northbound lanes. A guardrail was located along the outside edge of the rightmost lane in both directions.

In the transition section between the southern and northern ends of the project, which was about 160 ft long, the concrete median was gradually shifted to eliminate the northbound left shoulder and provide a southbound left shoulder.

This configuration allowed for a four-lane cross section in the existing roadway width, while intermittently providing a shoulder refuge area for both directions of travel in case of a crash or vehicle disablement.

EMERGENCY PULLOFFS

The Minnesota DOT made improvements to I-94 in Minneapolis in response to increased traffic demand after the I-35W bridge collapse. The improvements to I-94 included adding a lane to carry the additional traffic while the I-35W bridge was repaired. After the bridge repair was completed, a project was undertaken on I-94 to build an acceptable permanent configuration while keeping the additional lane that was constructed. Because some sections of the roadway were left with limited shoulder width, emergency pulloffs were constructed at multiple locations along the roadway to accommodate such incidents as vehicle breakdowns and crash investigations. The length of these emergency pulloffs was generally 150 to 200 ft. The cost of constructing a single pulloff was $75,000, unless a retaining wall was required. The construction of a retaining wall added $150,000 to the cost of constructing a vehicle pulloff. Construction of these pulloffs was completed in the summer of 2010.

CRASH INVESTIGATION SITES

The Georgia DOT installed approximately 50 or 60 crash investigation sites (or accident investigation sites, as they are called within Georgia DOT) in the late 1990s. These sites are 12-ft-wide shoulder extensions paved with asphalt. They are approximately 100 ft long with tapers on each end. At the time of construction, they cost roughly $10,000 per site. The sites do not include lighting. Two signs were installed for each site: one in advance of the site and one at the crash (accident) investigation site. The sign is blue with a white logo of a tow truck pulling a car.

RAMP TURN RESTRICTIONS

The Kansas Speedway in Kansas City, Kansas, hosts many popular racing events, including the NASCAR series. These races draw large crowds, resulting in much higher than usual demand on the nearby roadway network. To improve traffic operations for patrons and minimize the negative impacts to other users of the roadways, the Kansas DOT and the Kansas Highway Patrol implemented a comprehensive plan for directing traffic into and out of the speedway facility.

This comprehensive traffic control plan involves both advance set-up and manual direction of traffic while patrons stream into the facility. The following are the major interchanges that are involved in this effort:

- I-70 at K-7
- 110th and I-435
- I-435 and State Avenue
- I-435 and Parallel Avenue

Before race day, Kansas DOT staff erect 12 portable variable message boards and temporary signs at specific locations along the roadway, adjust permanent signs, and place traffic cones near where they will be needed. This advance work and the subsequent teardown after the race day costs Kansas DOT approximately $10,000 in wages to Kansas DOT staff and the use of Kansas DOT equipment.

Many races span the 2-day weekend, so an eight-person crew from Kansas DOT and a 16-person crew from the Kansas Highway Patrol are dispatched to manually direct traffic and manage the traffic control system. Ten cameras are located at various points along the route that provide staff with real-time information on the traffic patterns and help them make informed decisions. Kansas DOT spends approximately $10,000 on staff wages and equipment use during the two-day implementation of this system.

The additional cost to the Kansas Highway Patrol for the 2-day deployment of this system is approximately $50,000 in officer wages and use of police vehicles and equipment. These costs are covered by the department's own funds.

Two other agencies are involved in the implementation of this plan: the Kansas City Police Department and the Bonner Springs Police Department. Each of these agencies sends officers to various locations within their jurisdiction to improve local traffic flow. The costs to these agencies are unknown; they are covered from each agency's own funds.

Altogether, there are an estimated 1,000 person-hours spent between all these departments for a single deployment of this system. The total cost to all departments combined is approximately $70,000. This cost must be paid each time the system is used, and it does not include the installation cost of the permanent infrastructure and design plans needed before the system was implemented. Five of the 10 cameras placed at various points along the roadways were installed as part of a project completed in 2010, which also included improvements to the five existing cameras. The total cost of this project was approximately $400,000.

IMPROVEMENTS TO DETOUR ROUTES

On August 1, 2007, the I-35W Mississippi River Bridge collapsed, displacing 154,000 daily vehicle trips. A study of the I-94/I-35W interchange revealed that 40% of these trips began or ended within the downtown area and 60% were pass-through trips.

Three primary detour routes were identified for improvements:

- TH-280 from I-35W to I-94, and I-94 from Hwy 280 to I-35W (Route 1)
- I-694 from I-35W to I-94, and I-94 from I-694 to downtown (Route 2)
- TH-100 from I-694 to I-394 (Route 3)

The parenthetical letter designations that follow the descriptions of the projects listed in the following subsections are keyed to the locations marked in Figure 5.1.

