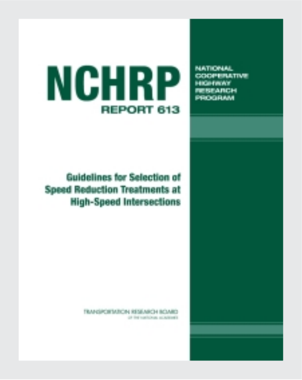

Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections

DETAILS

99 pages | | PAPERBACK
ISBN 978-0-309-09935-6 | DOI 10.17226/14162

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 613

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Planning and Administration

Research sponsored by the American Association of State Highway and Transportation Officials
in cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2008
www.TRB.org

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

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

NCHRP REPORT 613

Project 3-74
ISSN 0077-5614
ISBN: 978-0-309-09935-6
Library of Congress Control Number 2008927124

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

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

and can be ordered through the Internet at:

http://www.national-academies.org/trb/bookstore

Printed in the United States of America

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FOREWORD

By Christopher J. Hedges
Staff Officer
Transportation Research Board

This study evaluated the effectiveness of treatments to reduce vehicle speeds at high-speed intersections. The treatments included geometric design features as well as signage and pavement markings. In the first phase of research, potential treatments were evaluated based on their applicability, key features, speed effects, safety benefits, multimodal impacts, and maintenance issues. The most promising treatments were evaluated using field testing at 10 sites in Oregon, Washington, and Texas. The following guidelines are based on the research results and will provide highway planners and designers with an important new tool in their ongoing efforts to improve safety on our highway systems.

Intersection crashes, a significant portion of total crashes nationwide, account for an average of 9,000 fatalities and 1.5 million injuries annually. Fatalities and severe injuries are more likely to occur in high-speed environments in rural and suburban areas. An recent international scanning tour focused on innovative safety practices in the planning, design, operation, and maintenance of signalized intersections. The scanning team visited several European countries and developed an implementation plan with five major recommendations. One recommendation was to develop treatments that reduce speeds at the approaches to and through intersections. Under NCHRP Project 03-74, a research team led by Brian L. Ray of Kittelson & Associates, Inc., developed guidelines for selecting speed reduction treatments applicable to high-speed intersections. The first phase of the study consisted of a review of relevant literature and a survey of current practices of highway agencies across the country. The research team recommended three promising treatments for further evaluation in the second phase of the study: rumble strips, transverse pavement markings, and dynamic warning signs. These treatments were evaluated using before-and-after field studies at 10 sites in three states. Based on the results, the team developed guidelines illustrating sound practices for selecting appropriate speed-reduction treatments. These guidelines led the user through intersection pre-screening, treatment screening, and treatment implementation considerations. The guidelines also include information about the effects of speed and the conditions that may contribute to undesirably high speeds at intersection approaches. A final report documenting the entire research effort is available as *NCHRP Web-Only Document 124* on the TRB website at http://trb.org/news/blurb_detail.asp?id-9101.

PREFACE

Managing speeds on all roadway types is of key interest to transportation professionals. Because of potential conflicts and the risk of collisions, speed management at intersections is of special interest. Research supporting the practice of managing high-speed intersections, however, is in its infancy. The treatments, and discussion of their application, in these guidelines are based on relatively limited research results from high-speed intersection locations. We benefit from the intuitiveness of supplementing intersection testing results and applying what is known and documented about roadway segments and speed management.

Under NCHRP Project 3-74, Kittelson & Associates, Inc., conducted testing on three speed reduction treatments, and these guidelines provide a foundation for future research that is needed to quantify the effects of each listed treatment. Future research should test the speed reduction qualities of the various treatments in a variety of applications. Further, additional information is needed to understand the possible benefits of combining treatments to maximize speed reduction opportunities. In addition to quality data on speed reduction, more must be learned and documented about speed's role in, and relationship to, intersection safety.

These guidelines provide a substantial discussion about speed, the role it plays, and its impact on intersections. Roadway segments and intersections place different demands and risks on drivers. The discussion emphasizes the distinct relationship between roadway segments and intersections. Engineering solutions for speed management should feature elements that help drivers differentiate between the tasks needed in roadway segments versus those potentially needed at intersections. In some cases, speed reduction may not necessarily result in increased safety. Future studies may help professionals consider whether aiding drivers to be more alert and prepared to take needed actions at an intersection (versus along the upstream roadway segment) may be as valuable as actually reducing intersection speeds.

As we collect volumes of speed reduction data for a variety of treatment types, perhaps future professionals will establish values for "speed modification factors" similar to the concept of "accident modification factors" being applied in highway safety manual initiatives. With a sufficient database of speed reduction information for a variety of treatments in numerous applications, future users of updated guidelines may enjoy the benefits of predictive tools to consider the tradeoffs and benefits of various speed management treatments in a wide range of high-speed intersection environments.

CONTENTS

SUMMARY

Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections

NCHRP Report 613: Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections ("the *Guidelines*") assists roadway planners, designers, and operators as they consider and select appropriate speed reduction treatments at intersections located in high-speed environments. The *Guidelines* are not a new standard for implementing treatments. Rather, they are informational, describing good practices for selecting treatments.

These *Guidelines* were produced as a part of NCHRP Project 3-74, which studied speed reduction treatments for high-speed intersections. This project focused on physical treatments (geometry, signing, striping), rather than on enforcement. For the purposes of this report, high-speed intersections are defined as intersections where the posted speed limit is 45 mph or greater on one or more approaches.

In some cases, speeds through the intersection proper may be greater than 45 mph (e.g., major street approaches at two-way, stop-controlled intersections). In other cases, speeds at the intersection may be closer to zero (e.g., signalized intersections approached on red). The driver workload and desired response vary with these conditions along with a variety of other roadway and environmental features. To help *Guidelines* users select an appropriate treatment, the *Guidelines* focus on providing an understanding of all the elements that may affect conditions at a high-speed intersection.

Very little research has focused on speed at intersections, and most data relate to roadway segments. Furthermore, while much is surmised about the relationship between speed and safety, little data exist to clearly define this relationship. Finally, little data exist that isolate the effects of speed on overall intersection performance (safety, operations, and serving all modes).

A wide variety of treatments is presented in the *Guidelines.* As part of this research effort, some of the treatments were tested to determine how effectively they reduce speeds. The results of these tests, as well as the results of other studies, are presented in the *Guidelines*. In most cases, the body of research is limited and the available data may be useful to roughly indicate the promise of a particular treatment, but are generally not sufficient to predict effectiveness in potential applications.

Because of the lack of published data on this topic, the *Guidelines* focus on the principles affecting speed at intersections. The guidance provided to analyze the conditions that may affect driver behavior or may make a specific intersection particularly sensitive to speed are expected to be as useful as the data provided on each of the treatment types. The *Guidelines* are not intended as a new standard for implementing speed reduction treatments, but instead are presented as a reference guide that may be used in conjunction with local knowledge and professional judgment.

Section 1 introduces the *Guidelines* and presents their purpose, scope, and applicability. Section 2 discusses the fundamentals of speed. Section 3 leads users through the process of considering and implementing speed reduction treatments on intersection approaches. Section 4 describes the speed reduction treatments in detail. Appendices A through D provide a treatment implementation process framework, scenario-based case studies, testing data and results from the testing plan, and references to other relevant studies, respectively.

SECTION 1

Introduction

Drivers generally choose a reasonable travel speed based on their perception of safety and comfort; a variety of conditions and circumstances, however, can lead a driver to misinterpret what is safe and comfortable and result in speeds that are undesirably high for the conditions present at a specific intersection approach. Some of these circumstances are human factors that may be unique to the individual driver and his or her behavior, and others are physical. Physical changes to the roadway and surrounding environment may influence driver behavior, which can indirectly reduce speed and/or enhance environmental quality.

These *Guidelines* provide relevant information about the effects of speed, the conditions that may contribute to undesirably high speeds at intersection approaches, and the state of the practice related to speed reduction treatments used in the United States and abroad—including their effectiveness and implementation considerations. The *Guidelines* also provide insights into the relationship between speed and facility operations. There are many popular beliefs about the relationship between speed and safety, and it is common for people to assume a direct relationship between the two. In fact, there is little published data to actually link speed with safety performance.

This report does not discuss whether speed reduction is appropriate for a condition or what amount of reduction is necessary. This document assumes that the user already desires reduced speeds. The *Guidelines* provide users with information about speed, speed considerations at intersections, and the potential application of treatments to affect speed. Additional research is needed to fully understand the effects that speed reduction treatments and reduced speed may have on safety.

1.1 Intended Users

The *Guidelines* are designed to be useful to engineers, planners, students, and researchers.

1.2 Purpose of *Guidelines*

The *Guidelines* provide information to help users select speed reduction treatments at intersection approaches. Although the application of these treatments most often pertains to existing intersections that experience undesirably high speeds, the information also is relevant to new intersection designs.

1.3 Scope of *Guidelines*

The *Guidelines* apply to intersections with approach speeds of 45 mph or greater. Stop-controlled, yield-controlled, and uncontrolled approaches to signalized and unsignalized intersections are addressed. Because speeds tend to be lower in urban areas, the *Guidelines* primarily apply to suburban and rural roadways. Speeds on roadway segments outside the influence area of an intersection are not addressed; however, the relationship between segment speed and speed within the intersection influence area is addressed. Although this document focuses on public roadway intersections, many principles also apply to private driveways that include public roadway-like features.

Intersections are discrete features of roadway or corridor segments. They frequently occur in urban conditions, but are found more sporadically in rural and suburban areas. Some of the visual cues, physical features, and perceptible qualities that influence operating speeds on roadway segments are different from those that influence operating speed at intersections.

The *Guidelines* focus on speed reduction treatments within an intersection's geometric and operational influence areas and do not specifically address speed reduction in roadway segments. It is necessary to define the influence area of an intersection to differentiate between reducing speeds on the segment rather than the intersection. The influence area of an intersection includes the area within which the typical section of the roadway segment is modified and that is influenced by traffic operations (i.e., queuing and deceleration) related to the intersection. This is shown schematically in Exhibit 1-1.

1.4 Report Organization

Section 1 introduces the *Guidelines* and presents their purpose, scope, and applicability. Section 2 discusses the fundamentals of speed. Section 3 leads users through the process of considering and implementing speed reduction treatments on intersection approaches. Section 4 describes speed reduction treatments in detail. Appendices A through D provide a treatment implementation process framework, scenario-based case studies, testing data and results from the testing plan, and references to other relevant studies, respectively.

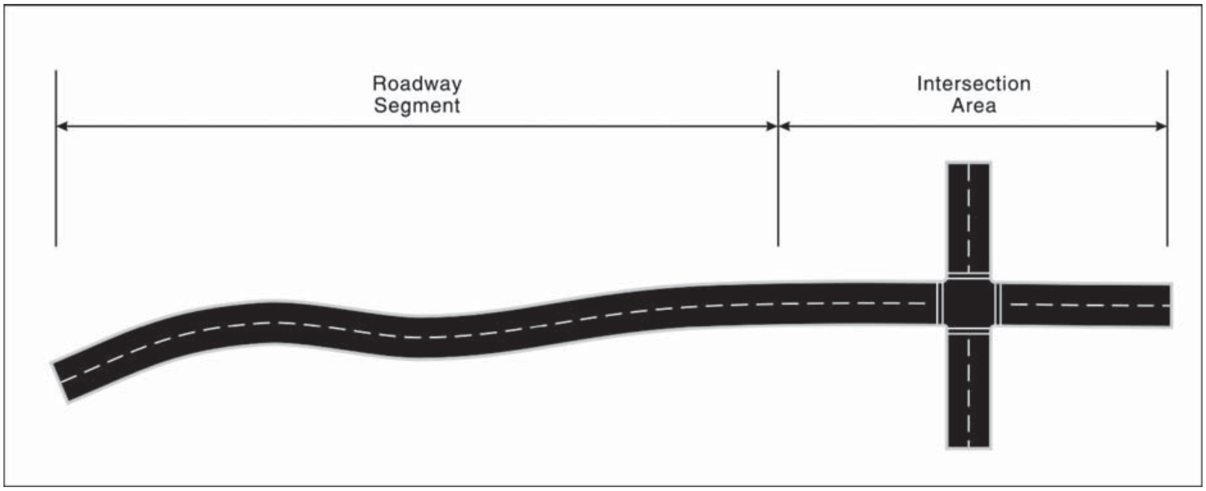


Exhibit 1-1. Roadway segment and intersection area.

SECTION 2

Speed Considerations

2.1 Overview

Although much is often assumed regarding the role of speed at intersections, little data exist that isolate the effects of speed on overall intersection performance (safety, operations, and ability to serve all modes). Speed is a product of many roadway and intersection features and, in turn, speed affects the performance of roadway facilities and the quality of adjacent environments. Speed reduction does not necessarily guarantee safety, nor does it guarantee operational or environmental benefits. Rather, the specific conditions of an intersection must be considered to determine what speeds are desirable for that particular location and environment.

Speed may be deemed "excessive" when drivers do not have sufficient time to react to and safely navigate around interruptions in the flow of traffic or adapt their operations to the current conditions at an intersection. Excessive speeds generally result when environmental and operational elements are incompatible, sending motorists a mixed message about appropriate behavior. Excessive speed may result when a driver misinterprets the tasks needed to operate safely. In some cases, excessive speed may be a deliberate result of driver attitude, risk assessment, and behavior. The conditions at an intersection may require an operating speed that is slower than required by the conditions of the adjacent roadway segments. Defining the intersection influence area and the transition area is necessary to identify the area within which speed reduction treatments are needed.

This section focuses on the role of speed in an intersection environment and discusses the ways in which speed affects intersection performance and the adjacent environment. It details ways in which speed is affected by roadway design and elements of the adjacent environment. This section also highlights some physical conditions and user characteristics that may make an intersection particularly sensitive to speed.

The considerations presented in this section may help practitioners understand concerns related to speed. The following discussion outlines an approach to consider the operational qualities of a specific location and factors a user may wish to consider when investigating intersection operations and design.

2.2 Intersection/Segment Relationship

Defining the influence area of an intersection is fundamentally necessary to differentiate between reducing speeds on the segment rather than the intersection proper. The *Guidelines* focus on speed reduction treatments within an intersection's geometric and operational influence areas and do not specifically address speed reduction in roadway segments. This report defines an intersection by geometric and operational influence area as follows:

- Geometric—The location where the typical section of the roadway segment is modified to create the intersection features. These modifications include tapers for adding or dropping lanes approaching and departing from the intersection.
- Operational—The area that is influenced by traffic operations, including queuing, lane changing, merging, and vehicle acceleration/deceleration capabilities. This operational influence area could be independent of the geometric influence area and can change by time of day, season, or other conditions.

Speed transition needs should be considered between a roadway segment and the intersection influence area to allow drivers the opportunity to react to changing conditions and adjust their speed accordingly. This could potentially include a change in the roadway cross section (i.e., adding curbs and landscaping or via a "gateway" treatment) or simply providing adequate sight distance from the upstream segment to the intersection's geometric or operational influence area. The length needed for the transition area will vary depending on the total desired speed reduction and the operating speeds in upstream segments. Exhibit 2-1 schematically depicts the roadway segment and intersection speed relationships.

In some cases, the design speeds of the adjacent roadway segments are appropriate for an intersection. In other cases, the intersection characteristics and driver workload vary and a reduced speed may be desirable. The need for speed reduction at intersections can be considered in the following general conditions:

- The posted speed of the segment is higher than the desired speed of the intersection approach (e.g., the intersection approach is stop controlled, or a transition from a rural to a more urbanized environment occurs at the intersection).
- The posted speed of the segment is the same as the desired speed of the intersection approach; however, drivers exceed the posted speeds.
- The posted and operating speeds at the segment and intersection are reasonable. However, potential conflicts at the intersection (e.g., diverging or merging maneuvers, crossing traffic, or queues) require drivers to be especially alert to the need to respond to these potential conflicts.

Stop-controlled intersection approaches will fall under the first condition, while uncontrolled and yield-controlled approaches may fall under any of these conditions. A stop-controlled condition requires operations that are independent of the roadway design speed (i.e., a tangent intersection

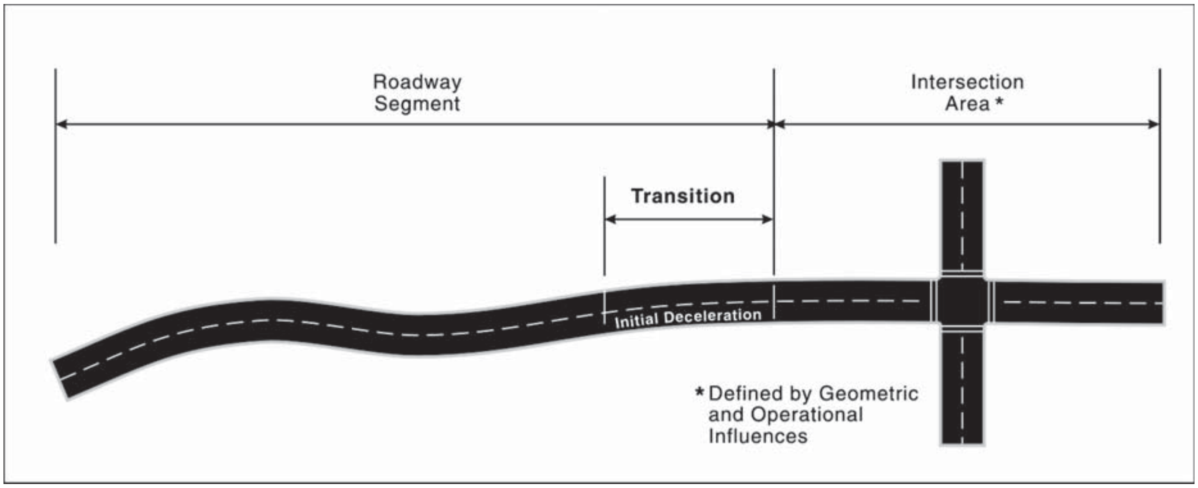


Exhibit 2-1. Roadway segment and intersection speed relationships.

approach on level grade with unlimited sight distance has an unlimited design speed regardless of the posted speed approaching the intersection). A yield condition may operate as a stop control during some time periods, depending on traffic flows. In other cases, a yield condition may be virtually free flow and the operating speeds for this movement may be dictated by the roadway approach geometry (i.e., a separate turn lane, turning roadway width, and turning roadway radius).