Route 1

TH-280 was converted from an expressway to a freeway to increase capacity. The projects along this corridor included the following:

- The addition of a second lane to the ramp from TH-280 to I-35W/Hwy 36. This project cost $375,000 and was completed in August 2007. (**A**)

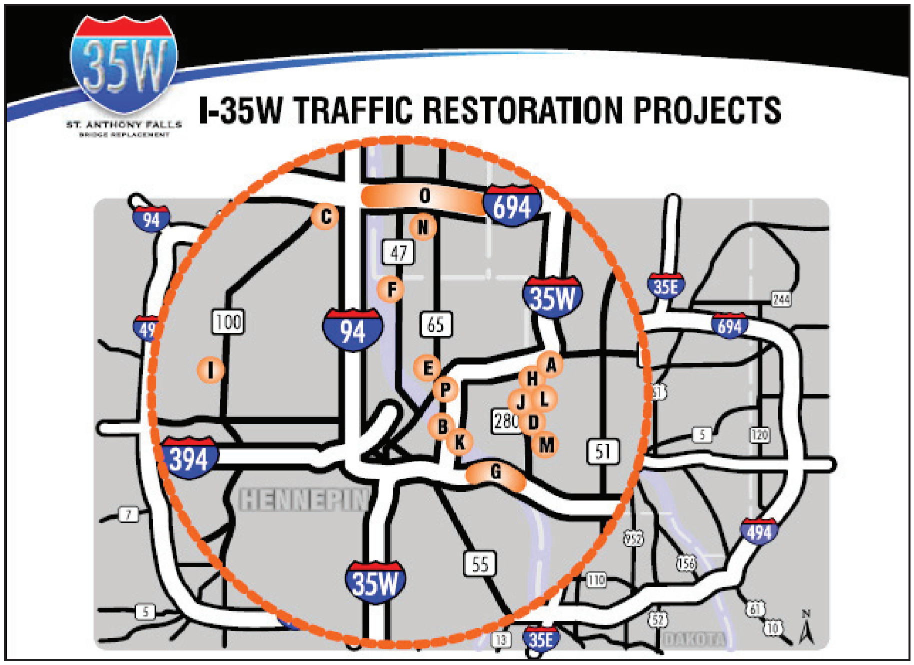


Figure 5.1. *Map of individual project locations.*

- The construction of a southbound one-way frontage road at Broadway Avenue to provide access to local business. This project cost $400,000 and was completed in August 2007. (**H**)
- The construction of continuous lighting along TH-280. This project cost $200,000 and was completed in August 2007. (**L**)
- The construction of a diamond interchange with two temporary signals at Hennepin–Larpenteur Avenue. This project cost $930,000 and was completed in August 2007. (**J**)
- The construction of traffic management system infrastructure along TH-280 that included cameras, vehicle detectors, and dynamic message signs. This project cost $500,000 and was completed in August 2007. (**D**)
- The elimination of access to TH-280 at each of two existing at-grade signals. This project cost $155,000 and was completed in August 2007. (**M**)

I-94 was improved by constructing a fourth lane along I-94 in the eastbound and westbound directions. This project cost $1.2 million and was completed in August 2007. (**G**)

Route 2

The following two projects were undertaken to improve operations along I-694:

- The construction of a fourth lane on eastbound I-694 to TH-47. The interchange at TH47 was also modified to extend a through lane and provide a better lane drop condition. This project cost $170,000 and was completed in September 2007. (**O**)

- The conversion of the shoulder of westbound I-694 to a bus-only lane. This project involved sign installation only. This project cost $10,000 and was completed in August 2007. (**N**)

Although part of the detour Route 2, no improvement projects were undertaken for this section of I-94.

Route 3

Travel lanes were added along TH-100 to increase capacity. The projects along this corridor included the following:

- The addition of a second lane to the ramp from northbound TH-100 to eastbound I-694. The project also included lane widening along TH-100 to increase capacity, which was accomplished mostly through pavement marking changes. This project cost $17,000 and was completed in August 2007. (**C**)
- The addition of an auxiliary lane along TH-100 from Duluth Street to TH-55. This lane addition was accomplished solely by changes to pavement markings. This project cost $30,000. (**I**)

Other Improvements

The following improvements were made near the immediate area of the collapsed bridge. Although not part of a formal detour route, these improvements provided operational benefits to traffic needing access to destinations near the site of the collapse:

- The conversion of the existing one-lane entrance and exit ramps at the I-35W and 4th Avenue interchange to two-lane ramps. This project cost $112,000 and was completed in August 2007. (**B**)
- The addition of cameras and vehicle detectors along Hwy 65. These improvements allowed signal operations personnel to monitor conditions and adjust signal timings, which improved traffic flow and operations. This project cost $70,000 and was completed in August 2007. (**E**)
- The addition of cameras and vehicle detectors along Hwy 47. These improvements allowed signal operations personnel to monitor conditions and adjust signal timings, which improved traffic flow and operations. This project cost $70, 000 and was completed in August 2007. (**F**)
- The addition of an eastbound right-turn lane on Washington Avenue for traffic entering the southbound I-35W on-ramp. The on-ramp was also widened, and new striping was installed on the improved ramp. This project cost $170,000. (**K**)
- The addition of ramps at the I-35W and Hennepin Avenue interchange. This project had an estimated cost of $1,250,000 but was never completed. (**P**)

REDUCED CONSTRUCTION DURATION

Several techniques for reducing construction duration are employed by the Texas DOT near Dallas, Texas:

- Charging the contractor a “lane rental fee” for each hour that a traffic lane is shut down
- Breaking a single project into multiple phases
- Paying the contractor a bonus (per day) for finishing ahead of schedule
- Charging the contractor a fine (per day) for finishing behind schedule

These techniques vary in cost and are very sensitive to the traffic demand volumes of the roadway affected by the project. The contractor bonuses can range from $10,000 to $20,000 per day, with a maximum limit of $250,000.

Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) is a software tool developed by the University of California Pavement Research Center through the UC Berkeley Institute of Transportation Studies and funded by the Federal Highway Administration (FHWA). This software helps agencies evaluate the cost of various construction scenarios for pavement rehabilitation projects, taking into account schedule, cost, and delay to traffic. FHWA obtained a group license from UC Berkeley for the software for use by all 50 state DOTs. The software has been used to justify accelerating construction schedules by showing how they can save the agency’s and the users’ money. One example is the I-15 Devore project in Iowa, which was completed in two 9-day periods, rather than the 10 months that would have been required if standard nighttime closures had been used. Traffic simulation models and the CA4PRS software showed that this accelerated schedule would save the agency $6 million and the road users $2 million.

IMPROVED WORK SITE ACCESS AND CIRCULATION

The Washington State Department of Transportation *Design Manual*, Chapter 10, Work Zone Safety and Mobility (Washington State Department of Transportation 2009) contains various techniques and strategies to minimize the effect of a work zone on traffic operations and traffic safety. Because state DOT policy prohibits hauling ingress and egress from a live traffic lane on high-speed or high-volume roadways, alternate methods of delivering materials are required. Examples of techniques that have been employed on Washington State DOT projects include the following:

- ***Material stockpiling on site***. This technique involves contractors planning ahead and creating stockpile sites within the work zone area. The materials are delivered during low-demand time periods and used when they are needed.
- ***Material processing on site***. The contractor strategically positions portable concrete or asphalt plants on site to minimize access conflicts.

- ***Dedicated truck deceleration and acceleration lanes***. This technique involves the construction of an additional temporary lane within the work zone space to allow delivery trucks to decelerate when entering and accelerate when exiting. Barrier separation of these lanes from normal travel lanes is preferred. In most cases, it may be difficult to find available space within the work zone, but when possible, this method works well.
- ***Temporary access granted from other property*** *owners*. This technique involves the contractor seeking cooperation from adjacent property owners, local agencies, and FHWA to allow access for delivery trucks via nearby nonfreeway roads.
- ***Alternate private or local access***. Through easements and local agency permits, contractors may obtain alternate access.
- ***Total closure***. This should be done during periods of low demand. By temporarily closing the entire roadway, work can be completed quickly. This technique is particularly useful in conjunction with weekend work.
- ***Lane closure for hauling access***. This technique should be used only during periods of low traffic demand to avoid significant congestion. This technique would be recommended in conjunction with night work, for example.
- ***Lane closure using QuickChange movable barrier***. This allows a traffic lane to be closed for periods of low demand and then easily reopened during periods of high demand.
- ***Closure of ramp to allow "wrong-way" material hauling***. This technique involves the full or partial closure of a downstream off-ramp. Trucks delivering materials to the project site travel in the closed lane in the opposite direction of normal traffic.
- ***Project staging***. This technique involves advance planning of a series of project phases, such that materials for later stages can be delivered and stockpiled before ramps or lanes are opened.
- ***Use of conveyer system***. Materials can be delivered to an area near the work site with low traffic volumes and brought to the location where they are needed through an on-site conveyer system.
- ***Hauling allowed only during specified conditions***. This technique involves a performance specification to the contractor that only allows materials to be delivered when certain conditions are met. For example, material delivery would only be allowed if vehicle demand volumes were below a certain threshold.
- ***Rolling slowdown operations***. These may be used to provide gaps in the normal traffic stream to allow trucks to deliver material to the site. This is intended to reduce the occurrence of sudden speed reductions and the potential for rear-end collisions.
- ***HOV lane use***. HOV-only lanes may be used by trucks delivering materials to the site.

ANIMAL–VEHICLE COLLISION DESIGN CONSIDERATIONS

Five wildlife crossings were constructed along US-93, a two-lane highway near Wells, Nevada, by the Nevada DOT between 2000 and 2010. This section of roadway is along a migratory path of mule deer. It is estimated that 3,500 deer use one of the five crossings each fall and again each spring.

These crossings were built over a series of three projects. The first project was an overcrossing built over an existing cut section of the roadway. The road profile remained as it was, so only a small amount of earthwork was required. The overcrossing was 185 ft long and 55 ft wide. The total cost to the Nevada DOT was $1.8 million, and another agency paid the $300,000 cost of installing fencing around the crossing.

The next project consisted of the construction of three undercrossings under US-93 that were constructed one-half at a time to allow traffic to continue to flow during construction. The undercrossings consisted of a 28-ft-wide by 16-ft-tall metal culvert. The total cost for these three undercrossings was $2.2 million.

The third project was the construction of an overcrossing 100 ft long by 55 ft wide. A significant amount of earthwork was required for this crossing, and the roadway was lowered 14 ft from its original profile. An 8-ft woven wire fence was installed with this crossing, and is included in the total $3.15 million cost of this project.

These five crossings are all along a single 12-mi section of US-93 that experienced an estimated 70 to 80 wild animal–vehicle crashes per year before these projects began. These crossings have resulted in an 80% to 90% reduction in wild animal–vehicle crashes along this roadway.