2.3 Designing for Appropriate Speeds

In general terms, good roadway geometric design provides a sufficient level of mobility and land-use access for motorists, bicyclists, pedestrians, and transit while maintaining an appropriate degree of safety. Higher-speed roadways are typically provided in locations where travel time and mobility are priority needs. Speed is often used as a performance measure to evaluate the effectiveness of highway and street designs. High speeds generally are associated with long trips, and low speeds generally are associated with short trips or with facilities that have more frequent access. Posted speeds frequently correlate with these intended uses. High-speed facilities serve key network needs—it is not always appropriate to expect reduced speeds at intersections.

Environmental and operational indicators should be in place to provide drivers with a consistent message about the potential for conflict so they are best able to select an appropriate speed. The goal is to provide geometric street designs that look and feel like the roadway's intended purpose. Because drivers choose their speed based on what they see on the roadway ahead, calling a driver's attention to roadway features that present a potential risk provides increased opportunities to avoid conflicts. Drivers who perceive potential risk can better adapt their driving behavior to roadway conditions.

A facility's design speed is a fundamental design criterion that affects three-dimensional roadway design parameters (plan, profile, and cross section). Aside from roundabouts, where entry speeds of about 25 mph are specifically attained through geometric design, there is no common intersection design speed. Intersection speed typically is assumed to be that of the roadway segment.

Although designers generally seek speed and operational consistency, intersection operations (e.g., queuing, deceleration, turning vehicles) and/or geometry may create localized conditions that require reduced speeds. Drivers must perceive and comprehend a greater variety of situations at an intersection than while driving through the high-speed roadway segment that precedes the intersection.

Intersection conditions should be considered independently from the adjacent roadway segments. For new facilities, this means ensuring that an intersection's operational and geometric elements are appropriately configured. The existing geometric and operational elements of an intersection should be assessed when considering appropriate actions for retrofit projects.

Such a design philosophy and approach can produce geometric conditions that are more likely to result in operating speeds consistent with driver expectations and commensurate with the roadway's function. This, of course, does not account for impaired or overly aggressive motorists or conditions such as adverse weather. Ideally, drivers should operate their vehicles in a manner appropriate for the conditions for as long as those conditions prevail.

2.4 Factors Affected by Speed

High speeds serve key network functions. However, operating speeds inconsistent with the prevailing conditions may adversely affect environmental quality and safety, or require a larger-than-desirable facility size.

The effects of speed are most pronounced at intersections where friction between competing movements is concentrated. This friction may manifest itself as decelerating or accelerating vehicles, queues, crossing traffic, or traffic yielding to crossing pedestrians. Any of these kinds of friction create the potential for conflicts.

The ways in which speeds through intersections affect intersection operations, environmental quality, and safety are discussed below.

2.4.1 Facility Size

Drivers' perception–reaction times are essentially constant; therefore, higher speeds require drivers to understand their driving tasks farther in advance of intersections, compared to slower-speed environments. This means that the distance between driver decision points must increase as speeds increase.

Higher-speed facilities require larger clear zones and flatter horizontal and vertical curves. In addition, fundamental dimensions for stopping-sight distance increase with speed, leading to flatter and more open roadways. Attaining appropriate sight distances affects horizontal and vertical alignments as well as such cross-sectional features as cuts, fills, and landscaping. For example, using values from Exhibit 9-58 from AASHTO's *Policy on Geometric Design of Highways and Streets*, known as the "Green Book," (AASHTO, 2004) for the case of a right turn from a stop or a crossing maneuver, the intersection sight-distance value for 45 mph is 430 ft. This value increases to 575 ft when speeds are 60 mph.

In urban environments, sight-distance needs can affect building setbacks, on-street parking locations, and other design elements such as the locations of street furniture and landscaping. The transition zones within which drivers are required to slow down as they approach an intersection need to be longer when a greater change in speed is required. This affects the length of alignment tapers, bay tapers, and the deceleration components of turn-lane designs.

2.4.2 Quality and Comfort of the Roadway Environment

The function of roadways and intersections must be balanced with the needs of adjacent land uses to both maintain environmental quality and to provide necessary mobility. High-speed intersections can create a barrier to the mobility of non-auto users crossing the facility. The increased noise levels and intense environments that result from proximity to motor vehicles can create discomfort for pedestrians and bicyclists who travel parallel to the facility. Adjacent neighborhoods and businesses may also experience adverse effects from high-speed traffic, such as tire and engine noise, and may benefit from buffer treatments.

Intersections near schools, hospitals, or other concentrations of pedestrians—particularly people who are elderly, young, or have disabilities—may be particularly sensitive to high speeds.

2.4.3 Safety

The relationship between speed and intersection safety is a critical concern for transportation professionals. Road safety is often divided into three constituent elements: exposure (increases with the number of conflicting movements), risk (increases with traffic volume), and consequence (increases with speed). Reducing speed at intersections has the potential to improve consequence, although it has little relationship to exposure or risk. There is a decisive relationship between speed and crash severity, but the relationships between speed and crash frequency are less clear.

The physical relationship between mass and energy explains that higher speeds and larger speed differentials create the potential for higher-severity crashes. As speeds increase, the energy from the mass of the vehicles increases. Studies of modern multilane roundabouts illustrate the relationship between speed and crash severity: total crash rates and frequency may stay the same after an intersection is converted to a roundabout, but the slower speeds help reduce the severity of crashes.

A variety of intersection traffic conditions create large speed differentials, increasing the potential for severe crashes. For example

- An unbalanced distribution of traffic for a given number and arrangement of lanes could create high differentials in speeds between vehicles traveling in the same direction. Consider that a channelized right-turn lane may operate under near free-flow conditions while the adjacent travel lanes experience queuing.
- An intersection or approach with extensive queuing, where the back of the queue is a significant distance from the intersection proper, could cause speed differentials. In these conditions, vehicle queues in turn lanes may exceed the storage length provided, requiring vehicles to decelerate in the through travel lanes.
- Uniform traffic congestion at an approach could lead to queues that extend outside an intersection approach's typical available sight distance. In these conditions, vehicle queues extending beyond the intersection's geometric influence area may require that drivers decelerate in advance of visual cues of the impending intersection.

No research was found that identified a relationship between crash frequency and mean or 85th-percentile speed. However, many studies have found that the likelihood of being involved in a crash increases with deviation from the mean speed of traffic on the facility. (Taylor and Foody, 1965; Hauer, 1971)

If the facility and intersection design provide adequate sight distance and appropriate user expectancy of potential conflicts, there should be adequate space and time to react to, and avoid, crashes. If, however, speeds are excessive for the facility and intersection design, there will be insufficient space and time to avoid crashes, and a high crash frequency may result.

High-speed travel may affect crash avoidance because faster moving vehicles travel farther than slow moving vehicles during the typical reaction time needed for a driver to avoid a potential hazard. In addition, the greater a vehicle's speed, the less time there is for other motorists, bicyclists, or pedestrians to react to, and avoid, that vehicle.

Thus, although there is no research to support the common assumption that reducing speeds will reduce crash frequency, reducing speed variation may achieve this. The relationships between intersection speed and safety are complex, and it cannot be assumed that reduced speeds will result in a safety improvement.

2.4.4 Traffic Operations

Traffic operations refers to a roadway's performance and is typically measured in terms of capacity, travel time, delay, number of stops, and queuing. Although vehicle speed directly correlates to the motorists' perceived level of service along an arterial or highway segment, it does not have a significant effect on the traffic operational performance of an individual intersection. Furthermore, vehicle speed through the influence area of an intersection has little effect on overall travel time.

2.4.4.1 Capacity

Vehicle speed is not a primary determinant of intersection capacity—the number of vehicles that the intersection can process in a given time period. For the case of a minor street left-turn movement from a two-way, stop-controlled intersection, research performed as part of NCHRP

Project 3-46, and documented in *Capacity and Level of Service at Unsignalized Intersections*, (TRB, 1996) found that speed did not have a significant effect on a driver's critical gap, which corresponds directly to the capacity of the stop-controlled movement.

For a signalized approach, the capacity of an intersection is a function of the saturation flow rate of the approaching lanes. Saturation flow rate is defined as the flow rate at which previously queued vehicles can traverse an intersection approach under prevailing conditions. As previously queued vehicles are starting from a stopped position, a vehicle's speed through an intersection is not relevant in the calculation.

2.4.4.2 Travel Time

Higher overall travel speeds along an arterial result in lower travel time and an improved level of service. Vehicle speed within the influence area of intersections does not generally have a significant influence on overall travel time. For example, given an intersection with a total influence area of 1,000 ft, the travel-time difference between a vehicle traveling at 50 mph versus a vehicle traveling at 30 mph through the intersection is less than 10 seconds, assuming an uncontrolled approach or a "green light" without interfering queues.

2.5 Factors that Affect Speed

A driver's selection of a safe speed and path is determined by his or her judgment, estimates, and predictions based on highway characteristics, traffic, and traffic control devices. (Lerner, 2002) Roadway design elements, environment, traffic type, and other factors help drivers determine an appropriate speed. Some elements affect traffic flow directly; others can influence driver behavior by contributing to the visual complexity (or simplicity) of the roadway edge. The design and characteristics of an intersection proper affect speed at the intersection as do the design and characteristics of the roadway facility and adjacent segments. This section presents a variety of human, vehicle, and roadway characteristics that affect drivers' speed.

2.5.1 Roadway Facility Design and Characteristics

Intersections are often relatively infrequent occurrences on high-speed facilities and drivers may expect that they can operate at a consistent speed. Without clear indications of the need to reduce speed and without adequate transition distance within which to do so, drivers will navigate the intersection area at speeds they deem appropriate for the adjacent roadway segments. The chosen speed may or may not be appropriate for the actual conditions at the intersection.

The characteristics of the roadway segment prior to an intersection affect speeds at the intersection. Exhibit 2-2 provides a list of roadway facility factors that may affect speeds on intersection approaches. These features may influence driver behavior or vehicle operations and result in speed changes. Many of these relationships are derived from relationships documented in *NCHRP Report 504: Design Speed, Operating Speed, and Posted Speed Practices*. (Fitzpatrick et al., 2003)

2.5.2 Speed Adaptation

Drivers often underestimate their speeds, particularly in the medium- and high-speed ranges. Thus, excessive speed is not always a conscious decision. In some cases, excessive speed can be attributed to speed adaptation. The speed adaptation hypothesis states that the perceived speed of one's vehicle will be lower than the actual speed if the driver has recently operated the vehicle at a higher speed.

Intersection Variable	Potential Relationship to Speed
Facility Type	Speeds tend to be higher on higher-order facilities. Speeds tend to be slightly lower when a raised median or no median is provided than when a depressed median or a two-way, left-turn lane is present. Limited access, low signal density, unimpeded visibility, and viaducts may promote high speeds.
Roadway Characteristics	Wide shoulders, medians, and overall pavement widths are associated with higher speeds. Lane widths, horizontal/vertical geometry, sight distance, curbs, and bike lanes may influence measured speeds and desired speeds.
Conflicts and Friction	As the distance between points of friction (driveways, intersections, pedestrian crossings, lane drops) increases, speeds increase to a point and then plateau.
Posted Speed	Posted speed and 85th-percentile speed increase or decrease together.
Roadside Environment	Higher speeds occur in rural and undeveloped areas compared to urban or developed areas. Lower speeds occur in areas with higher levels of pedestrian activity.
Pavement Type and Condition	Poor, cracked, or uneven pavement and joint details may slow travel speeds, while smooth pavement may allow faster speeds. The absence of centerline or edge line markings is associated with lower speeds.
Transition	The intersection location in relation to the roadway segment (tangential, curvilinear, flat, mountainous) may influence measured and desired speeds.

Exhibit 2-2. Roadway facility characteristics that may affect intersection speed.

Speed adaptation may contribute to excessive speeds in transition areas between rural and built environments, or between access controlled or other high-speed facilities and street environments that have driveways, multiple intersections, and non-motorized users. Drivers who have adapted to higher speeds may not appreciate the need to slow down at intersections. These drivers may have attained a feeling of comfort or safety that may not be appropriate for the potentially changing conditions at a high-speed intersection.

2.5.3 Intersection Design and Characteristics

The physical characteristics of the intersection proper affect speed, as do the changing conditions at the intersection (i.e., lighting and congestion patterns). Exhibit 2-3 summarizes many intersection characteristics that may influence drivers' speed choice. Exhibit 2-3 originates from relationships documented in *NCHRP Report 504: Design Speed, Operating Speed, and Posted Speed Practices*. (Fitzpatrick et al., 2003)

Intersection Variable	Potential Relationship to Speed
Traffic Control/Approach Type	A signalized intersection, a stop-controlled intersection, and a yield-controlled intersection require different driver tasks and operating speeds.
Wayfinding	Complex intersection maneuvers tend to reduce speeds, especially for unfamiliar drivers.
Visual Complexity	Roadside development, pedestrians, bicyclists, signage, and environmental elements that interest drivers may affect speed.
Roadside Impedances	Roadside parking, bus stops, and vehicle loading zones may interrupt traffic flow near intersections and effect speed reductions.
Lane Drops	Drivers may slow down to make lane changes. Increased lane densities may also reduce speeds.
Merging	Through drivers may need to slow down to create gaps for vehicles entering the traffic stream.
Sight Distance	Drivers may travel at higher speeds through intersections without sight-distance constraints. Sight-distance restrictions can induce a small reduction in speeds, although only for the faster vehicles.
Lighting	Inadequate lighting may not allow drivers to perceive and react in advance of an intersection.
Traffic Conditions	Congestion, queuing, directional distribution, and low volumes influence speeds through intersections.

Exhibit 2-3. Intersection characteristics that may affect intersection speed.

2.5.4 Drivers and Vehicles

Different types of drivers will choose different speeds at intersections. Commuters and other familiar drivers may tend to drive faster than infrequent users. Driver age and attitude also influence speed through intersections.

Additionally, transit vehicles, heavy vehicles, and recreational vehicles may have especially slow turning speeds, requiring them to travel slower than general traffic to maneuver through an intersection.

2.5.5 Weather Conditions

Weather conditions may affect driver behavior and speeds. Drivers may use caution and drive slower during snow, ice, rain, fog, or dust than they do in clear and sunny conditions.

2.6 Conditions Potentially Sensitive to Speed

This section identifies a variety of conditions, elements, and data that may indicate that an intersection is particularly sensitive to speed. In some cases, these are contextual considerations related to the intersection configuration, location, or environment; in other cases, the sensitivity might be attributed to specific users or user characteristics at that location. Field conditions may also provide insights into an intersection's sensitivity to speed. This might include observing user behavior or evaluating traffic and safety data.

2.6.1 Common Conditions

There are a variety of conditions that may be associated with a heightened sensitivity to speed. Many of these are related to the characteristics that affect speed identified in Exhibit 2-2. If drivers are alert to the characteristics of an intersection that make lower speeds desirable, they may slow down. If, however, they are not alert to these characteristics it can create a condition that is sensitive to speed. Examples include the following:

- Intersections that are difficult to detect—horizontal or vertical curvature of an intersection approach may make it difficult to detect.
- Intersections within a corridor with a variety of changing contexts (land uses, design philosophies)—drivers need to be warned of the increased need to respond to pedestrians, buses, driveway traffic, or other interruptions in traffic flow.
- Intersections that link high-order and low-order roadway segments—gateways between rural and urban areas.
- Intersections with complex geometry or irregular route continuity—requiring a high driver workload to comprehend or navigate through the intersection.
- Intersections proximate to concentrations of sensitive or high-risk populations—children, elderly, or disabled.
- An approach with limited sight distance—roadside obstacles, sunlight at certain times of day.
- Intersections with high-speed differentials or limited acceptable gaps at certain times of day—long queues for one or more approach lanes.

2.6.2 Observed Field Conditions

Field observations of an intersection's operating conditions may provide an opportunity to identify intersections sensitive to speed.

2.6.2.1 Crash Avoidance Patterns

Skid marks on a roadway are often an indicator that drivers do not have sufficient time to react to interruptions in the flow of traffic. The direction and location of skid marks may be useful clues for deciphering operating conditions. Skid marks may indicate that drivers are traveling faster than their ability to perceive and react to an intersection condition (i.e., a single, stopped vehicle turning left, a vehicle that is accelerating or decelerating, or the back of a queue that extends beyond the perceived area of the intersection).

2.6.2.2 Driver Behavior

Undesirable driver behavior, such as lack of compliance with signals or stop signs, may indicate that excessive speeds approaching an intersection do not give drivers enough time to see and react to traffic control. The speeds may be the result of adaptation from the prior segment with drivers unaware of their speed and required stopping distances. Desired speeds might be attained if drivers had assistance in transitioning from one segment to the other.

2.6.2.3 Congestion Patterns

Congestion patterns can increase the intersection influence area, creating sensitivity to speed. Congestion patterns that create high-speed differentials (such as those listed in Section 2.4.3), that are associated with increased pedestrian or transit use, or that reduce the availability of acceptable gaps for side street traffic, may indicate a particular sensitivity to speed.

2.6.2.4 Speed Data

Speed data can provide insights about effective roadway conditions. For example, the measured 85th-percentile speed, mean speed, and speed variance can be compared to the implied design speed based on the "Green Book" (AASHTO, 2004) intersection-sight-distance and stopping-sight-distance criteria. Comparing measured speeds to the posted speed could help identify differences between desired operations (as indicated by a posted speed) and actual conditions.