CONTRAFLOW LANES: EVACUATION

The Texas DOT has identified I-10 West as a potential hurricane evacuation route for the City of Houston. In several places along this route, water-filled traffic barriers have been used to separate directions of travel. In an emergency evacuation, the water can be drained from these barriers, allowing them to be moved to allow contraflow of the eastbound lanes of I-10 during the evacuation. In addition, the outside shoulder of I-10 may be used as a travel lane during evacuations. This may be done with or without the use of contraflow lanes. For other evacuation routes, the inside shoulder may be designated as the “evaculane” and marked with a hurricane evacuation symbol. Residents know when they are permitted to use the lane through local media reports and signs along the route. During times when the shoulder serves as an evaculane, minor accidents and disabled vehicles must be moved off the shoulder or to the nearest ramp.

The entire I-10 evacuation route from Houston to San Antonio covers nearly 200 mi of freeway. Costs for using the water-filled barriers along the route were approximately $250,000. However, the most significant cost associated with this treatment is personnel time during each evacuation event. At each interchange, it is recommended that three workers direct traffic onto the freeway. Law enforcement personnel are preferred for this role, and it is also recommended that each person directing traffic have a vehicle to bring attention to themselves and for their protection. Many interchanges are involved in the Houston evacuation route, so dispatching all necessary personnel can be an expensive undertaking.

Texas DOT has posted several videos illustrating and explaining the use of emergency evacuation routes. They provide guidance to drivers on what to expect during an evacuation and show renderings of the temporary traffic control to guide drivers onto the contraflow section, as well as the signs they should expect to encounter. Contraflow guide signs are typically folded signs that are opened during an evacuation.

Evacuation plans have also been developed for Corpus Christi, Texas. The main evacuation route is I-37 toward San Antonio, although the DOT states that this route would not be able to accommodate all coastal traffic and that other routes should be considered depending on the predicted path of the storm. The I-37 evacuation plan has three stages. In the first stage, shoulders are opened for use. In the second stage, contraflow is deployed between the urban areas, and in the third, contraflow begins in the urban center of Corpus Christi and includes several interchanges where traffic control will be modified to accommodate contraflow.

HOV LANES AND TOLL LANES

Several freeways in Houston, Texas, have reversible HOV lanes between opposing directions of travel. These lanes are available to inbound HOV traffic in a.m. peak periods and outbound HOV traffic in p.m. peak periods. I-45 near Sam Houston Tollway is one such road. The HOV lane is separated from the general travel lanes by concrete barriers and may only be entered or exited at specific access points along the freeway. Barriers are moved at each end of the reversible HOV lane during off-peak periods to switch the direction of travel.

When major incidents take place that block freeway lanes and cause significant congestion, the HOV lanes are temporarily opened to all traffic. This occurs approximately four times per year. The traveling public is made aware of the lane opening by dynamic message signs and via television and radio news announcements. The Texas DOT Traffic Management Center makes the decision to open the lane and relays the message through news station personnel. Thus, there is little, if any, cost to implement this treatment.

Opening the HOV lane to all traffic is done relatively rarely because of the negative impact it has on HOV vehicles. Texas DOT prefers to give an advantage to HOV drivers, so that they have better travel conditions than the general traffic, in order to encourage carpooling and bussing. Temporarily opening the HOV lane to all traffic eliminates this incentive.

On very rare occasions, the DOT waives toll fees on certain toll-only facilities in the Houston area in response to major incidents. The cost of doing this is the lost revenue that would have been collected at the toll booths. The public is apprised of the temporarily waived tolls via television and radio in the same way as the HOV lane opening.

WORK ZONE EXPRESS LANES

Work zone express lanes were used during a construction project in downtown Tucson, Arizona, along the I-10 corridor from 2007 through 2009. The existing freeway improvements included lane additions and the reconstruction of seven bridges and underpasses along a 4.5-mi segment as part of a $200 million project. Before construction, express lanes were built along the entire length of the work zone for traffic desiring to bypass local traffic. A mobile intelligent transportation system center was established with approximately 72 cameras to monitor the entire project area comprehensively. Because shoulders were not provided along the express lanes, existing ramps (not in use by through traffic) were designated as emergency pullouts, and tow trucks were available at all times to assist in clearing any incidents. In addition, parallel arterial roads were upgraded to provide additional through lanes, and the traffic signals along the route were retimed to adjust to the new traffic demands.

RAMP METERING

Minnesota

Approximately 430 ramp meters were in operation in 2006 during the morning and evening peak periods in the Minneapolis–St. Paul metropolitan area. Some of the installations were pretimed, and others were traffic responsive and part of a larger networkwide metering system. This metropolitan area has the most comprehensive metering system in the nation. In 2000, the Minnesota DOT conducted a state legislature–mandated study of the metering program. Key results from this study are included in the Chapter 3 discussion of this treatment.

Washington

Seattle has had approximately 120 ramp meters in place since 2002. They are all part of a traffic-responsive systemwide initiative. The meters operate during the morning and afternoon peak periods, as well as during incidents and special events. The system is designed to be able to respond to special nonrecurrent congestion needs.

California

The California DOT (Caltrans) has over 1,000 ramp meters in place throughout the state, including installations in major metropolitan areas such as Los Angeles and San Diego. The installations include a variety of approaches, from local pretimed installations to large networkwide traffic-responsive systems. Caltrans has even developed a ramp metering design manual for the state.

FOG DETECTION

California

Caltrans District 10 experiences seasonal fog and dust-related visibility problems that have caused numerous multivehicle crashes. In 1990, Caltrans proposed a multisensor automated warning system based on the expansion of SR-120 connecting I-5 and SR-99. The system includes 36 traffic speed monitoring sites, nine complete report meteorological stations, and nine changeable message signs for warning drivers. This system is referred to as the Caltrans Automated Warning System (CAWS). CAWS detects reduced visibility conditions and traffic congestion. When sensors determine visibility is below 500 ft, changeable message signs display "FOGGY CONDITIONS AHEAD"; when visibility is below 200 ft, the signs display "DENSE FOG AHEAD." The traffic monitoring system sensors collect traffic count and speed information. When speeds are below 35 mph, the changeable message signs display "SLOW TRAFFIC AHEAD" warnings, and when speeds are below 11 mph, the signs display "STOPPED TRAFFIC AHEAD" warnings.

The weather-related instruments of CAWS also measure wind speed. When wind speeds register above 25 mph, the changeable message signs display "HIGH WIND WARNING." These messages are intended to reduce crashes caused by low visibility due to dust.

The cost of the San Joaquin Valley system that was implemented in the early 1990s was estimated at approximately $3.6 million ($1.32 million for Caltrans and $2.35 million for the California Highway Patrol).

Tennessee

In Tennessee, two major fog-related crashes triggered the installation of a fog detection system in 1993, on the Hiwassee Bridge on I-75. The system includes the following:

- Road weather information systems
- Fog detectors
- Speed detectors
- Variable message signs
- Changeable speed limit signs
- Swing gates
- Fixed signs with flashers
- Highway advisory radio systems

If speeds fall below 45 mph or if visibility falls below 1,320 ft, an alert is sent to dispatch a highway patrol officer to assess the situation. An automatic message is sent to the variable message sign notifying drivers of potential fog ahead. If the highway patrol officer confirms the presence of fog, the variable message changes from "POTENTIAL FOG AHEAD" to "FOG AHEAD." Variable speed limit signs are also activated, as follows:

- When visibility is between 480 and 1,320 ft, the speed limit is set to 50 mph.
- When visibility is between 241 and 480 ft, the speed limit is set to 35 mph.
- When visibility is below 240 ft, the road is closed and traffic is detoured onto a nearby U.S. highway.

From December 1993 to January 1995, there were 77 activations for fog. All activations required lowering the speed limit to 50 mph; 10 of the activations required a further lowering of the speed to 35 mph. Two road closures took place: one due to fog, the other due to a nearby chemical plant explosion of toxic smoke. The system is monitored by the highway patrol but was installed and maintained by officials from the Tennessee DOT.

This system was installed for a total cost of approximately $4.5 million.

FLOOD WARNING SYSTEM

Dallas, Texas

The City of Dallas, Texas, implemented a flood warning system in April 2000. The system is made up of three components:

- A central computer system
- One sensor at each site
- One to six changeable message signs at each site

The sensor monitors the elevation of a nearby stream and reports every 20 min to the central computer. When the flood water reaches the edge of the roadway, a float switch tells the sensor to signal the sign to change to the warning text and turn on the flashing lights. The sign sends a message back to the sensor confirming that everything is working properly. The sensor radios this information back to the central computer. Pages are sent to staff, and messages are printed out at the appropriate street services district alerting them of the need to place barricades at the location as soon as possible.

The signs and sensors are battery powered and recharged with solar cells. All communication between the sensors and signs and the sensors and the central computer are by radio. The sensors normally control the signs without intervention from the central computer. However, the central computer can issue commands to turn on the signs and lights.

The signs include changeable text messages and red flashing lights. In the nonalarm state, the lights are off and the sign shows "HIGH WATER WHEN FLASHING." In the alarm state, the lights alternate flashing and the sign changes to "DO NOT ENTER HIGH WATER." The signs and lights are equipped with sensors to detect the status.

Fort Worth, Texas

The City of Fort Worth, Texas, has a system consisting of both manual and automatic barrier gates, as well as flashing beacons that warn motorists of flooded roadways. The system, which the city installed in 2003, includes 43 advance warning signs at 18 sites.

Houston, Texas

The City of Houston, Texas, has over 185 sites with 550 sensors that include 12 low-water crossing areas.

WIND WARNING SYSTEM

Oregon

A wind warning system used on the Yaquina Bay Bridge in Oregon includes an anemometer to measure wind speed, which automatically activates flashing beacons on two static signs when wind speeds reach a preset level. This system was constructed for approximately $20,000.