2.6.2.5 Crash Data

A high crash rate at an intersection may indicate any number of operational or geometric issues and does not, in isolation, indicate excessive speeds. A closer analysis of the crash types, locations, time of day, weather conditions, and other factors is useful for understanding the role of speed, if any, in the crashes. Crash patterns that may be associated with excessive speeds include the following:

- Frequent rear-end crashes—drivers not anticipating the location of the back of a queue,
- Frequent run-off-road crashes—drivers avoiding conflicts in the roadway proper, or
- Angle crashes—drivers accepting gaps that are too small.

A close analysis of the crash data is necessary to determine if these patterns could also be attributed to other factors such as driver inattention or impairment, geometric conditions (alignment, sight distance), or other conditions that do not meet a driver's expectations.

2.7 Summary

Reduced speeds do not guarantee safety, nor do they guarantee operational or environmental benefits at a high-speed intersection. Speed is a product of many features, including the adjacent roadway segment, the user and vehicle type, and the general environmental context. Intersection approach speeds can affect a facility's safety and performance. Speed, when considered as a design criterion or consideration, can affect the roadway design while also influencing the environmental context. Understanding how speed affects intersection conditions and how those conditions affect speed is considered first to evaluate and select an appropriate speed reduction treatment.

SECTION 3

Selecting an Appropriate Treatment

3.1 Introduction

There are a variety of treatments with the potential to reduce vehicle speeds at high-speed intersections. This section provides information about these treatments, including their applicability, cost, secondary impacts, implementation considerations, and potential to effectively reduce speeds and increase safety. This information was compiled from a variety of national and international sources. However, there are very little data that clearly quantify how effectively these treatments reduce speeds at high-speed intersections. Furthermore, there are relatively little data on the safety performance of potential treatments and, when information is provided, there is no direct correlation to the change in safety caused by reduced speeds. Quantifying the safety effects of speed reduction treatments at high-speed intersections will require conditions to be monitored for a number of years after the treatments are implemented.

The information provided in this section highlights the considerations that will help determine which treatments may be appropriate at a specific location. In many cases, one or more treatments may be appropriate for a given intersection. To determine the most appropriate treatment, the information provided in this section must be balanced with local practices and engineering judgment related to the specific situation.

The treatments covered by the *Guidelines* include those commonly used in the United States, those currently being researched, and those for which there was an expressed interest by state highway agencies. National use and interest in the treatments was determined through a national survey of state highway agencies conducted as part of the research efforts for NCHRP Project 3-74. More information about the survey and the responses can be found in *NCHRP Web-Only Document 124.*

Some of the treatments included in the *Guidelines* have had limited or no documented application at high-speed intersections; however, their functions indicate they have potential to be applied at certain high-speed locations. For example, speed tables are generally used in low-speed residential environments, but they may be able to be applied at the stop-controlled approaches of high-speed intersections to reinforce the need to decelerate in advance of the intersection proper.

Additionally, many of the treatments included in the *Guidelines* can be applied in both high-speed and low-speed environments. Identifying a treatment as a "high-speed" treatment does not imply it is inappropriate for low-speed applications.

3.2 Determining the Need for a Treatment

Speed reduction treatments are appropriate when an engineering study indicates the need for reduced speed. The *Manual on Uniform Traffic Control Devices* (*MUTCD*) (FHWA, 2003) lists the following factors that may be considered when establishing speed limits:

- Free-flowing traffic's 85th-percentile speed;
- Road characteristics (shoulder condition, grade, alignment, and sight distance);
- Pace speed;
- Roadside development and environment;
- Parking practices and pedestrian activity; and
- Reported crash experience for at least a 12-month period.

Logic indicates that similar elements should be considered when determining the need for speed reduction treatments. It is not advisable to install treatments based on requests from local officials or residents when an engineering study has not taken place.

In some cases, treatments might be applied to define the location where deceleration should begin to attain the desired speeds in the intersection area. In other cases, the visible presence of treatments at the intersection proper (i.e., roundabouts, splitter islands) may be sufficient to cause the desired speed reduction in advance of the intersection. A treatment may not significantly reduce speeds; however, that does not necessarily mean the treatment is ineffective. There may be safety benefits to alerting drivers to the changing roadway conditions as they travel from the roadway segment to the intersection influence area.

3.3 Treatment Selection Process

Specific treatments are not necessarily appropriate in all circumstances and conditions. A treatment applied at one location on a facility may not be appropriate at a different location on the same facility. The unique characteristics of each intersection and the speed issues that exist must be assessed during the selection process. Many treatments are appropriate to use in a variety of conditions, but it is likely that their effectiveness will vary considerably depending on the conditions of the specific application. This section describes a process to select appropriate speed reduction treatments for a particular condition. The steps of the treatment selection process are

- Intersection pre-screening,
- Treatment screening, and
- Treatment implementation.

Appendix A provides a treatment implementation process framework to help the user assess an intersection and potential treatments. Appendix B provides several case studies that detail treatment selection and design.

3.3.1 Intersection Pre-Screening

The pre-screening process involves identifying an intersection that may benefit from a speed reduction treatment and then assessing the data for that intersection to make decisions about which treatments may be appropriate and most effective at a particular candidate site. Gathering data (i.e., crash history, speed study data, and aerial photos) can be helpful in understanding the site context, including the relationships between the roadway segment and intersection influence area, as well as the influence of the overall facility geometry and environment. Understanding these aspects of the intersection and segment can then help determine if speed is the contributing factor for the problems experienced at a particular location.

3.3.1.1 Identify Intersection as Needing Attention

The first step in intersection pre-screening is identifying the need for further study of speed issues at the intersection. This determination may be based on reports of high speeds, high crash frequency and/or severity, recurring crash types, and/or near misses.

3.3.1.2 Gather Intersection Information

The next step is to gather information about the intersection including intersection features, crash history, speed data, traffic volumes, traffic composition, aerial photographs, and site observations.

3.3.1.3 Assess Data

The final step of pre-screening is assessing the data to determine whether speed is a primary problem. Appropriate questions to answer are as follows:

- What is the primary problem?
- Is speed a contributing factor or should other actions be considered?
- What can be learned anecdotally from agency staff?

3.3.2 Treatment Screening

After the pre-screening process is completed to verify that speed may be a primary issue, the treatment screening process is used to eliminate candidates with "fatal flaws" and identify promising treatments.

3.3.2.1 Identify Fatal Flaws

Fatal-flaw screening may eliminate treatments based on cost, agency policies, or existing intersection characteristics. Examples of fatal-flaw screening include

- Cost—funding issues may prevent installing a dynamic warning sign or approach curvature.
- Time to implement—some treatments take longer to install than others, and some can only be installed during certain weather conditions.
- Noise considerations—rumble strips may be undesirable in residential areas.
- Right of way—approach curvature may require right of way.
- Energy/power source—dynamic warning signs require a power source.
- Land use and environment—existing driveway locations may prohibit some types of treatments.
- Policy—some jurisdictions may have policies that prohibit some treatments.
- Novelty—depending on the user (commuter, recreational), some treatments may be more prone to having limited long-term effects.

3.3.2.2 Evaluate Potential Treatments

After the list of treatments has been narrowed through the fatal-flaw analysis, the next step is to gain a better understanding of each remaining potential treatment and determine the objectives for the treatment. Appropriate questions to answer are as follows:

- What is the target speed?
- Where speeds should be reduced, how much should the speeds be reduced?
- What information is available about each treatment?
- Has there been any past research conducted on that particular treatment? Was the treatment effective? Were there any side effects of the treatment?

The *Guidelines* do not address the first two questions regarding target speed and the desired speed reduction. These must be determined based on the specific conditions and context of the intersection. Later in this document, Exhibits 3-3 and 3-4 and Section 4 provide information to answer the last two questions regarding available treatment information, treatment research, and effects. This information should be supplemented with local experience and professional judgment to select one or more treatments for implementation.

3.3.3 Treatment Implementation

The basic goal of the treatments is to achieve a target approach speed at or before drivers reach the intersection influence area. To achieve this, it is useful to determine the boundaries of the intersection influence area, the target approach speed, and the length of the transition area. Exhibit 3-1 shows the key elements used in treatment design.

3.3.3.1 Target Approach Speed

The target approach speed generally is selected so that drivers can operate safely and without an adverse affect on non-motorized users within the influence area. For example, if the geometry of an intersection approach has limited sight distance, the target speed may be selected such that vehicles traveling at that speed will have sufficient stopping sight distance as they approach the intersection. Alternatively, if there is a school in one quadrant of an intersection, the target speed may be selected such that the noise and perceived risk are acceptable. In either case, the target speed should be reached in advance of the intersection influence area to ensure acceptable conditions within the intersection influence area. The location of the target speed may be affected by the intersection's geometric and operational influence area. For example, a recurring long queue on one approach may shift the target speed location upstream on the roadway segment to provide sufficient distance for drivers to comfortably decelerate to the back of the queue.

3.3.3.2 Intersection Influence Area

As described in Section 2.2, the intersection influence area is determined by the geometric and operational influences. Determining the operational influence area generally involves identifying the location of a potential conflict (i.e., a crossing maneuver, yield point, or back of queue) and calculating the stopping sight distance needed in advance of that location. For a stop-controlled approach, a comfortable deceleration rate should be assumed. For other approach types, it is appropriate to assume a rapid deceleration rate. Exhibit 3-2 shows the

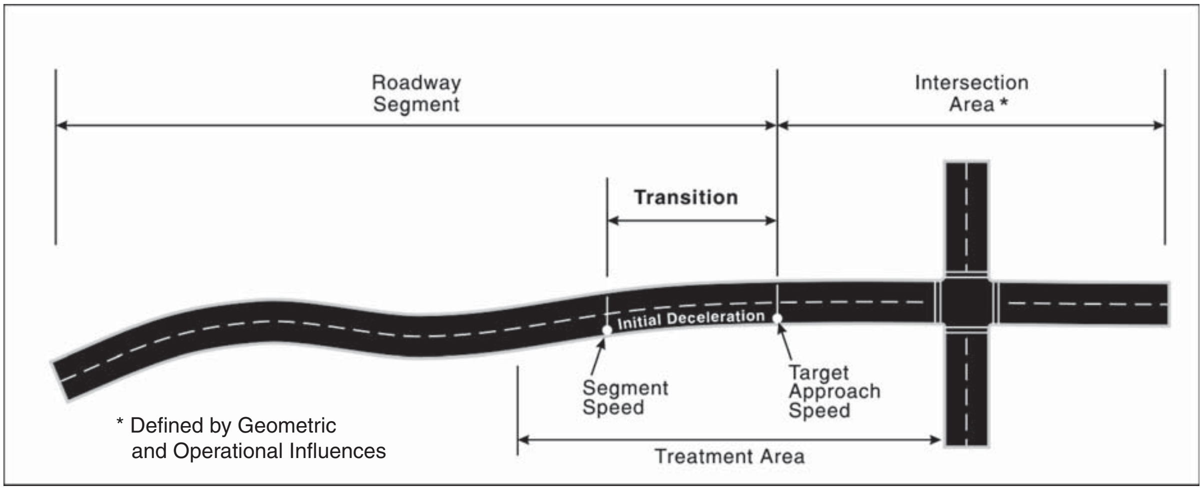


Exhibit 3-1. Roadway segment and intersection speed relationships.

Target Approach Speed (Va) (mph)	Perception Reaction Distance (feet)	Deceleration Distance (feet)	Total Transition Distance (feet)
Uncontrolled or Yield Intersection Approach			
50	185	530	715
45	165	435	600
40	150	320	470
35	130	280	410
30	110	235	345
Stop- or Signal-Controlled Intersection Approach			
50	185	240	425
45	165	195	360
40	150	155	305
35	130	120	250
30	110	90	200
20	75	40	115

Notes:
Va is the average speed of the roadway segment.
Perception and reaction time is assumed at 2.5 seconds.
Deceleration distances for uncontrolled or yield intersection approaches are interpreted from Chapter 10: Grade Separations and Interchanges, Exhibit 10-73. (AASHTO, 2004, p. 851)
Deceleration distances for stop- or signal-controlled intersection approaches are from Exhibit 3-1. (AASHTO, 2004, p. 112)

Exhibit 3-2. Intersection area: operational influence distance from conflict or stop.

required transition that should be assumed in determining the operational influence area for several conditions.

3.3.3.3 Transition Area

Upstream of the intersection and within the roadway segment, a transition area may be required for drivers to adjust their speeds to the target speed. The size of the transition area will vary based on segment speed and the amount of speed reduction required. The length of the transition area should support comfortable deceleration rates. Exhibit 3-3 shows appropriate transition distances for several roadway segment and target speed conditions.

3.3.3.4 Treatment Area

To achieve this pattern of speed reduction, treatments should be designed to take effect at the beginning of the transition area. Depending on the type of treatment, it may be appropriate to carry the treatment through the intersection, or, as in the case of a dynamic warning sign, the treatment may be placed in one discrete location. In either case, the treatment should be perceived by motorists no later than the beginning of the transition area to ensure that adequate space and time are provided for the desired speed reduction.

Treatment design should reinforce existing intersection features including signs, lighting, pavement markings, lane drops or added lanes, medians and splitter islands, horizontal and vertical curves, and any other features that provide visual cues of the impending intersection. Typical layouts for treatment designs can provide guidance. However, modifications based on specific conditions will generally provide the best results.

Mid-Block Speed (Vs)	Target Approach Speed (Va) (mph)	Perception Reaction Distance (feet)	Deceleration Distance (feet)	Total Transition Distance (feet)
60	45	220	390	610
60	20	220	620	840
55	45	200	280	480
55	20	200	500	700
50	45	185	240	425
50	20	185	480	665
45	35	165	225	390
45	20	165	350	515

Notes:
Vs is the average speed of the segment.
Va is the target approach speed.
Perception and reaction time is assumed at 2.5 seconds.
Deceleration distances are interpreted from Chapter 10: Grade Separations and Interchanges. (AASHTO, 2004)

Exhibit 3-3. Transition distance between segment and intersection area.

3.4 Combining Treatments

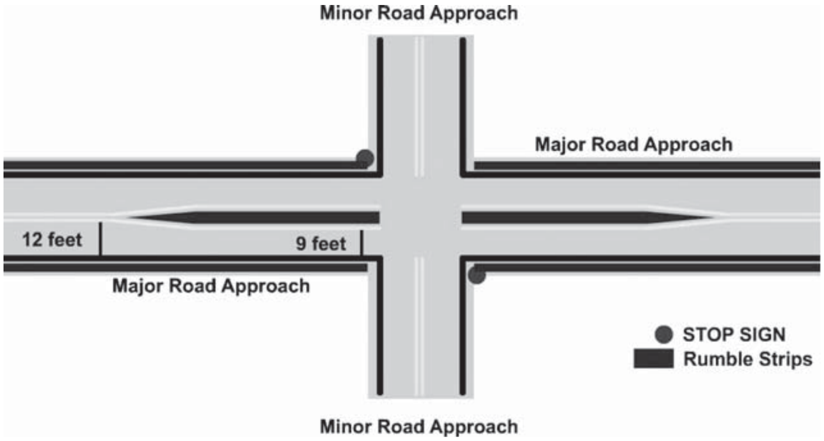
Intuition suggests that combining treatments will increase the potential to reduce speed. Although there is little research that determines this potential, it is expected that combining treatments will have a benefit up to a point, after which, no more speed reduction will occur. This is because drivers will operate at a speed at which they feel comfortable or safe. Below this speed, the cumulative application of treatments becomes ineffective. Additional treatments can provide benefits by reinforcing the need to be prepared to slow down, even if additional speed reduction is not observed.

An example of combining treatments is a low-cost concept for two-way, stop-controlled intersections on high-speed, two-lane rural highways as studied by FHWA and documented in Low-Cost Intersection Treatments on High-Speed Rural Roads. (FHWA, 2006) As shown in Exhibit 3-4, the concept incorporates a variety of individual treatments, including lane narrowing, splitter islands on each approach, and lateral pavement markings on each side of the traveled way.

The objectives of this FHWA study were to identify, promote, and evaluate low-cost concepts to reduce speeds at intersections. The research team investigated two concepts that combined various roadway treatments. The first concept was to reduce the lane width, add rumble strips, and add pavement markings on the major road. The second concept was to install a mountable splitter island with stop signs on the minor road approaches.

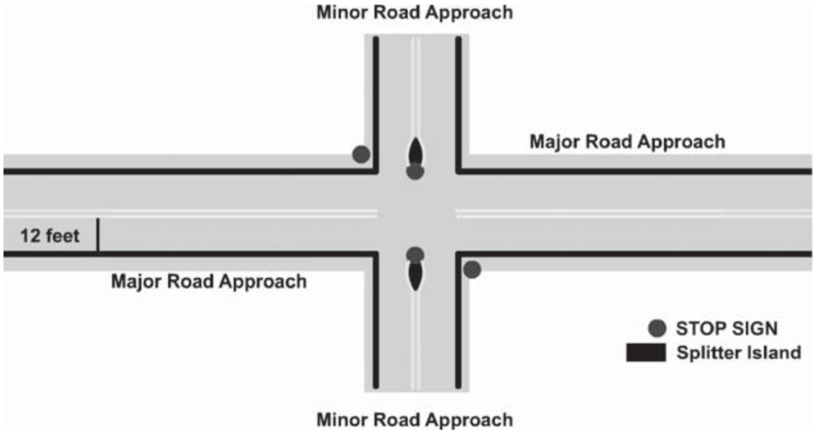
The treatment concepts were implemented in multiple locations in Pennsylvania, New Mexico, and Illinois. The results from this study showed statistically significant speed reduction at all sites. The combination of treatments reduced all vehicle speeds by an average of 3 mph, and reduced the 85th-percentile speeds by 4 mph. In addition, testing results for trucks revealed an average speed reduction of 5 mph and a reduction in the 85th-percentile speeds of 4 to 5 mph. (FHWA, 2006)

The team collected crash data for five years before deployment and will collect data for two years after deployment to determine whether these treatments yield quantifiable results. The team also plans to analyze crash data at the various sites at the project's end in June 2009 because



(Credit: FHWA, 2006)

(a) Reduced lane width, added rumble strips, and added pavement markings on major road



(Credit: FHWA, 2006)

(b) Installed mountable splitter island with stop signs on minor road approaches

Exhibit 3-4. FHWA low-cost treatment concepts.

several years of data are needed to determine the potential effects the treatments had on roadway safety. (FHWA, 2006)

3.5 Treatment Considerations

This section provides information to aid in screening treatments and to identify one or more treatments that may be most appropriate for a particular condition. Exhibits 3-5 and 3-6 provide a summary of the considerations for each treatment. Treatments for which specific testing has been conducted are shown in the shaded sections.

As described in the following sections, Exhibit 3-5 summarizes typical uses of the treatments, indicates how they may be applied at high-speed intersections, indicates whether research was found to document their effectiveness, provides order-of-magnitude cost relationships, and indicates the treatments' experimental status with respect to the *MUTCD*. Exhibit 3-6 provides the documented treatment applications, their effectiveness, and noteworthy considerations.

Section 4 provides supplemental information, diagrams, and photos for each treatment. The information provided in Section 4 represents the best available data based on the extensive literature review and field testing conducted under NCHRP Project 3-74.

Treatment	Documented Uses	Potential High-Speed Intersection Applications
Dynamic Warning Signs	Horizontal curves Work zones	Rural, unsignalized intersections Use caution in high driver-workload contexts
Transverse Pavement Markings	Traffic circle and stop-controlled intersection approaches Horizontal curves, bridges, freeway off-ramps Work zones	History of high-speed crashes
Transverse Rumble Strips	Approaches to intersections Approaches to toll plazas	Use caution in noise-sensitive contexts and with motorcycle traffic
Longitudinal Rumble Strips	Rural highways	Consider impacts to bicycle traffic
Wider Longitudinal Pavement Markings	Crash history involving curves, hills, roadway cross section Work zones	Run-off-road crashes Use caution as increased visibility may lead to increased speeds
Roundabouts	Rural highways Transition areas	Rural Highways Gateways Use caution with steep grades, unusual geometry, constrained right-of-way
Approach Curvature	Roundabout approaches	Stop- and yield-controlled approaches Use caution with run-off-road crash history, grades
Splitter Islands	Roundabout and stop-controlled approaches	Minor approaches of T-intersections and two-way, stop-controlled intersections
Speed Tables/ Plateau	Local and collector streets Plateaus installed on facilities with 35 to 50 mph speeds in New Zealand	Stop-controlled approaches
Reduced Lane Width	Work zones Low-speed urban and residential locations Rural two-lane highways	Uncontrolled approaches
Visible Shoulder Treatments	Rural two-lane highways	Wide shoulders Run-off-road crashes
Roadside Design Features (Including Gateways and Landscaping)	Transition areas Adjacent to roadway or intersection beyond clear zone and line of sight	Transition areas Consider sight distance at driveways

Note:
Shaded rows indicate treatments tested through NCHRP Project 3-74.

Exhibit 3-5. Treatment application summaries matrix.

Treatment	Function	Documented Speed Reduction	Documented Safety Improvement	Cost	Experimental Status
Dynamic Warning Signs	Encourage deceleration Reduce comfortable approach speed	Yes	Yes	$$	No
Transverse Pavement Markings	Improve intersection visibility Alert drivers to upcoming intersection	Yes	Yes	$	Yes
Transverse Rumble Strips	Encourage deceleration Reduce comfortable approach speed	Yes	No	$$	No
Longitudinal Rumble Strips	Reduce comfortable approach speed	No data	Yes*	$$	No
Wider Longitudinal Pavement Markings	Increase visibility and demark the intersection influence area	No data	No data	$	No
Roundabouts	Reduce speed through intersection Reduce conflicts	Yes	Yes	$$$	No
Approach Curvature	Reduce comfortable approach speed	Yes*	Yes	$$$	Yes
Splitter Islands	Improve intersection visibility Alert drivers to upcoming intersection	No data	Yes	$$	Yes
Speed Tables/Plateau	Encourage deceleration Reduce comfortable approach speed	Yes*	Yes*	$$	No
Reduced Lane Width	Reduce comfortable approach speed	Yes*	No	$$	No
Visible Shoulder Treatments	Alert drivers to upcoming intersection Improve intersection visibility	No data	Yes	$	No
Roadside Design Features (Including Gateways and Landscaping)	Reinforce transitioning roadway environment Improve intersection visibility Reduce comfortable approach speed	Yes*	Yes*	Varies	No

Notes:
Shaded rows indicate treatments tested through NCHRP Project 3-74.
* Indicates data for low-speed intersections and/or roadway segments only.

Exhibit 3-5. **(Continued).**

Treatment	Documented Applications		Documented Speed Effects
Dynamic Warning Signs	High-speed intersections	2 test sites (WA, TX) uncontrolled approaches	Mean speeds reduced up to 2.8 mph Initial reduction of 3 to 4 mph at two TX sites, one site had sustainable results
	Others	Rural interstate work zones (SD, VA) Freeway ramps (MD, VA) School zones (TX) Curve approaches	1.4 to 4 mph mean speed reduction in work zones Reduction in the number of speeding vehicles in work zones: 20–25% for cars, 40% for trucks
Transverse Pavement Markings	High-speed intersections	5 test sites (OR) Stop-controlled and uncontrolled approaches	Up to 0.9 mph mean speed reduction
	Others	Horizontal curves Roundabout approaches Work zones Highway off-ramps Bridges	20-30% speed reduction on segments Peripheral lines almost as effective as full transverse lines
Transverse Rumble Strips	High-speed intersections	3 test sites (TX) uncontrolled approaches	1.3 mph mean speed reduction at the perception-response time location
	Others	Some stop-controlled approaches Toll plazas, horizontal curves, and work zones	More gradual deceleration Increased speed variation Not successful in significantly reducing approach speeds
Longitudinal Rumble Strips	High-speed intersections	No data	No data
	Others	Shoulder or center of expressways, parkways, and rural highways	No data
Wider Longitudinal Pavement Markings	High-speed intersections	No data	No data
	Others	Work zones Vertical and horizontal curves Access-controlled highways Toll roads	No data
Roundabouts	High-speed intersections	Many applications on high-speed and low-speed facilities	Geometry yields 13 to 17 mph 85th-percentile entry speeds
	Others	Roundabout type and design vary based on facility speed, access, volumes, vehicle composition, and other factors	

Note:
Shaded rows indicate treatments tested through NCHRP Project 3-74.

Exhibit 3-6. Treatment effectiveness summaries.

Treatment	Documented Safety Effects	Key Considerations
Dynamic Warning Signs	No data Reduction in rollover crashes on freeway ramps	Power supply Urban vs. rural applications Target speed Coordinate with other treatments closer to intersection
Transverse Pavement Markings	No data 50-65% crash reduction at roundabouts and high crash locations	Driver familiarity Human factors considerations
Transverse Rumble Strips	No data Marginal safety benefits at best	Noise impacts to adjacent land uses May make bicycling difficult Vibrations can startle drivers and bicyclists, causing quick and unsafe maneuvers Maintenance
Longitudinal Rumble Strips	No data Reductions in injury, sideswipe, and opposite direction crashes 46% reduction in shoulder encroachment	Truck traffic, if narrowing lane width Vibrations can startle drivers and bicyclists, causing quick and unsafe maneuvers Maintenance
Wider Longitudinal Pavement Markings	No data No data	Improved visibility, especially with older drivers
Roundabouts	All roundabout conversions: approximate 35% reduction in total crashes and 77% reduction in injury crashes Rural two-way stop conversions: approximate 72% reduction in total crashes and 87% reduction in injury crashes	Operational performance Right-of-way needs Pedestrian and bicycle safety Gateway treatment

Note:
Shaded rows indicate treatments tested through NCHRP Project 3-74.

Exhibit 3-6. **(Continued).**

3.5.1 Typical Uses

Many of the treatments mentioned in Section 4 have not been documented as having been used at high-speed intersections; however, they may be effective for those applications. The typical uses listed for each treatment are provided to indicate applications for which the treatment is known to have been used. The documented effects are primarily based on these known applications. The lists of typical uses are helpful when considering driver expectations associated with a treatment.

3.5.2 High-Speed Intersection Applications

The high-speed intersection applications provided in Section 4 describe high-speed intersection conditions for which a treatment may be well suited. This section also describes conditions for which the treatment is not well suited. For example, dynamic warning signs may be appropriate on approaches to rural unsignalized intersections, but may not be appropriate in contexts where there is already a high driver workload or in a complex visual environment where the dynamic warning signs may prove ineffective.

3.5.3 Function

The function(s) of the treatments describe the role that each treatment plays in the intersection environment to produce lower speeds. The treatments should be screened to ensure that those selected have functions that are suited to the specific speed problem(s) identified in the intersection assessment. For example, if speed adaptation is identified as the root of a speeding problem, it is likely that a treatment that reinforces an impression of changes in the character of the roadway environment sufficiently in advance of the target speed location will be most successful in reducing speeds. Similarly, if driver attentiveness is identified as the likely root of the problem, appropriate treatments might be those that alert drivers to the upcoming intersection.

3.5.4 Documented Effects

There is limited documented research that identifies how much speed reduction (if any) may be expected from a given treatment. Most available documentation relates to segment speed reduction applications rather than intersection speed reduction. However, these data are included because it is logical to assume that, in many cases, similar effects may be achieved on high-speed intersection approaches. Data that specifically address speed reduction effectiveness on high-speed intersection approaches are available for the following treatments: dynamic warning signs, transverse pavement markings, roundabouts, approach curvature, and rumble strips. Because the extent of these data is quite limited, the speed reduction actually realized will likely vary with each application. The information available related to each specific treatment's effectiveness is provided as part of the detailed treatment descriptions.

3.5.5 Cost

Cost is often a factor that limits treatment implementation. In general, treatments that do not involve changes to the paved roadway section have the lowest costs, while treatments that modify or reconstruct the roadway section are the most costly. Secondary costs such as establishing a power source in a rural location could also increase implementation costs.

3.5.6 Experimental Status

Identifying whether a treatment would be considered experimental—whether or not it is included in the *MUTCD*—helps the user determine if additional authorization may be needed before an experimental treatment can be installed.

3.5.7 Documented Applications, Speed Effects, and Safety Effects

The columns for documented applications, speed effects, and safety effects in Exhibit 3-6 describe the tested applications for which the listed documented speed and safety effects were achieved. This information should be considered to determine the extent of research and data on a particular treatment and to identify similarities and differences in the tested applications that may produce similar or dissimilar effectiveness in a candidate site under consideration.

3.5.8 Key Considerations

Many treatments are likely to have significant impacts on multimodal users, site-specific maintenance considerations, and/or other issues that should be considered as part of the screening process. These secondary impacts may be limiting factors depending on the context for installation. For example, maintenance concerns related to snow removal will be significant in some environments and insignificant in others. Conditions in which particular treatments are not advised also are key considerations.

3.6 Treatment Evaluation

Monitoring and evaluating the effectiveness of treatments can provide valuable data and feedback for determining appropriate treatments for future applications.

3.6.1 Speed Monitoring

Speed monitoring is the most direct way to evaluate the effectiveness of a speed reduction treatment. To evaluate speed effects, before-and-after data should be collected and compared. Driver acclimation effects can be expected with many of the treatments; therefore, the after-data collection should be targeted to identify both short- and long-term effectiveness. Speed monitoring can also be used to evaluate how effective treatments are under particular weather or lighting conditions.

Data collection efforts should consider the driver behavior desired on the intersection approach, and should target data collection to determine to what extent the desired behavior has been achieved. In most cases, speed reduction is desired not only at the intersection proper, but on the approach as well. Collecting speed data at several points on an intersection approach will give the best picture of drivers' deceleration curves (a speed profile) as they respond to the treatment(s) approaching the intersection. Appendix B identifies the speed data collection points for several case studies. Additional information about speed testing programs can be found in the testing results section of *NCHRP Web-Only Document 124*.

3.6.2 Safety Monitoring

As stated repeatedly in these *Guidelines*, there are no data to support the use of speed as a surrogate for safety or vice versa. An improved safety record based on implementing one or more of these treatments does not necessarily indicate that speeds were reduced. Nevertheless, safety is a critical concern for transportation professionals, and monitoring the safety effects of these treatments may be desirable.

Safety effects must be monitored and analyzed over a period of several years before any significant conclusions can be drawn. Crashes are infrequent events and extensive data are needed to evaluate improvements in safety performance.

3.6.3 Driver Perception, Satisfaction Surveys

Surveying drivers about their perception of the treatment may provide insights into the effectiveness of a treatment. If drivers indicate that they were aware of the treatment, that the treatment increased their awareness of the intersection, or that it influenced them to slow down, these results may indicate that a treatment is effective.

It is not advisable to implement treatments based on neighborhood or political complaints if these complaints are not supported by an engineering analysis that indicates a speeding problem. However, the observations and perceptions of local residents and businesses can provide insight into the effectiveness of a treatment.

3.7 Summary

Various treatments have the potential to reduce speeds at high-speed intersections. These include specific intersection treatments as well as design elements typically considered for roadway segments.

Each intersection must be assessed to understand its unique characteristics and how it may be affected by speed. With this understanding, the user can consider which treatments are most likely to reduce speeds. The effectiveness of a particular treatment will vary considerably depending on the conditions of the specific application.

The potential treatments have a wide range of applicability, cost, secondary impacts, implementation considerations, and potential effectiveness in reducing speeds and increasing safety. To quantify the safety effects of speed reduction treatments at high-speed intersections, conditions will need to be monitored for a number of years after the treatment is implemented.

The next section provides more detail on each treatment type, including a discussion of treatment applications, considerations, and possible effectiveness.

SECTION 4

Treatment Descriptions

4.1 Overview

This section provides a summary of the findings reported in published literature on potential speed reduction treatments. Some of the reported treatments originate from applications for roadway segments; others are specific intersection applications. Once the intersection characteristics described previously in Section 3 have been assessed, the user can apply this information to help determine which treatment(s) may be appropriate at a specific location. This section contains an overview of each treatment, as well as more detailed descriptions, summaries of applicability and pertinent considerations such as maintenance, discussions of potential layouts and designs, and summaries of the documented effectiveness of each treatment in reducing speeds and improving safety. The treatments discussed are

- Dynamic warning signs,
- Transverse pavement markings,
- Transverse rumble strips,
- Longitudinal rumble strips,
- Wider longitudinal pavement markings,
- Roundabouts,
- Approach curvature,
- Splitter islands,
- Speed tables and plateaus,
- Reduced lane width,
- Visible shoulder treatments, and
- Roadside design features.

In some cases, more than one treatment may be appropriate for a given intersection.

To apply a treatment, users select a target speed and determine the location upstream of the intersection where sufficient distance is provided for drivers to react to potential conflicts related to the intersection when traveling at the target speed. A transition area is needed upstream of this target speed location to allow drivers to decelerate from their segment speed. The transition length and target speed location help determine an appropriate treatment layout.

The information provided in this section should be considered in tandem with appropriate local engineering practices and professional judgment related to the site-specific situation.

4.2 Dynamic Warning Signs

4.2.1 Overview

Two NCHRP Project 3-74 test sites, one in Washington and one in Texas, provided documented applications for the high-speed intersection treatments discussed in this section. Dynamic warning signs can alert drivers to the need to reduce their speed and encourage earlier deceleration. These treatments can be applied in rural, non-signalized intersections in advance of abnormal roadway features. Design variations include speed activation, message, image, size, and location. Driver workload and power supply issues should be considered.

4.2.2 Applicability and Considerations

Dynamic warning signs are placed along the side of the roadway prior to a location that requires reduced speed. The signs are activated by vehicles that exceed a predetermined speed (typically in excess of the posted speed limit) or by potential vehicle conflicts at the intersection. This type of sign is not intended to enforce the speed limit; rather it is assumed that drivers will reduce their speeds once brought to their attention. (Maze et al., 2000) Although most commonly applied in work zones, these signs have potential to be applied at intersections. Dynamic warning signs have been used at curve approaches, in work zones, and in other locations that require reduced speeds.

Dynamic warning signs have also been used to warn drivers of conflicting cross-traffic at intersections. Called *collision countermeasure systems* (CCS) in this application, they are used to reduce side-impact crashes at rural non-signalized intersections. On low-volume rural highways with a history of high intersection crash rates, dynamic warning signs of this type are a cost-effective alternative to a conventional traffic signal. (Hanscom, 2001)

Dynamic warning sign systems typically combine a radar device or pavement loop detectors with a variable message sign. The system measures the speed of the approaching vehicle or detects a potential vehicle conflict. The system provides a message to drivers who are traveling at excessive speeds or whose movements are in potential conflict with another vehicle. Examples of the types of messages displayed on the variable message sign include *Slow Down*, *XX mph Curve Ahead*, *Your Speed XX mph* or *Traffic Ahead*. (Torbic et al., 2004; Hanscom, 2001) Some systems are designed to provide messages to only a certain type of vehicle, such as trucks. In these cases, the dynamic warning systems involve weigh-in-motion devices, loop detectors, and height detectors. (Torbic et al., 2004)

One of the challenges for implementing dynamic warning signs is to determine the maximum safe speed above which the sign will be activated. Vehicle loads, suspension, vehicle size, tires, and variable weather conditions can affect this speed. (Torbic et al., 2004) The maximum safe speeds selected by both Washington and Texas for the NCHRP Project 3-74 research test sites were higher than the posted speed limit.