Montana

A wind warning system is used along I-90 in the Bozeman–Livingston area in Montana. The following messages are displayed to motorists:

- If wind speeds are between 20 and 39 mph: CAUTION: WATCH FOR SEVERE CROSSWINDS
- If wind speeds are over 39 mph: SEVERE CROSSWINDS: HIGH PROFILE UNITS EXIT

Nevada

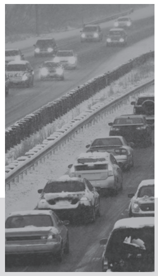
A wind warning system is used along US-395 in Washoe Valley, between Carson City and Reno, Nevada. The following messages are displayed to motorists:

- If wind speeds are between 15 and 30 mph and maximum wind gusts are 20 to 40 mph: CAMPERS AND TRAILERS NOT ADVISED
- If wind speeds are greater than 30 mph and maximum wind gusts greater than 40 mph: CAMPERS AND TRAILERS PROHIBITED

New York

A wind warning system is used on the Ogdensburg–Prescott International Bridge in New York. The following messages are displayed to motorists:

- If wind speeds are between 30 and 40 mph: HIGH WIND ADVISORY. USE CAUTION ON BRIDGE. (No vehicle restrictions.)
- If wind speeds are between 40 and 50 mph: HIGH WINDS. REDUCE SPEED ON BRIDGE. (Restrictions: escorted vehicles are individually assessed on their load.)
- If wind speeds are greater than 50 mph: HIGH WINDS. REDUCE SPEED TO 5 mph. (Restrictions: intermittent restrictions of recreational vehicles [motor homes and travel trailers], motorcycles, and empty container trucks, as warranted by bridge manager or designee.)
- If wind speeds are greater than 75 mph: BRIDGE CLOSED. (All traffic restricted.)



REFERENCES

American Association of State Highway and Transportation Officials. 2004. *Guide for High-Occupancy Vehicle (HOV) Facilities*, Washington, D.C.

American Association of State Highway and Transportation Officials. 2010. *Highway Safety Manual*, Washington, D.C.

American Association of State Highway and Transportation Officials. 2011. *A Policy on Geometric Design of Highways and Streets* (AASHTO *Green Book*), Washington, D.C.

Bahar, G., M. Masliah, R. Wolff, and P. Park. 2007. *Desktop Reference for Crash Reduction Factors*. FHWA-SA-07-015. U.S. Department of Transportation.

Boselly, S. E. *Roadway Flash Flooding Warning Devices Feasibility Study*. 2001. Final Report for ITS-IDEA Project 79. Transportation Research Board, National Research Council, Washington, D.C.

Darnell & Associates. 2006. *OMNITRANS Bus Stop Design Guidelines*. http://www.omnitrans.org/about/BusStopGuidelines_10-04-06.pdf. Accessed April 9, 2012.

DeCorla-Souza, P. 2007. High-Performance Highways. *Public Roads*, Vol. 70, No. 6, May/June. FHWA-HRT-07-004. U.S. Department of Transportation.

Downs, H. G., Jr., and D. W. Wallace. 1982. *NCHRP Report 254: Shoulder Geometrics and Use Guidelines*. HRB, National Research Council, Washington, D.C.

Dudek, C. L., W. R. McCasland, and E. N. Burns. 1988. Location, Design, and Operation of Accident Investigation Sites in Urban Freeway Corridors. In *Transportation Research Record 1173*, TRB, National Research Council, Washington, D.C.

Dunn Engineering Associates, P.E., Consulting Services. 2006. *Alternate Route Handbook*. FHWA-HOP-06-092. U.S. Department of Transportation.

Dustbusters Research Group. 2011. *Large Area Land Managers Guide to Controlling Windblown Sand and Dust*. http://www.nmenv.state.nm.us/aqb/documents/Large_Area_Guide.pdf. Accessed April 9, 2012.

Federal Highway Administration. *Movable Barriers in Work Zones*. http://www.fhwa.dot.gov/hfl/innovations/pdfs/moveablebarrier.pdf. Accessed April 9, 2012.

Federal Highway Administration. http://www.ops.fhwa.dot.gov/wz/traffic_mgmt/tcg.htm. Accessed July 26, 2013.

Federal Highway Administration. *Federal Aid Policy Guide*. June 1998. http://www.fhwa.dot.gov/legsregs/directives/fapg/0630csup.htm. Accessed April 9, 2012.

Federal Highway Administration. 2003. *Full Road Closure for Work Zone Operations: A Cross-Cutting Study*. U.S. Department of Transportation.

Federal Highway Administration. July 2004. *Research and Technology Transporter*. U.S. Department of Transportation.

Federal Highway Administration. 2005. *Traffic Signal Preemption for Emergency Vehicles: A Cross-Cutting Study*. FHWA-JPO-05-010. U.S. Department of Transportation.

Federal Highway Administration. 2006. *Using Highways During Evacuation Operations for Events with Advance Notice: Route to Effective Evacuation Planning Primer Series*. FHWA-HOP-06-109. U.S. Department of Transportation.

Federal Highway Administration. 2009. *Manual on Uniform Traffic Control Devices*. U.S. Department of Transportation.

Federal Highway Administration. 2010. *Transportation Conformity Brochure*. FHWA-HEP-10-030. Office of Planning, Environment, & Realty (HEP), U.S. Department of Transportation.

Federal Highway Administration. June 2011. *Every Day Counts: Adaptive Signal Control*. http://www.fhwa.dot.gov/everydaycounts/technology/adsc/faqs.cfm.

Federal Highway Administration and Institute of Transportation Engineers. September 2007. Traffic Signals. Issue Brief. http://www.ite.org/safety/issuebriefs/Traffic%20Signals%20Issue%20Brief.pdf. Accessed March 5, 2014.

Fischer, M. J., D. N. Ahanoutu, and J. M. Waliszewski. 2003. Planning Truck-Only Lanes: Emerging Lessons from the Southern California Experience. Presented at 82nd Annual Meeting of the Transportation Research Board, Washington, D.C.