Dynamic warning signs can vary in complexity; therefore, some systems can be installed in a very short period of time, while others may take years to implement. The radar and video equipment, loop detectors, and weigh-in-motion detectors can be expected to encounter the same maintenance issues as when placed at conventional signalized intersections or other locations.

When dynamic warning sign equipment and posts are placed outside of pedestrian and bicycle zones, they are not expected to impact multimodal users.

Exhibits 4-1, 4-2, and 4-3 show three different types of dynamic warning signs.

(Credit: WSDOT)

Exhibit 4-1. Dynamic warning sign.

4.2.3 Treatment Layout/Design

Dynamic warning signs are placed in a location that provides adequate advance warning time for drivers to reduce their speed appropriately. The placement of a dynamic warning sign should be determined from estimated perception–reaction time, deceleration, and the stopping sight distance in advance of the intersection. Sign placement will reflect the desired target speed location and the driver deceleration rates from the operating speed of the upstream segment.

Vertical and horizontal alignments must provide a clear sight line for the radar or video equipment. A power source is also necessary. (Torbic et al., 2004) Constraints such as steep slopes, bridges, and power supplies also should be considered to determine the appropriate location for the sign.

If a radar unit is included as part of the dynamic sign treatment, it must be placed to detect drivers' speeds in advance of the sign.

4.2.4 Speed Effects

At each NCHRP Project 3-74 test site in Washington and Texas, dynamic warning signs were tested at two approaches. Dynamic warning signs reduced speeds significantly at three of these four high-speed intersection approaches. Speed data were collected at three locations on each intersection approach. A mean speed reduction of 1.7 mph was observed at the sign locations

(Photo: TXDOT)

Exhibit 4-2. Dynamic curve-warning sign.

(Credit: PennDOT)

Exhibit 4-3. Dynamic warning sign used as a collision avoidance system.

after a three-month acclimation period. At the perception–reaction data collection locations, mean speeds were reduced by 2.3 mph. At the accident avoidance data collection locations, mean speeds were reduced by 2.8 mph.

During a study of warning signs installed at two high-speed intersection sites in Texas, Ullman and Rose (2004) recorded an initial reduction of 3 to 4 mph at both sites, with one site sustaining the lowered speeds after the novelty effect of the sign diminished.

Studies examining the effectiveness of speed displays at rural interstate work zones in South Dakota and Virginia found that the speed monitoring displays reduced mean vehicle speeds by 1.4 to 4 mph within the work zones and reduced the number of vehicles speeding through the work zone by 20%-40%. Maze et al. (2000) concluded that sign placement can impact the effectiveness of this treatment.

A study of three dynamic curve warning systems installed on ramps in Virginia and Maryland showed that the three systems significantly influenced truck speeds—drivers reduced their speeds if they had exceeded the maximum safe speed. (Torbic et al., 2004)

In the field evaluation of the CCS installed in Prince William County, Virginia, it was observed that the CCS resulted in lower intersection approach speeds and longer projected times to collision. (Hanscom, 2001)

4.2.5 Safety Effects

No documentation of the safety benefits of dynamic warning systems at intersection approaches was found. However, the study of dynamic curve warning systems in Maryland and Virginia identified that prior to installation there had been 10 truck rollover crashes and after three years in operation, no rollover crashes had been reported.

4.3 Transverse Pavement Markings

4.3.1 Overview

Five NCHRP Project 3-74 test sites in Oregon provided documented applications for the high-speed intersection treatments discussed in this section. Transverse pavement markings improve visibility and driver attention. These treatments can be applied to provide visual cue reinforcements to changing conditions and the need to reduce speed. Design variations include peripheral or full transverse lines. Long-term effectiveness and driver familiarity should be considered.

4.3.2 Applicability and Considerations

As defined by the *MUTCD*, transverse pavement markings are "pavement markings that are generally placed perpendicular to and across the flow of traffic." (FHWA, 2003, p. 1A-14) Peripheral transverse lines, as shown in Exhibit 4-4, involve bars only at the edge of a travel lane, instead of bars extending across the travel lane. Transverse chevrons are painted geometric arrows that converge to give the illusion of speed. (Griffin and Reinhardt, 1995) Transverse pavement markings are commonly used in speed management to reinforce the need to reduce speed or to warn drivers of an approaching condition that may require vehicular maneuvers.

Common applications of transverse pavement marking locations include approaches to traffic circles and intersections, horizontal curves, construction areas, bridges, and freeway off-ramps. (Griffin and Reinhardt, 1995) Transverse pavement markings have also been placed at locations

Exhibit 4-4. Peripheral transverse pavement markings.

where excessive speed was a contributor to crashes and other speed reduction treatments had not been effective. (Agent, 1980)

Peripheral transverse lines require less maintenance than transverse lines that extend across the travel lane because most drivers do not track over the markings. (Human Factors North, Inc., 2002) Transverse pavement markings have no known impact to multimodal users—it is not expected that multimodal users would be adversely affected by transverse pavement markings.

4.3.3 Treatment Layout/Design

Transverse pavement markings should be placed in a location that provides adequate advance warning time for drivers to reduce their speeds appropriately. The placement of transverse pavement markings that is optimal to reduce speeds on intersection approaches has not been quantified. The "Green Book" (AASHTO, 2004) values for deceleration may provide a starting point in locating transverse pavement markings.

Transverse pavement lines may be installed in several small clusters on a high-speed intersection approach. The number of lines, their spacing, and the distance from the intersection proper should be determined through a combination of a review of field conditions, driver sight lines and desired response, and local practice and judgment.

As guidance, the *MUTCD* suggests, ". . . because of the low approach angle at which pavement markings are viewed, transverse lines should be proportioned to provide visibility equal to that of longitudinal lines." (FHWA, 2003, p.1A-14) The appropriate location and length of the lines depends on the speed at which the driver is traveling, the deceleration rate, and the driver's perception–reaction time. (Agent, 1980)

Appropriate installation points may be selected to reinforce other new or existing treatments or features on the intersection approach such as warning signs, shoulder markings, parking space markings, and pavement legends (*SLOW DOWN*, *REDUCE SPEED*, etc.), and at the intersection proper (such as lane-use legends, stop lines, crosswalk lines, and others). The transverse pavement markings have the potential to draw additional attention to those signs and markings and to encourage drivers to reduce their speeds as they approach the intersection. Other appropriate locations for treatment installation may include the stopping sight distance for the approach speed, or a point where the roadway environment changes, such as at the point of tangency or at a driveway. Appendix B describes and illustrates the treatment layout for one of the NCHRP Project 3-74 research test sites.

The spacing of the transverse bars and transverse chevrons may reflect the desired travel speeds of the vehicles on the roadway. Some applications of transverse bars have used a rate of advancement of two stripes per second. In some applications transverse bars are spaced progressively closer together at an increasing rate as the driver travels along the roadway. When applied in this way, the bars are referred to as *optical speed bars*. The intent is that the reduced spacing gives the driver the perception of acceleration, causing the driver to slow down; however, there are no data to support this claim. (Agent, 1980)

4.3.4 Speed Effects

After a 90-day acclimation period, transverse pavement markings were found to reduce speed marginally at four high-speed intersection approaches tested through NCHRP Project 3-74. Overall, the markings reduced mean speeds by 0.6 mph (standard error of 0.3 mph). Additionally, at the perception–response time data collection locations, transverse pavement markings were found to reduce mean speeds by 0.9 mph (standard error of 0.4 mph).

Studies of segment applications of transverse pavement markings have reported reduced mean and 85th-percentile speeds on the order of 20%-30%. (Katz et al., 2003; Griffin and Reinhardt, 1995)

At the Newbridge Roundabout in Scotland, transverse pavement markings resulted in reduced mean and 85th-percentile speeds. The overall mean speed throughout the day was reduced by approximately 23%, and the overall 85th-percentile speed throughout the day was reduced by approximately 30%. (Katz et al., 2003)

In a study conducted on US Highway 60 in Meade County, Kentucky, transverse bar pavement markings were placed prior to a sharp curve with a high crash rate. This study revealed that the treatment became less effective as a speed reduction technique as drivers became familiar with the treatment. Furthermore, the long-term effects during the nighttime were less than the long-term effects during the day. (Agent, 1980)

Research by Godley et al. (2000) using a driving simulator found that transverse lines with both constant and reducing spacing (i.e., optical speed bars) lowered speeds. The research determined that speed perception was not influenced by the decreased spacing of the lines. Additionally, Godley found that the peripheral transverse lines induced speed reduction almost as effectively as full transverse lines.

No studies have been found that evaluate the effectiveness of the transverse chevron markings with respect to speed.

4.3.5 Safety Effects

No published data were found to address the effects of transverse pavement markings on safety at conventional intersections. Safety improvements associated with segment or roundabout applications of transverse pavement markings were reported by each of the studies referenced below.

In 1993, a study in Osaka, Japan, reported that converging chevron pavement markings on the Yodogawa Bridge were more effective than conventional signing in helping to prevent crashes at a high-crash location. No crashes resulting in injuries occurred in the two years after the chevron markings were installed. In the past, the bridge had a history of crashes causing injuries and fatalities. (Griffin and Reinhardt, 1995)

At the Newbridge Roundabout in Scotland, transverse pavement markings reduced the number of reported crashes from 14 in the year prior to installation to 2 in the 16 months after installation. (Katz et al., 2003)

A study conducted on US Highway 60 in Meade County, Kentucky, found crashes were reduced after transverse pavement markings were installed. During the previous six years, an average of eight crashes occurred at this location each year, and speed was identified as a contributing factor in 75% of those crashes. During the year after installation, three crashes were reported, with one attributed to high speed. (Agent, 1980) Data for additional years after treatment installation were not included in the study.

In another study, transverse lines were applied at 42 approaches to roundabouts. Each approach had a minimum of 3.2 km (2 mi) of uninterrupted road to allow drivers to adapt to the high-speed environment. During the two-year period after the transverse lines were installed on the approaches, speeds were reduced by 57%. The before-and-after studies conducted at all 42 approaches also indicated that the number of crashes decreased from 96 to 47. A follow-up study conducted at seven of the sites four years after installation indicated that the treatment continued to be effective with speed-related crashes showing a significant decline. (Human Factors North, Inc., 2002)

4.4 Transverse Rumble Strips

4.4.1 Overview

Three NCHRP Project 3-74 test sites in Texas provided documented applications for the high-speed intersection treatments discussed in this section. Rumble strips provide audible and tactile warning to encourage deceleration and reduce comfortable speed. These treatments can be applied to stop-controlled approaches, toll plazas, horizontal curves, and work zones. Design variations include paved, rolled, or milled; raised or depressed; painted or unpainted; and cluster spacing. Noise, as well as adverse effects for motorcycles and bicycles, should be considered.

4.4.2 Applicability and Considerations

Rumble strips are raised or grooved patterns installed on the roadway travel lane or shoulder pavements. The texture of rumble strips is different from pavement and produces both an audible warning and physical vibration when vehicle tires pass over them. (FHWA R&T, 2007) Rumble strips can be installed to warn drivers of an upcoming need to act, such as the need to stop at a traffic signal, slow down at an intersection, change lanes in a work zone, or steer back into the travelway. Their purpose is to provide motorists with an audible and tactile warning that their vehicles are approaching a decision point of critical importance to safety.

Although rumble strips warn drivers that some action may be necessary, they do not identify what action is appropriate. The driver must use visual cues to decide what type of action is appropriate. Thus, rumble strips serve only to supplement, or call attention to, information that reaches the driver visually. In many cases, the objective of a transverse rumble strip is to call attention to a specific traffic control device, such as a *Stop Ahead* sign.

Transverse rumble strips are placed perpendicular to the direction of travel, and are designed to reduce the deceleration rate and the potential for sudden braking, skidding, and loss of control.

The most common use of rumble strips is on intersection approaches controlled by a stop sign, but they have also been used on approaches to signalized intersections, especially for isolated signals on high-speed roadways where drivers may not expect the presence of a signal. Transverse rumble strips are generally installed on approaches to intersections of expressways, rural highways, and parkways. Transverse rumble strips have also been placed prior to toll plazas, horizontal curves, and work zones. (FHWA R&T, 2007)

The noise impacts of transverse rumble strips may make them a poor choice for locations where pedestrians or others will spend time adjacent to the treatment. Transverse rumble strips have the potential to adversely affect bicycles and motorcycles due to the vibrations generated, startle drivers as they cross over the rumble strips, and cause drivers to maneuver quickly to avoid the in-lane rumble strips.

Rumble strip design, as shown in Exhibits 4-5, 4-6, and 4-7, varies by state and depends on the type of facility to which the treatment is being applied.

4.4.3 Treatment Layout/Design

Rumble strips should be placed so that either the upcoming decision point, or a sign that identifies the action that may be required, is clearly visible as the driver passes over the rumble strip.

(Credit: TTI, 2006)

Exhibit 4-5. Transverse rumble strips in wheel path.

Exhibit 4-6. Transverse rumble strips.

(Credit: Corkle et al., 2001)

Exhibit 4-7. Transverse rumble strips across the entire travel lane.

Rumble strip locations should be selected to provide adequate advance warning time for drivers to take the potentially required action. Values for deceleration in the "Green Book" (AASHTO, 2004) provide a starting point for locating the strips.

Transverse rumble strips can be installed to cover either the entire width of the travel lane, as shown previously in Exhibit 4-7, or just the width of a vehicle's wheel path, as shown previously in Exhibit 4-5, enabling drivers familiar with the area to straddle the rumble strips to avoid driving over them. (Corkle et al., 2001)

Transverse rumble strips may be installed in several small clusters on a high-speed intersection approach. The number of strips, their spacing, and the distance from the intersection proper should be determined through a review of field conditions, driver sight lines and desired response, and local practice and judgment.

Appropriate installation points may be selected to reinforce other new or existing treatments or features such as warning signs. The markings have potential to draw additional attention to those warning signs and to encourage drivers to reduce their speeds as they approach the intersection. Other appropriate locations for installation may include the stopping sight distance for the approach speed, or at a point where the roadway segment environment changes, such as at a point of tangency or at a driveway in advance of the intersection.

To accommodate bicycles on roadways with rumble strips, agencies should provide a smooth, clear, paved surface wide enough for a bicycle to travel comfortably to the right of the rumble strips. Some agencies have begun to redesign rumble strips to make them safer for bicycles. A skip pattern enhances rumble strip safety for bicycles, providing cyclists the opportunity to enter and exit the bike path without having to cross over the rumble strips. (Walls, 1999)

There are a variety of rumble strips that vary in their installation methods, shape, size, and amount of noise and vibration produced. (FHWA Safety, 2007) Rolled rumble strips must be installed when constructed or reconstructed shoulder surfaces are compacted. Formed rumble strips are appropriate for Portland cement concrete shoulders and involve grooves or indentations formed into the concrete surface during the finishing process. (Elefteriadou et al., 2001) Raised rumble strips are strips of material that adhere to new or existing surfaces. Raised and surface-mounted rumble strips can easily be removed by snowplows, causing the need for replacement. Thus, the use of raised rumble strips is usually restricted to warmer climates. (Morgan and McAuliffe, 1997) Some agencies paint over rumble strips to make them more visible. (FHWA

R&T, 2007) Milled continuous shoulder rumble strips are easy to install on existing and new pavement, maintain the integrity of the pavement structure, and produce more noise and vibration than other types of rumble strips. (FHWA Safety, 2007)

4.4.4 Speed Effects

At the high-speed intersection approaches tested through NCHRP Project 3-74, rumble strips produced statistically significant speed reductions at the perception–response time data collection location, where a mean speed reduction of 1.3 mph (standard error of 0.5 mph) was observed. At each site, this data collection point was beyond the rumble strips, and about 250 ft upstream of the intersection. Overall, no statistically significant speed reduction was observed at the data collection point where the rumble strips were installed or at the accident avoidance data collection point (roughly 100 ft upstream of the intersections).

Transverse rumble strips have been used with mixed results. On stop-controlled approaches, transverse rumble strips have repeatedly resulted in more gradual deceleration by drivers and increased the percentage of drivers making a full stop at the stop sign by about 30%. (Kermit and Hein, 1962; Owens, 1967; Zaidel et al., 1986; Harder et al., 2001) However, they have also increased speed variance. (Morgan and McAuliffe, 1997) The research conducted by Owens found an increase in speed variance on the intersection approach, indicating that some drivers slowed down more than others.

University of Minnesota research involving a driving simulator concluded that drivers started to slow down and finish braking at the same time with and without rumble strips, but braking occurred earlier with rumble strips. It was also found that drivers brake more and brake earlier with full-width rumble strips than with wheel-track rumble strips. (Harder et al., 2001)

Miles et al. (2005) found that transverse rumble strips produced mostly small changes in traffic operations at both horizontal curve and stop-controlled intersection sites. This research concluded that the treatment was not successful in significantly reducing approach speeds to an intersection.

4.4.5 Safety Effects

NCHRP Synthesis 191 (Harwood, 1993) summarized 10 before-and-after studies that investigated the safety effectiveness of transverse rumble strips. The synthesis concluded that transverse rumble strips may effectively reduce crashes, although more rigorous evaluation is needed to better understand the safety effects. (Harwood, 1993) However, a 2006 Texas Transportation Institute (TTI) study found that transverse rumble strips produced marginal safety benefits at best, only slightly reducing erratic lane movements. The study did note a 46% reduction in shoulder encroachments. (Miles et al., 2005)

4.5 Longitudinal Rumble Strips

4.5.1 Overview

No test sites provided documented applications for the high-speed intersection treatments discussed in this section. Longitudinal rumble strips provide audible and tactile warning to reduce comfortable speed and to minimize off-the-road or crossover crashes. These treatments can be applied to rural, undivided highways. Design variations are paved, rolled, or milled; raised or depressed; painted or unpainted; and cluster spacing. Noise, as well as adverse effects for motorcycles and bicycles, should be considered.

4.5.2 Applicability and Considerations

Like transverse rumble strips, longitudinal rumble strips are raised or grooved patterns installed on the roadway travel lane or shoulder pavements to warn drivers of an upcoming need to act. Longitudinal rumble strips are placed parallel to the direction of travel and may be located in the centerline or along the shoulder. Refer to Section 4.4 for more information on rumble strips.

Longitudinal rumble strips are most commonly used to reduce head-on, sideswipe, and run-off-road crashes along roadway segments. The treatment may be a useful speed management treatment for high-speed intersections that exhibit these crash patterns. Bicycle and motorcycle impacts should be considered as the treatment for intersection applications is designed.

Continuous shoulder rumble strips are the most common type of longitudinal rumble strip. These are placed on the roadway shoulder to help prevent drivers from running off the road and are generally used along expressways, interstates, parkways, or two-lane rural roadways. (FHWA Safety, 2007) Continuous shoulder rumble strips are typically installed with breaks or gaps only at exits and entrances to ramps and at street intersections or major driveways. This allows drivers and bicyclists to maneuver near the intersections and driveways without having to cross over the rumble strips.

Centerline rumble strips are placed on either side of the centerline (see Exhibit 4-8), located either along the width of the centerline pavement markings (see Exhibit 4-9), or extend slightly into the travel lane (see Exhibit 4-10). Centerline rumble strips are generally installed to reduce head-on and sideswipe crashes along undivided roadways. Their primary function is to use tactile and auditory stimulation to alert inattentive or drowsy drivers that their vehicles are encroaching on the opposing lane. Centerline rumble strips may also discourage drivers from cutting across the inside of horizontal curves.

(Credit: MnDOT, 2004)

Exhibit 4-8. Centerline rumble strips.

(Credit: Torbic et al., 2004)

Exhibit 4-9. Centerline rumble strips on the centerline pavement markings.

(Credit: Torbic et al., 2004)

Exhibit 4-10. Centerline rumble strips extending into the travel lane.

4.5.3 Treatment Layout/Design

The placement and dimensions of longitudinal rumble strips on high-speed intersection approaches should be determined through a combined review of field conditions, driver sight lines and desired response, and local practice and judgment.

The distance that the treatment extends from the intersection proper should be related to stopping sight distance and/or the distance required to achieve the desired deceleration at a comfortable deceleration rate. The distance should also be selected to work in concert with other treatments or features, such as warning signs. The markings have the potential to draw additional attention to those warning signs and to encourage drivers to reduce their speeds as they approach the intersection.

The dimensions of the rumble strips will vary by application. If the treatment is being used to narrow the functional width of the approach lane, the treatment should extend beyond the existing striping. Consideration of truck traffic is likely to constrain the amount of narrowing that may occur.

Treatment design considerations related to the types of rumble strips (raised, milled, etc.) were discussed previously in Section 4.4.3.

4.5.4 Speed Effects

No documentation was found regarding the speed effects of longitudinal rumble strip applications in segment or intersection locations. However, it is expected that longitudinal rumble strips have the greatest potential to reduce speeds when they are used to narrow the functional width of the roadway. FHWA is conducting research into these applications. However, this study applied multiple treatment types at a given location and, therefore, the direct effects of the rumble strips are not documented.

At non-intersection locations on two-lane highways, one study found that the presence of centerline rumble strips had no effect for sites with 11- and 12-ft lanes. (Porter et al., 2004)

4.5.5 Safety Effects

Safety improvements have been documented at locations where continuous or shoulder rumble strips were installed along roadway segments However, there has been no documentation to show the results of this specific application at intersection approaches.

Shoulder rumble strips have proved to be a very inexpensive and effective treatment to reduce run-off-road crashes. Reports from Maine, New York, and California have reported run-off-road crash reductions of 20%-72% after continuous shoulder rumble strips were installed. (Corkle et al., 2001)

Similarly, centerline rumble strips have been shown to improve safety along undivided highways. A study analyzing the safety effectiveness of centerline rumble strips along approximately 210 miles of treated roads in seven states found a 14% reduction for all injury crashes combined, as well as a 25% reduction for frontal and opposing-direction sideswipe injury crashes. (Persaud et al., 2004)

4.6 Wider Longitudinal Pavement Markings

4.6.1 Overview

No test sites provided documented applications for the high-speed intersection treatments discussed in this section. Wider longitudinal pavement markings increase intersection visibility and attract driver attention to the intersection ahead. These treatments can be applied to address the needs of older drivers and a lack of driver expectancy. Design variations include marking width, length, and reflectivity. A secondary effect of these treatments is that speed may increase with increased visibility.

4.6.2 Applicability and Considerations

Many transportation departments increase the width of pavement markings to improve the visibility of centerline, lane line, and edge-line striping, which can provide added guidance to drivers from greater distances. (Gates and Hawkins, 2002) Although no documentation for wider longitudinal pavement marking applications at intersection approaches was found, this treatment may be an effective speed reduction treatment for some high-speed intersections because it may increase driver awareness of the presence of an intersection and help reinforce the need for drivers to operate differently at the intersection than in the roadway segment.

The most common reasons that jurisdictions apply wider longitudinal pavement markings are to improve visibility, assist older drivers, and reduce crashes. Many transportation departments have policies to apply wider longitudinal pavement markings to routes of a certain roadway classification—most commonly access-controlled highways. Some jurisdictions have policies that require using wider edge lines on all state routes while others install this treatment exclusively at hazardous locations that could benefit from greater driver visibility. (Gates and Hawkins, 2002)

Wider longitudinal pavement markings (see Exhibit 4-11) assist peripheral vision by improving the peripheral signal, thus decreasing driver workload and increasing driver comfort and performance. The largest visibility benefit is seen with older drivers, because visual and cognitive capabilities decline with age. (Gates and Hawkins, 2002)

The higher cost of wider longitudinal pavement markings may be somewhat offset by greater durability.

Pavement lighting systems are an alternative to wider longitudinal pavement markings that serve the same function, and may have similar effects. This treatment does require a power source that may require maintenance or replacement over time.

4.6.3 Treatment Layout/Design

The placement and dimensions of wider longitudinal pavement markings on high-speed intersection approaches should be determined through a review of field conditions, driver sight lines and desired response, and local practice and judgment.

Exhibit 4-11. Wider longitudinal pavement markings in France.

The distance that the treatment extends from the intersection proper should be related to stopping sight distance and/or distance to achieve the desired deceleration at a comfortable deceleration rate. The distance should also be selected to work in concert with other treatments or features such as in-pavement markings at pedestrian crosswalks, lane drops or adds, or warning signs. The markings have potential to draw additional attention to those warning signs and to encourage drivers to reduce their speeds as they approach the intersection.

The standard width for longitudinal pavement markings is four inches. Wider pavement markings generally range from 5 to 10 inches wide.

4.6.4 Speed Effects

No specific information was found to describe the impacts of wider longitudinal pavement markings on speed at intersection approaches or roadway segments. The increased visibility and comfort associated with wider pavement markings could lead to increased speed in some applications. Although this treatment may not directly affect reduced speeds, it may increase driver awareness of an impending intersection, thereby indirectly reducing speeds if drivers perceive a greater risk.

FHWA is conducting demonstration projects in Alaska and Tennessee to evaluate the impacts and effectiveness of increasing the width of pavement marking edge lines from four inches to six inches; a report is due in June of 2009.

4.6.5 Safety Effects

There is no conclusive data associated with the crash-reduction effects of wider longitudinal pavement markings.

Cottrell (1988) conducted a before-and-after evaluation of wider pavement edge lines on rural two-lane highways in Virginia and found no evidence to indicate any safety benefit.

Conclusive evidence suggests wider longitudinal pavement markings are easier for drivers to see, which can contribute to roadway safety. (Gates et al., 2002) The greatest improvement in visibility is achieved at night.

4.7 Roundabouts

4.7.1 Overview

The high-speed intersection treatments discussed in this section are widely used throughout the United States, United Kingdom, France, and Australia. Roundabouts use intersection geometry to reduce speeds and conflict points. These treatments can be applied to a variety of applications. Design variations include roundabout type, size, number of lanes, and geometry. Secondary effects and considerations should include operations, right-of-way, access, horizontal and vertical geometry, and driver expectancy.

4.7.2 Applicability and Considerations

A roundabout is a type of circular intersection with specific design and traffic control features to ensure that travel speeds on the circulatory roadway are typically less than 30 mph (50 km/h). These features include channelized approaches and geometric curvature. (FHWA, 2000b) The following qualities distinguish a roundabout from other circular intersections:

- Yield control is provided on all entries,
- Right-of-way is given to circulating vehicles,
- Pedestrians can cross only the roundabout approaches (behind the yield line),
- Parking is not allowed within the circulatory roadway or at the entries, and
- Vehicles circulate in a counter-clockwise direction.

Roundabouts have been designed to improve some of the safety and operational deficiencies that occur in other types of circular intersections, such as traffic circles and rotaries. The specific design features of a roundabout can reduce speeds and the number and severity of collisions.

Roundabouts are appropriate for locations with a high crash frequency or severity, intersections where queues need to be minimized, intersections with irregular geometry, intersections that need to accommodate U-turns, and areas with a large amount of right-of-way available.

Pedestrians are accommodated at a roundabout by crossings through splitter islands located around the perimeter of the roundabout. Roundabouts potentially are difficult for visually impaired pedestrians to navigate. NCHRP Project 3-78, *Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities*, provides additional information on the impacts roundabouts have on visually impaired pedestrians.

At single-lane roundabouts (see Exhibit 4-12), bicyclists have the option to mix with traffic or use the pedestrian crossings. At multilane roundabouts, bicycle paths should be separate and designated from the circulatory roadway, for example, by providing a shared bicycle-pedestrian path.

Landscaping placed on the center island of a roundabout may need to be maintained to keep the intersection aesthetically pleasing and to manage intersection sight distance. A maintenance program should be developed for the landscape design of a roundabout. (FHWA, 2000b)

4.7.3 Treatment Layout/Design

Roundabouts can be adapted to a variety of user and vehicle types based on the environment, number of lanes, and space used by the intersection. Identifying the proper dimensions of the

(Credit: Oregon DOT)

Exhibit 4-12. Single-lane roundabout.

key design features—including an appropriate design vehicle—is critical to ensure proper operations and safety for all users at roundabouts (FHWA, 2000b).

To distinguish roundabouts from other types of circular intersections, key design features such as a central island, splitter islands, circulatory roadway, yield lines, pedestrian crossings and, in some cases, an apron, have been defined and are shown in Exhibit 4-13.

A mountable apron may be designed around the perimeter of the central island to provide additional width required for tracking through a single-lane roundabout. Large vehicles may use the entire circulatory roadway at double-lane roundabouts to track and maneuver. (FHWA, 2000b)

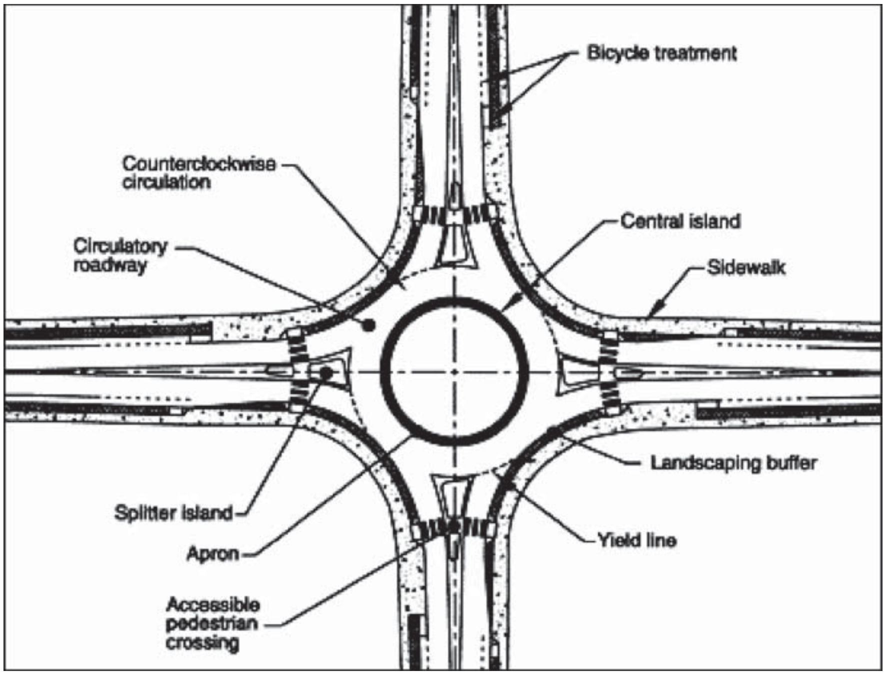
Single-lane, four-leg roundabouts have a typical daily service volume of approximately 20,000 entering vehicles per day. Two-lane, four-leg roundabouts have a typical daily service volume of approximately 40,000 entering vehicles per day. (FHWA, 2000b)

4.7.4 Speed Effects

Roundabouts have the potential to lower speeds to allow drivers more time to react to potential conflicts. Traffic measured at 43 locations revealed that the geometry yields 85th-percentile entry speeds between 13 and 17 mph. (Rodegerdts et al., 2007)

4.7.5 Safety Effects

One of the most significant benefits of roundabout installation is the overall improvement to intersection safety. Crash reduction research for conversions of all types of intersections to roundabouts (55 sites studied) found a 35% reduction in all crashes and 76% reduction in injury crashes. Specifically for rural two-way stop-controlled intersections that have been converted to roundabouts (10 sites studied), research found a 72% reduction in all crashes and an 87%



(Credit: FHWA, 2000b)

Exhibit 4-13 . Key roundabout design features.

reduction in injury crashes. (Rodegerdts et al., 2007) The crash reduction is achieved because there are fewer conflict points at roundabouts than at conventional intersections and because speeds are reduced. (FHWA, 2000b)

Single-lane and multilane roundabouts have different operational characteristics that affect their relative safety benefits. Although the number of crashes and the severity of injuries were reduced at both single-lane and multilane roundabouts, a smaller reduction in total crashes was observed at the multilane roundabouts. Both single-lane and multilane roundabouts exhibit similar reductions in injury crashes. (Rodegerdts et al., 2007)

Roundabouts improve safety for bicyclists by slowing automobiles to speeds closer to bicycle speeds (thus reducing high-speed conflicts) and by simplifying turning movements for bicycles. (FHWA, 2000b) Crashes involving bicycles comprise approximately 1% of all reported crashes at roundabouts. (Rodegerdts et al., 2007)

Roundabouts also decrease the risk of severe pedestrian collisions, due to reduced vehicle speeds and a reduced number of conflict points for pedestrians. A Dutch study conducted at 181 roundabouts found a 73% reduction in all pedestrian crashes and an 89% reduction in injury crashes for pedestrians. (FHWA, 2000b) Crashes involving pedestrians comprise approximately 1% of all reported crashes at roundabouts. (Rodegerdts et al., 2007)

Bicycles do not experience the same safety benefit at roundabouts as vehicles and pedestrians. In some cases, roundabouts can be less safe for bicycles than conventional intersections, despite the speed reduction benefits. (FHWA, 2000b)

4.8 Approach Curvature

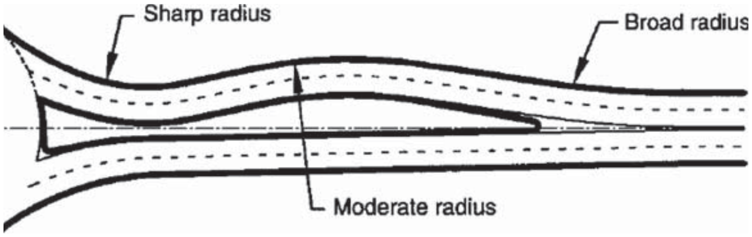
4.8.1 Overview

No test sites provided documented applications for the high-speed intersection treatments discussed in this section. The high-speed intersection treatments discussed in this section have been applied at roundabout approaches only. These treatment applications introduce horizontal curve geometry to induce lower speeds. Approach curvature can be applied to new roundabouts and may be especially effective on rural highways. Designs vary with curve geometry. Secondary effects and considerations should include right of way, grading, driver workload, and truck movements.

4.8.2 Applicability and Considerations

Approach curvature is a geometric design treatment that can be used at high-speed intersection approaches to force a reduction in vehicle speed though the introduction of horizontal deflection.

As shown in Exhibit 4-14, approach curvature consists of successive curves with progressively smaller radii. Research and applications of approach curvature have focused on



(Credit: FHWA, 2000b)

Exhibit 4-14. Approach curvature.

roundabouts. However, this geometric design treatment has potential to be applied to conventional intersections.

Appropriately designed curve radii and length of curve can reduce vehicle speeds at the entry of a roundabout or conventional intersection, as well as reduce certain types of crashes. If successive curves are installed in high-speed environments, introducing other speed reduction treatments prior to the approach curvature may reduce the speed changes needed between successive curves. (Arndt, 2000)

The use of approach curvature at downhill approaches is discouraged. Experience with approach curvature suggests that this geometric treatment should be used in conjunction with reduced speed limit signs or advisory speed signs.

Sight distance should also be considered at the intersection approaches to ensure appropriate visibility of pedestrians and bicycles crossing the intersection approach or traveling through the intersection. Excessive sight distance should be discouraged to focus driver attention to the immediate roadway.

Raised medians to reinforce speed reduction may become problematic for maintenance, especially in areas subject to snow plowing.

4.8.3 Treatment Layout/Design

The length and curve geometry should be determined from the upstream segment operating speed and the target speed at the intersection. Design control information from the "Green Book" (AASHTO, 2004), as well as published documentation from Australian applications at roundabouts (FHWA, 2000b), may provide design guidance. It may be appropriate to introduce the curved geometry concurrently with additional treatments such as warning signs.