Fitzpatrick, K., K. Hall, D. Perkinson, L. Nowlin, and R. Koppa. 1996. *TCRP Report 19: Guidelines for the Location and Design of Bus Stops*. TRB, National Research Council, Washington, D.C.

Goodwin, L. 2003. *Best Practices for Road Weather Management*. Version 2.0. FHWA-OP-03-081. U.S. Department of Transportation.

Graham, J. L., and R. Burch. 2006. Internal Traffic Control Plans and Worker Safety Planning Tool. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1948*, Transportation Research Board of the National Academies, Washington, D.C.

Gray, M. Advances in Wildlife Crossing Technology. 2009. *Public Roads Magazine*, Vol. 73, No. 2. FHWA-HRT-09-006. U.S. Department of Transportation.

Hughes, W., R. Jagannathan, D. Sengupta, and J. Hummer. 2010. *Alternative Intersections/Interchanges: Informational Report (AIIR)*. FHWA-HRT-09-060. U.S. Department of Transportation.

Huijser, M. P., P. McGowen, J. Fuller, A. Hardy, A. Kociolek, A. P. Clevenger, D. Smith, and R. Ament. 2008. *Wildlife-Vehicle Collision Reduction Study: Report to Congress*. FHWA-HRT-08-034. U.S. Department of Transportation.

Jacobson, L., J. Stribiak, L. Nelson, and D. Sallman. 2006. *Ramp Management and Control Handbook*. FHWA-HOP-06-001. U.S. Department of Transportation.

Knauer, H., S. Pedersen, C. Reherman, J. L. Rochat, E. S. Thalheimer, M. C. Lau, G. G. Fleming, M. Ferroni, and C. Corbisier. 2006. *Highway Construction Noise Handbook*. FHWA-HEP-06-015. U.S. Department of Transportation.

Konchar, M. 1997. *A Comparison of United States Project Delivery Systems*. Technical Report No. 38. Department of Architecture Engineering, Pennsylvania State University, University Park.

Koonce, P., L. Rodegerdts, K. Lee, S. Quayle, S. Beaird, C. Braud, J. Bonneson, P. Tarnoff, and T. Urbanik. 2008. *Traffic Signal Timing Manual*. FHWA-HOP-08-024. U.S. Department of Transportation.

Kuhn, B. *Efficient Use of Highway Capacity Summary*. 2010. FHWA-HOP-10-023. U.S. Department of Transportation.

Levinson, H., S. Zimmerman, J. Clinger, J. Gast, S. Rutherford, and E. Bruhn. 2003. *Bus Rapid Transit Volume 2: Implementation Guidelines*. Federal Transit Administration.

Minnesota Department of Transportation. 2006. *Guidelines for the Selection of Temporary Lane Control Systems in Work Zones*. Minnesota Department of Transportation, St. Paul.

Morena, D., W. Wainwright, and F. Ranck. 2007. Older Drivers at a Crossroads. *Public Roads*, Vol. 70, No. 4. FHWA-HRT-2007-002. U.S. Department of Transportation.

Neudorff, L. G., J. E. Randall, R. Reiss, and R. Gordon. 2003. *Freeway Management and Operations Handbook*. FHWA-OP-04-003. U.S. Department of Transportation.

Parham, A. H., M. D. Woodridge, D. W. Fenno, K. Fitzpatrick, D. Jasek, and S. Ranft. 1999. *Facilitating Incident Management Strategies on Freeways*. Report No. FHWA/TX-00/1848-1. Texas A&M Transportation Institute, College Station.

Rodegerdts, L. A., B. Nevers, B. Robinson, J. Ringert, P. Koonce, J. Bansen, T. Nguyen, J. McGill, D. Stewart, J. Suggett, T. Neuman, N. Antonucci, K. Hardy, and K. Courage. 2004. *Signalized Intersections: Informational Guide*. FHWA-HRT-04-091. U.S. Department of Transportation.

Romin, L. A., and J. A. Bissonette. 1996. Deer Vehicle Collisions: Status of State Monitoring Activities and Mitigation Efforts. *Wildlife Society Bulletin*, Vol. 24, No. 2.

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

Tabler, R., and J. Meena. 2006. Effects of Snow Fences on Crashes and Road Closures: A 34-Year Study on Wyoming Interstate-80. *Cold Regions Engineering*. American Society of Civil Engineers.

U.S. Fire Administration. 2008. *Traffic Incident Management System*. Federal Emergency Management Agency, Federal Highway Administration, U.S. Department of Transportation.

Washington State Department of Transportation. 2009. *Design Manual M 22-01.06*. Washington State Department of Transportation, Olympia.

Wolshon, B., and L. Lambert. 2004. *NCHRP Synthesis of Highway Practice 340: Convertible Roadways and Lanes: A Synthesis of Highway Practice*. TRB, National Research Council, Washington, D.C.

Zaccagnino, W. 1996. Technology for Work and Travel. *Public Roads*, Vol. 59, No. 4. Federal Highway Administration, U.S. Department of Transportation.

Zegeer, C. V., D. W. Reinfurt, J. Hummer, L. Herf, and W. Hunter. 1988. Safety Effects of Cross-Section Design for Two-Lane Roads. In *Transportation Research Record 1195*, TRB, National Research Council, Washington, D.C., pp. 20–32.