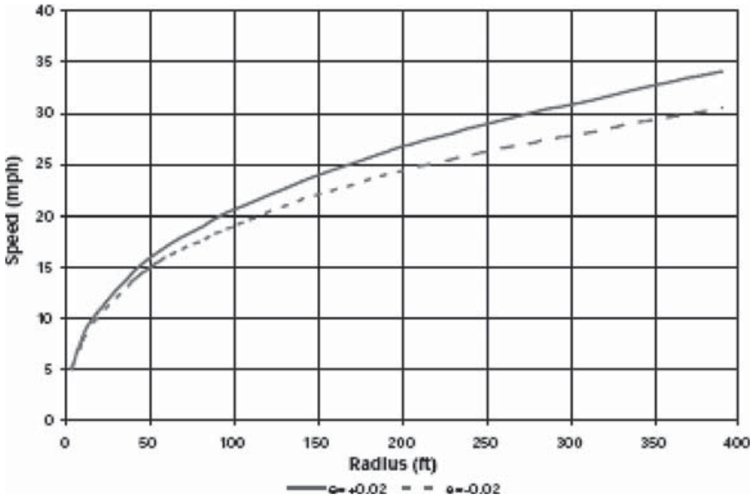
The dominant feature of approach curvature treatments is the radius of the curve. When designing successive curves, each curve must be visible before the next curve to allow drivers adequate time to adjust speeds. The length of the approach curvature affects speed reduction. Adequate curve length must be provided to discourage drivers from traveling into adjacent lanes; however, excessive curve lengths can result in an increase of single-vehicle crashes. (Arndt, 2000) Super-elevation and side friction also affect vehicles traveling through the curvature. To provide required super-elevation on each curve, short tangent sections can be designed between each successive curve.

Similar to roundabout design, approach curvature should be designed with an appropriate "design vehicle" to ensure that all trucks, buses, and emergency vehicles may traverse the approach without encroaching on the shoulder or adjacent sidewalks.

4.8.4 Speed Effects

Current information about approach curvature and how it impacts speed and safety relates exclusively to roundabouts. Although no published research or testing results have been found that describe the impacts on speed and safety at conventional intersection approaches, similar safety benefits might be realized by applying this treatment to conventional intersections.

The geometric design of roundabouts shows that the curve radius directly impacts vehicle speeds. As the radius of the curve decreases, a larger reduction in vehicle speed is required to negotiate the curve. Exhibit 4-15 shows the speed–radius relationship for curves with +0.02 and –0.02 super-elevations.



(Credit: FHWA, 2000b)

Exhibit 4-15. Speed–radius relationship.

4.8.5 Safety Effects

Although the majority of research and testing includes approach curvature at roundabouts, similar safety benefits might be realized by applying this type of geometric treatment to conventional intersections.

Approach curvature that includes successive curves reduces crashes at a roundabout and minimizes single-vehicle crashes. A Queensland, Australia, study found that reducing the change in 85th-percentile speed on successive curves to 12 mph reduced single-vehicle and sideswipe crashes. Although decreasing the curve radius on an approach can generally minimize rear-end crashes, it may also increase the potential for single-vehicle crashes. (FHWA, 2000b)

4.9 Splitter Islands

4.9.1 Overview

No test sites provided documented applications for the high-speed intersection treatments discussed in this section. However, the treatments in this section have been applied at roundabout intersection approaches and conventional intersection approaches in New Zealand and France. Splitter islands slow, direct, and separate conflicting traffic. These treatments can be applied to stop- or yield-controlled approaches. Design variations include length, geometry, and landscaping. Secondary effects and considerations should recognize that splitter islands can provide refuge for pedestrians crossing at the intersection.

4.9.2 Applicability and Considerations

A splitter island is a raised or painted area on an intersection approach used to separate entering and exiting traffic, to deflect and slow entering traffic, and to provide refuge for pedestrians crossing the road in two stages. (FHWA, 2000b) These islands can increase driver awareness by channeling the traffic on the minor approaches.

In some cases, these treatments are called throat or fishtail islands; these are shown in Exhibit 4-16. The geometry of fishtail islands introduces deflection at the approach, thereby reducing vehicle speeds at the intersection.

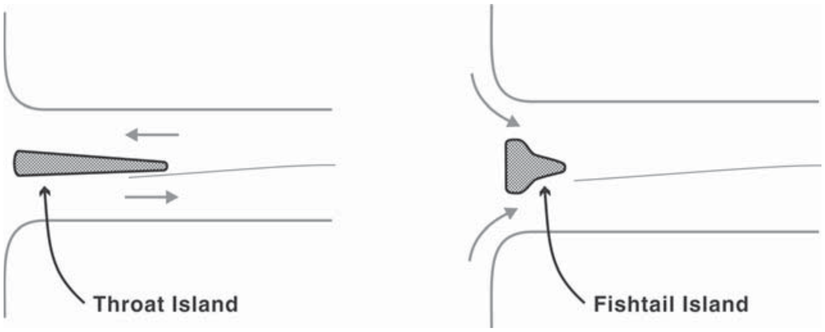


Exhibit 4-16. Throat and fishtail islands.

Although splitter islands have generally been used at roundabout approaches, this treatment has been applied to the minor approaches of T-intersections and two-way stop-controlled intersections in France and New Zealand. Exhibit 4-17 depicts a splitter island at a T-intersection in France.

Similar to a splitter island at a roundabout, splitter islands at conventional intersections can benefit pedestrians crossing at the intersections. The island shortens the crossing distance, creates a refuge area, and allows pedestrians to cross the approach in two stages, if necessary.

FHWA has sponsored a study to determine the effectiveness of combining splitter islands on minor approaches with other types of speed reduction treatments, such as centerline rumble strips or pavement markings, on major approaches at two-way stop-controlled intersections on rural highways.

4.9.3 Treatment Layout/Design

The length and geometry of splitter islands vary significantly. Splitter islands can either take the form of a cross-section change, including either visually or physically narrowing the travel way, or create horizontal deflection. In Exhibit 4-18, Splitter Island A creates a cross-section change without directly creating horizontal deflection. Splitter Island B conceptually creates horizontal deflection. Form A could present a visual cue to drivers to slow before the intersection. Form B could potentially reduce speed by creating a deflected path, similar to a roundabout through movement.

Exhibit 4-17. Splitter island at a T-intersection in France.

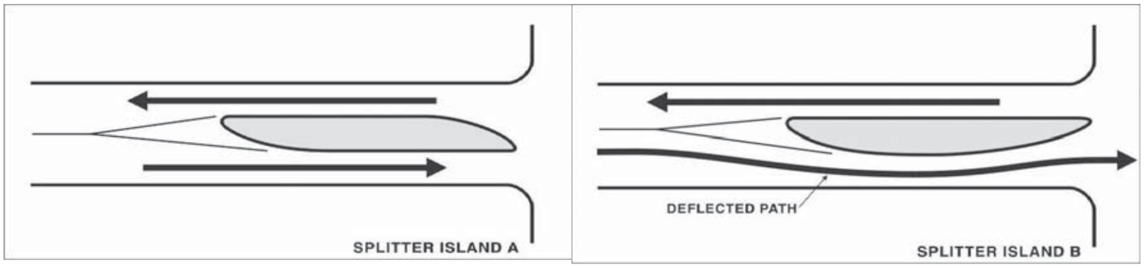


Exhibit 4-18. Splitter islands.

Exhibits 4-19 and 4-20 depict schematic layouts of signing and striping for teardrop splitter islands. The oval shape of the island aids in reducing vehicle approach speeds and increases intersection visibility.

This splitter island can be mountable to allow larger vehicles to maneuver through the intersection. U.K. standards recommend that no obstacles, such as signs or signals, be placed on the splitter island; that the color of the median be uniform (no striping) but different than the pavement color to offer increased day and night visibility; and that the splitter islands be constructed of a mineral treatment rather than turf or grassy compositions. (Ministry of Equipment, 1998) In U.S. applications, a sign is usually mounted on the splitter island to increase its visibility.

4.9.4 Speed Effects

Much of the information about splitter islands and how they impact safety and speed relates specifically to roundabouts. There is little published research or test results to describe the impacts of approach splitter islands on speed or safety at conventional intersection approaches.

Splitter islands create deflection at roundabouts, which reduces the speeds of vehicles traveling through the intersection.

4.9.5 Safety Effects

The limited literature that is available on splitter islands shows that there is a safety benefit to applying this treatment to conventional intersections. However, there is no information to indicate to what extent the safety effects of splitter islands are due to speed reduction and to what extent they are due to the separation between traffic moving in opposite directions.

A study of 134 intersections in New Zealand found that installing throat or fishtail islands resulted in crash reductions of 30%-60% for fatal, injury, and pedestrian crashes during both

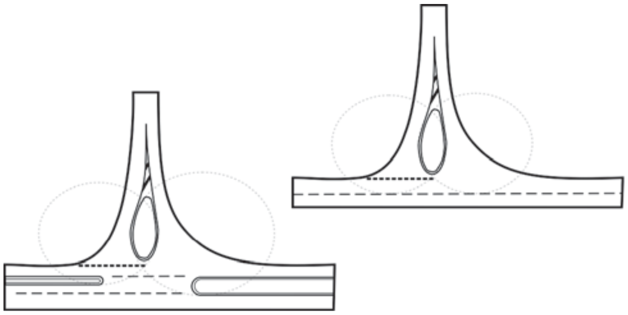


Exhibit 4-19. Example layout of a splitter island at a T-intersection.

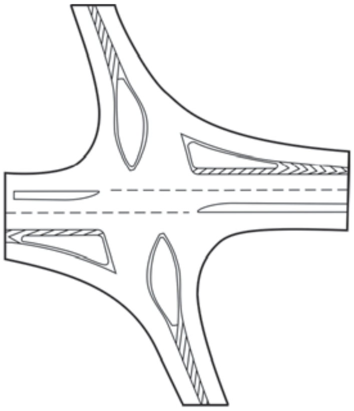


Exhibit 4-20. Example layout of a splitter island at a four-legged intersection.

day and night. The majority of the reduction in injury crashes involved vehicles crossing paths at the intersection. Most of the treated intersections were four-legged intersections in urban areas on local roads. (LTSA, 2001; FHWA, 2006)

Implementations in France and New Zealand resulted in a total crash reduction of 30% and a reduction of angle and crossing crashes by 30%. (FHWA, 2006)

Although no evidence was found to support this claim, it is possible that installing these types of islands at intersections could increase collisions with obstructions. (LTSA, 2001)

4.10 Speed Tables and Plateaus

4.10.1 Overview

No test sites provided documented applications for the high-speed intersection treatments discussed in this section. These applications create vertical deflection and alert drivers to the need to slow down. These treatments can be applied to stop-controlled approaches. Design variations include geometry and materials. Secondary effects and considerations should include snow removal and driver expectancy.

4.10.2 Applicability and Considerations

Speed tables are speed humps with a flat section on top, allowing the entire wheelbase of a passenger car to rest on the raised, flat section. The flat section of the speed table can be aesthetically treated (see Exhibits 4-21 and 4-22) with decorative surface material or constructed with brick or other textured materials. Speed tables have gently sloped ramps on both ends, which allow slightly higher vehicle speeds and a smoother transition than speed humps. (ITE, 2007)

A plateau is an alternative speed table design that has been used in the Netherlands and installed on facilities with speeds ranging from 60 to 80 km/h (35 to 50 mph). In applications of this treatment, plateaus are generally installed on all intersection approaches and the minor approaches are yield-controlled. Advance warning devices are also recommended on all approaches. (Schermers and van Vliet, 2001)

Although speed tables are generally applied on low-speed facilities in the United States, they may have applications on approaches to high-speed intersections where low speeds are desired.

(Credit: Fehr & Peers, 2007)

Exhibit 4-21. Speed table combined with textured pavement in Naples, FL.

Speed tables can provide benefits for multimodal users when user needs are considered in design and application. Speed tables that are used at crosswalks can eliminate the need for curb ramps, increase pedestrian visibility, and provide more sidewalk area for multimodal users. Detectable warnings are recommended for speed tables used at crosswalks to accommodate visually impaired users. (ITE, 2007) When designed with a gentle rise, speed tables have little impact on bicyclists. (Cochituate Rail Trail, 2007)

Vertical deflection devices such as speed tables are sometimes prohibited on emergency response routes because of the friction they create. Snow and ice removal may require special attention when plowing roadways. Speed tables should be constructed downstream of storm sewer inlets and should have a tapered edge along the curb line to allow for drainage. (ITE, 1997) Additional or new street lighting may be necessary to improve the visibility of speed tables.

4.10.3 Treatment Layout/Design

Speed tables and plateaus should be placed at a location where vehicles will not abruptly encounter them at a high speed. A report from the Institute of Transportation Engineers (ITE, 1993) suggests that the first speed table in a series be placed no more than 200 ft from a stop sign or horizontal curve, and not within 250 ft of a traffic signal. Both horizontal and vertical sight distance should be considered to determine the placement of a speed table. Many jurisdictions have standard placement guidelines for the location of speed tables. (Hallmark et al., 2002)

(Credit: Fehr & Peers, 2007)

Exhibit 4-22. Speed table combined with striping and colored concrete in Charlotte, NC.

The most distinguishing design features of a speed table are the flat section in the middle of the table, the ramps on each end, and the aesthetic treatments often applied to the top. The entire speed table is typically 22 ft long in the direction of travel, with a 10-ft flat section in the middle and 6-ft ramps on both ends. The vertical deflection of a speed table typically ranges from three to four inches, but has been designed for a height of six inches in some cases. The ramps on each side of the speed table typically have a parabolic or linear shape. (ITE, 2007)

Plateaus should be located approximately 50 to 100 m (165 to 325 ft) from the intersection and designed for a speed of 40 km/h (25 mph). (Schermers and van Vliet, 2001)

4.10.4 Speed Effects

Much of the information about the effectiveness of speed tables relates to roadway segments with operating speeds less than 45 mph. No information was found that describes the affect speed tables have on speeds at intersections on high-speed facilities.

Most research has shown that speeds were reduced after speed tables were installed. A study in Gwinnett County, Georgia, in which 43 speed tables were installed, found that speeds were reduced by an average of 9 mph. (Bretherton, 2003) Another study reported an average 18% decrease in the 85th-percentile travel speeds for a sample of 58 test sites. (Fehr & Peers, 2007) However, in some cases speed tables may be too gentle to mitigate excessive speed. A test site in Fort Lauderdale, Florida, found no speed reduction. (ITE, 2007) When designed to the typical dimensions, speed tables have an 85th-percentile speed of 25 to 30 mph. (ITE, 1999)

Although the speed reduction potential of speed tables is not well known, the ITE (1999) study noted above suggests that the provision of speed tables results in an 85th-percentile speed of 25 to 30 mph. Thus, if a speed table is used at an intersection, the speed reduction on the intersection approach may be from the 85th-percentile mid-block speed to 25 to 30 mph. It is expected that most intersections where speed tables have been used have moderate mid-block or approach speeds.

Speed tables located at intersections and mid-block locations have been shown to reduce speeds and collisions as well as to lower traffic volumes.

4.10.5 Safety Effects

Speed tables located at intersections and mid-block locations have been shown to reduce speeds and collisions as well as lower traffic volumes. Some studies have reported that collisions have been reduced by an average of 45% on streets treated with speed tables at particular test sites. (ITE, 2007; Fehr & Peers, 2007)

Speed tables have potential to increase safety on the treated road by lowering volumes and reducing the probability of a crash. The study conducted in Gwinnett County showed a 7% reduction in traffic volumes based on 24-hour traffic counts collected on 18 streets before and after speed tables were installed. (Bretherton, 2003) ITE reported a 12% reduction in traffic volumes on roadways with speed table applications, depending on the availability of alternative routes. (ITE, 2007)

4.11 Reduced Lane Width

4.11.1 Overview

No test sites provided documented applications for the high-speed intersection treatments discussed in this section. Reduced lane widths heighten driver attention by narrowing the available lane width. These treatments can be applied on intersection approaches. Design variations

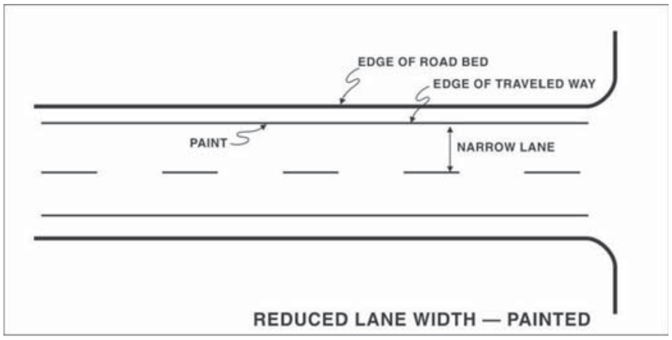


Exhibit 4-23. Reduced lane width—painted.

can involve re-striping only or narrowing the paved section. Secondary effects and considerations should include using with caution when heavy truck traffic or multilane facilities are present and where curvilinear alignments exist.

4.11.2 Applicability and Considerations

Reduced lane width could come in two basic forms: lanes narrowed with paint (see Exhibit 4-23) or a physically reduced roadbed width (see Exhibit 4-24). Lane narrowing benefits using paint may be negated by the relative open field of vision. Narrow roadbeds physically constrain the cross section but may have secondary impacts. Lane widths that are considered "reduced" tend to range from 9 to 12 ft.

Lane-width reductions have been used in both temporary and permanent applications. Permanent lane width reductions that reduce the overall pavement width are expected to have the greatest potential to reduce speeds because both the pavement width and the striping contribute to drivers' perceptions of the roadway environment. Lane-width reductions have been documented for work zone applications and low-speed urban and residential locations.