RELATED RESEARCH FOR L07

Establishing Monitoring Programs for Travel Time Reliability (L02)

Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies (L03)

Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes (L05)

Incorporating Travel Time Reliability into the Highway Capacity Manual (L08)

Evaluating Alternative Operations Strategies to Improve Travel Time Reliability (L11)

Development of Tools for Assessing Wider Economic Benefits of Transportation (C11)

TRB OVERSIGHT COMMITTEE FOR SHRP 2*

Chair: **Kirk T. Steudle,** *Director, Michigan Department of Transportation*

MEMBERS

H. Norman Abramson, *Executive Vice President (retired), Southwest Research Institute*
Alan C. Clark, *MPO Director, Houston–Galveston Area Council*
Frank L. Danchetz, *Vice President, ARCADIS-US, Inc.*
Malcolm Dougherty, *Director, California Department of Transportation*
Stanley Gee, *Executive Deputy Commissioner, New York State Department of Transportation*
Mary L. Klein, *President and CEO, NatureServe*
Michael P. Lewis, *Director, Rhode Island Department of Transportation*
John R. Njord, *Executive Director (retired), Utah Department of Transportation*
Charles F. Potts, *Chief Executive Officer, Heritage Construction and Materials*
Ananth K. Prasad, *Secretary, Florida Department of Transportation*
Gerald M. Ross, *Chief Engineer (retired), Georgia Department of Transportation*
George E. Schoener, *Executive Director, I-95 Corridor Coalition*
Kumares C. Sinha, *Olson Distinguished Professor of Civil Engineering, Purdue University*
Paul Trombino III, *Director, Iowa Department of Transportation*

EX OFFICIO MEMBERS

Victor M. Mendez, *Administrator, Federal Highway Administration*
David L. Strickland, *Administrator, National Highway Transportation Safety Administration*
Frederick "Bud" Wright, *Executive Director, American Association of State Highway and Transportation Officials*

LIAISONS

Ken Jacoby, *Communications and Outreach Team Director, Office of Corporate Research, Technology, and Innovation Management, Federal Highway Administration*
Tony Kane, *Director, Engineering and Technical Services, American Association of State Highway and Transportation Officials*
Jeffrey F. Paniati, *Executive Director, Federal Highway Administration*
John Pearson, Program Director, *Council of Deputy Ministers Responsible for Transportation and Highway Safety, Canada*
Michael F. Trentacoste, *Associate Administrator, Research, Development, and Technology, Federal Highway Administration*

** Membership as of March 2014.*

RELIABILITY TECHNICAL COORDINATING COMMITTEE*

Chair: **Carlos Braceras,** *Deputy Director and Chief Engineer, Utah Department of Transportation*
Vice Chair: **John Corbin,** *Director, Bureau of Traffic Operations, Wisconsin Department of Transportation*
Vice Chair: **Mark F. Muriello,** *Assistant Director, Tunnels, Bridges, and Terminals, The Port Authority of New York and New Jersey*

MEMBERS

Malcolm E. Baird, *Consultant*
Mike Bousliman, *Chief Information Officer, Information Services Division, Montana Department of Transportation*
Kevin W. Burch, *President, Jet Express, Inc.*
Leslie S. Fowler, *ITS Program Manager, Intelligent Transportation Systems, Bureau of Transportation Safety and Technology, Kansas Department of Transportation*
Steven Gayle, *Consultant, Gayle Consult, LLC*
Bruce R. Hellinga, *Professor, Department of Civil and Environmental Engineering, University of Waterloo, Ontario, Canada*
Sarath C. Joshua, *ITS and Safety Program Manager, Maricopa Association of Governments*
Sandra Q. Larson, *Systems Operations Bureau Director, Iowa Department of Transportation*
Dennis Motiani, *Executive Director, Transportation Systems Management, New Jersey Department of Transportation*
Richard J. Nelson, *Nevada Department of Transportation*
Richard Phillips, *Director (retired), Administrative Services, Washington State Department of Transportation*
Mark Plass, *District Traffic Operations Engineer, Florida Department of Transportation*
Constance S. Sorrell, *Chief of Systems Operations, Virginia Department of Transportation*
William Steffens, *Vice President and Regional Manager, McMahon Associates*
Jan van der Waard, *Program Manager, Mobility and Accessibility, Netherlands Institute for Transport Policy Analysis*
John P. Wolf, *Assistant Division Chief, Traffic Operations, California Department of Transportation (Caltrans)*

FHWA LIAISONS

Robert Arnold, *Director, Transportation Management, Office of Operations, Federal Highway Administration*
Joe Conway, *SHRP 2 Implementation Director, National Highway Institute*
Jeffrey A. Lindley, *Associate Administrator for Operations, Federal Highway Administration*

U.S. DEPARTMENT OF TRANSPORTATION LIAISON

Patricia S. Hu, *Director, Bureau of Transportation Statistics, U.S. Department of Transportation*

AASHTO LIAISON

Gummada Murthy, *Associate Program Director, Operations*

CANADA LIAISON

Andrew Beal, *Manager, Traffic Office, Highway Standards Branch, Ontario Ministry of Transportation*

** Membership as of July 2014.*