Lane widths on multilane facilities, roadways with curvilinear alignments, and facilities with high heavy truck or transit vehicle use should be reduced with caution, particularly if the width of the paved section will be reduced. Reducing lane widths can negatively impact bicyclists if bicycle lanes or wide curb lanes are not maintained, but it can also improve bicyclist conditions if the additional space is used to provide or widen bicycle lanes. Reducing lane width can provide positive effects such as space for other roadway features (i.e., medians and curbside parking), space for roadside features (i.e., sidewalks and clear zones), and reduced interference with existing roadside development. (Zegeer et al., 2002)

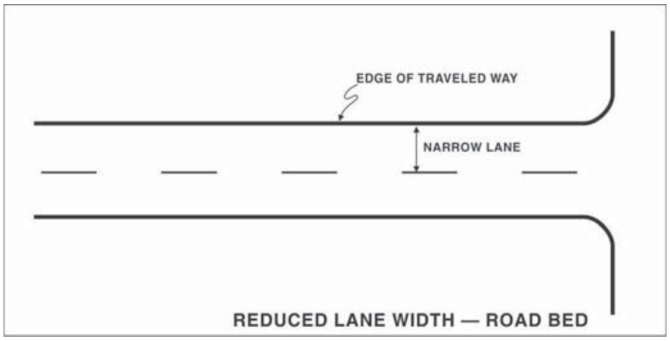


Exhibit 4-24. Reduced lane width—roadbed.

Reduced lane widths improve pedestrian conditions at intersections by reducing crossing distances and exposure time. Excessive crossing distances increase pedestrian exposure time, heighten the potential for vehicle–pedestrian conflicts, and may add to vehicle delay. At signalized intersection approaches, reducing lane widths and thereby the pedestrian crossing distance provides more flexibility for the intersection's signal timing.

4.11.3 Treatment Layout/Design

NCHRP Project 3-72, "Lane Widths, Channelized Right Turns, and Right-Turn Deceleration Lanes in Urban and Suburban Areas," evaluated the operational, speed, and safety effects of reduced lane widths on roadway segments and intersections. The research findings indicate that reducing lane widths to less than 10 ft may not be advisable on four-lane undivided arterials or on the approaches to four-leg stop-controlled intersections. Additionally, it suggests that it may not be advisable to reduce lane widths to less than 9 ft on four-lane divided arterials. These findings are consistent with the "Green Book" (AASHTO, 2004), which recommends lane widths of 10 to 12 ft on urban and suburban arterials.

Redesigned lanes can be reduced using concrete barriers (for short-term solutions), curbs, or standard striping. The effects of reducing the width of pavement on turning radii at intersections should be evaluated to ensure that adequate radii are available to accommodate the design vehicle.

4.11.4 Speed Effects

Research related to the speed, safety, and operational effects of reduced lane widths provides inconsistent results, indicating that the relationships are complex and difficult to evaluate without considering other elements of the intersection or roadway environment.

Research and analysis conducted for NCHRP Project 3-72, which included both high-speed and low-speed facilities, made the following conclusions regarding the speed effects of reduced lane widths:

- Reduces mid-block speeds on four-lane arterials (average lane-width reduction of 2.7 ft associated with average speed reduction of 4 mph),
- Reduces driver comfort on higher-speed facilities,
- May decrease capacity due to reduced saturation flow rates, although the calculated reductions were about half of the reductions suggested in the *Highway Capacity Manual (HCM)*, and
- May increase capacity at signalized intersections due to decreases in pedestrian crossing times.

Research that evaluates how effectively reduced lane widths reduce speeds in work zones found that the treatment was most effective on two-lane rural roads and found that a 7% reduction in speed was achieved by reducing lane widths to 11.5 and to 12.5 ft. (Benekohal et al., 1992) In low-speed environments, research has concluded that speed is not consistently related to lane width. (Gattis, 1999)

It is also likely that wider lanes induce faster travel speeds that may increase crash risk and increase crash severity. Earlier editions of the *HCM* suggested that wider lanes on multilane highways also increase capacity and, therefore, reduce following distances. (TRB, 1985) However, *HCM* editions since 1985 have indicated that wider lanes of up to 12 ft on multilane highways increase free-flow speeds but do not increase capacity and, therefore, do not reduce vehicle headways. (TRB, 1994; TRB, 2000)

4.11.5 Safety Effects

The documented safety effects of reduced lane widths generally address segment applications, although some intersection approach data may be included. Despite inconsistent data, concern remains that narrower lanes may be accompanied by reduced safety. The two principal aspects to the potential link between lane width and safety are as follows:

- Wider lanes increase the average separation between vehicles moving into adjacent lanes and may provide a wider buffer to accommodate small, random deviations from drivers' intended paths; and
- Wider lanes may provide more room for correction maneuvers by drivers in near-crash circumstances. (Hauer, 2000)

Research and analysis conducted for NCHRP Project 3-72 found no decrease in safety at midblock locations or intersection approaches with narrow lanes except in the following limited cases:

- Four-lane undivided arterials with lane widths less than 10 ft,
- Four-lane divided arterials with lane widths less than 9 ft, and
- Four-leg stop-controlled intersections with lane widths less than 10 ft.

Research by Harwood et al. (2000) developed accident modification factors (AMFs) for crash types related to cross-section elements (including opposite direction, and single-vehicle run-off-road) for two-lane highways. The AMFs range from 1.05 to 1.5 for 9- to 11-ft lanes compared to 12-ft lanes, indicating that two-lane facilities with narrower lanes would be expected to experience higher crash rates for certain crash types. (Harwood et al., 2000) The AMF of 1.50 for 9-ft lanes implies that a roadway with 9-ft lanes would be expected to experience 1.5 times as many crashes as a roadway with 12-ft lanes. However, some studies indicate that lanes wider than 12 ft may also be associated with higher crash frequencies.

4.12 Visible Shoulder Treatments

4.12.1 Overview

No test sites provided documented applications for the high-speed intersection treatments discussed in this section. Visible shoulder treatments heighten driver attention by narrowing the visual width of the roadway. These treatments can be applied at transition areas, roadways with existing shoulders, and roadways in rural areas with no sight line limitations. There are many design variations. Secondary effects and considerations should recognize that bicyclists using the shoulder may be impacted by these treatments, depending on the materials used.

4.12.2 Applicability and Considerations

Visible shoulder treatments are used to change the appearance of the paved area to either aesthetically blend roadway facilities into the surrounding landscape or to create a contrast between the shoulder and travel lane to heighten drivers' awareness of the roadway. Visible shoulder treatments can consist of shoulder pavement markings, pavement coloring, shoulder composition, and shoulder rumble strips. If introduced in advance of the intersection, these treatments may be used to alert drivers of the change from roadway segment to the intersection influence area.

Exhibit 4-25 shows an example of a visible shoulder treatment using brick.

(Credit: Dan Burden)

Exhibit 4-25. Example of a shoulder composition application.

The applicability of visible shoulder treatments depends on the presence or absence of existing shoulders and the ability to acquire right of way, if needed. Generally, visible shoulder treatments are most cost efficient for intersection approaches with existing shoulders.

Shoulder coloring can have an effect on the thawing and freezing characteristics of the shoulder pavement. Black shoulders retain heat longer while light-colored shoulders have the potential to freeze more easily. Though not documented, colored treatments could fade or deteriorate because of snow removal. (Straub et al., 1969)

Consideration should be given to the effects of textured shoulder treatments on bicyclists.

4.12.3 Treatment Layout/Design

Shoulder dimensions generally are presented in the roadway design typical sections. In cases where the shoulder exists or is planned, the special treatment area might be limited to the vicinity of the intersection influence area to help differentiate between the roadway segment and the impending intersection.

4.12.4 Speed Effects

No documentation was found that describes the effect visible shoulder treatments have on speed or safety at high-speed intersection approaches. No documentation was found that describes multimodal impacts.

4.12.5 Safety Effects

No documentation has been found that describes the safety benefits of visible shoulder treatment applications at high-speed intersection approaches.

4.13 Roadside Design Features

4.13.1 Overview

No test sites provided documented applications for the high-speed intersection treatments discussed in this section. Roadside design features reinforce the transitioning environment, draw attention to multimodal users, and reduce comfortable approach speeds. These treatments have many applications. Design variations include roadside design features, gateways, and landscaping. Secondary effects and considerations should include horizontal and intersection sight distance.

4.13.2 Applicability and Considerations

The roadway environment can influence drivers' perceptions of the road and provide safety benefits when implemented appropriately. Landscaping, cross-sectional changes, and gateways are three characteristics of the roadway environment that can affect the speed and safety of a roadway while providing aesthetically pleasing surroundings.

Landscaping is typically planted along the roadside, set back from the edge or within a center median (see Exhibit 4-26). Landscape improvements should not be planted in an area that obstructs signs, sight lines, or the visibility of motorists, bicyclists, or pedestrians.

A roadway's cross section includes travel lanes, shoulders, curbs, drainage channels, side slopes, and clear zones. Other cross-sectional elements include sidewalks, bike lanes, barriers, medians, and frontage roads. Specific design guidelines for each of these elements generally depend on surrounding environment, adjacent land uses, and roadway facility type.

Gateways (see Exhibit 4-27) are prominent physical features that inform drivers they are transitioning into a new roadway environment and can include landscaping, lighting, signage, or physical structures.

Maintaining landscaping treatments can be costly and difficult. Maintenance tasks can be labor- and infrastructure intensive, and include mowing, pruning branches and shrubs, watering, and fertilizing. In addition, removing and replanting vegetation or trees can be a significant investment, especially during the first few years until the vegetation is established. Maintenance tasks require a minimum clear space of three ft from the edge of a travel lane to allow maintenance crews to work without being in danger of passing vehicles. (Mok et al., 2006)

(Credit: FHWA, 2000a)

Exhibit 4-26. Landscaped median treatment.

Exhibit 4-27. Gateway.

Gateways are typically installed as an entrance to a city, neighborhood, or downtown area. The intent of these treatments is to create a welcoming physical feature that informs motorists that they are about to enter an activity area where lower speeds are desirable. Gateways are also placed at the exits of these same areas, typically to inform drivers that they are leaving an activity area.

4.13.3 Treatment Layout/Design

Drivers must have a clear sight distance to view other vehicles approaching or pulling out at intersections; landscape heights and locations should not impede visibility.

Canada's Ontario Ministry of Transportation conducted a study on transition zones near intersections; however, the results of this study are not yet available.

4.13.4 Speed Effects

Much of the information about how the roadway environment impacts safety and speed relates to roadway segments. No information has been found to describe the speed reduction benefits associated with roadway environment changes at intersection approaches.

Cross-sectional changes can influence the way a driver perceives the road and can affect driver behavior. A roadway with several lanes, wide shoulders, and clear zones gives the driver a feeling of openness, thus increasing the impression that they can drive fast. A narrow road with horizontal curves, steep slopes, or even a cliff on the side of the road, induces drivers to slow down. Changing the appearance of the road primarily impacts unfamiliar drivers. A study of 30 test sites in Canada reported 85th-percentile speeds of 30 mph on sites with side friction, such as parking, heavy pedestrian and bicycle activity; whereas the 85th-percentile speed was measured to be 39 mph at sites with simple and open road situations. The posted speed limit at all of the sites was 30 mph. (Smiley, 1999)

Trees and vegetation can help define the edge of the roadway and slow traffic. Shinar et al. (1974) conducted a study on two-lane rural highways that indicated that trees growing close to the edge of the road caused drivers to maintain lower speeds than on an open stretch of highway. Drivers were requested to maintain a speed of 60 mph, yet, on the stretches of roadway with trees, drivers maintained a speed of 53 mph and on the open stretches of highway drivers maintained 57 mph. (Human Factors North, Inc., 2002)

4.13.5 Safety Effects

There is information quantifying how the roadway environment impacts safety, and much of the available information relates to roadway segments.

Landscaping can be a significant safety hazard when placed within the clear zone or when it obstructs sight distance for drivers pulling out into the roadway. However, when implemented appropriately, it can provide a safety benefit.

A before-and-after study conducted by TTI implemented landscape improvements to 10 Texas Department of Transportation projects. After the landscaping was in place for three years, the mean crash rate per 1 million vehicle miles traveled decreased approximately 20% while the pedestrian crash rate was reduced by 40%. (Mok et al., 2006)

4.14 Summary

There are a variety of treatments and potential applications that should be customized for each unique intersection need. The information provided here should supplement and complement the user's experience and professional judgment. Appendix A provides a treatment implementation process flowchart. Appendix B provides scenario-based case studies to aid the user in applying the screening process. By understanding the fundamentals and considerations of speed and potential treatments and applications, the user can consider possible treatments. The case studies provide examples of actual projects where the process was applied and treatments were recommended.

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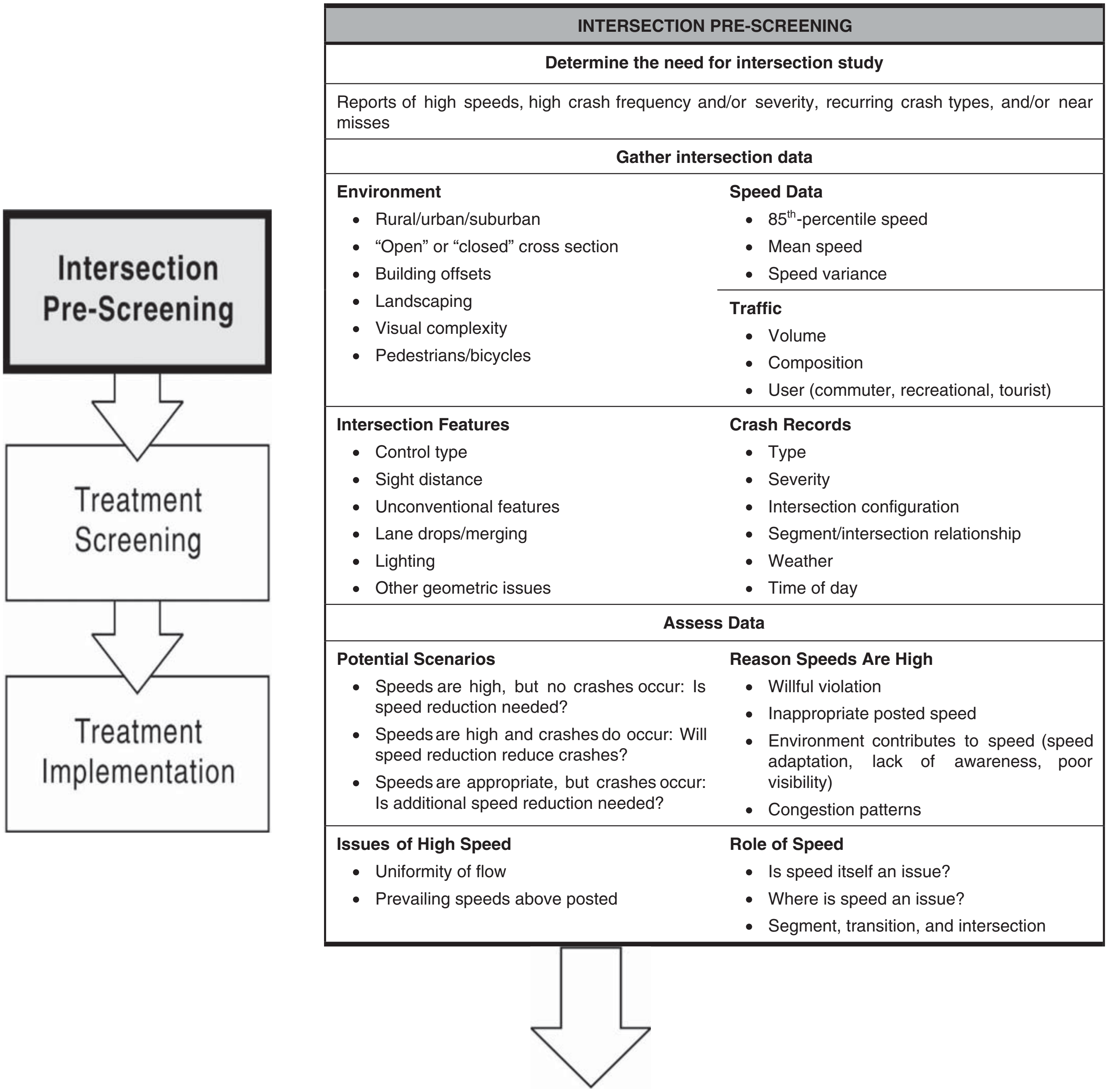
APPENDIX A

Treatment Implementation Process Framework

The framework shown in Exhibit A-1 provides an outline of basic steps needed to evaluate an intersection and consider possible speed reduction treatments.



INTERSECTION PRE-SCREENING

Determine the need for intersection study

Reports of high speeds, high crash frequency and/or severity, recurring crash types, and/or near misses

Gather intersection data

Environment
- Rural/urban/suburban
- “Open” or “closed” cross section
- Building offsets
- Landscaping
- Visual complexity
- Pedestrians/bicycles

Speed Data
- 85^{th}-percentile speed
- Mean speed
- Speed variance

Traffic
- Volume
- Composition
- User (commuter, recreational, tourist)

Intersection Features
- Control type
- Sight distance
- Unconventional features
- Lane drops/merging
- Lighting
- Other geometric issues

Crash Records
- Type
- Severity
- Intersection configuration
- Segment/intersection relationship
- Weather
- Time of day

Assess Data

Potential Scenarios
- Speeds are high, but no crashes occur: Is speed reduction needed?
- Speeds are high and crashes do occur: Will speed reduction reduce crashes?
- Speeds are appropriate, but crashes occur: Is additional speed reduction needed?

Reason Speeds Are High
- Willful violation
- Inappropriate posted speed
- Environment contributes to speed (speed adaptation, lack of awareness, poor visibility)
- Congestion patterns

Issues of High Speed
- Uniformity of flow
- Prevailing speeds above posted

Role of Speed
- Is speed itself an issue?
- Where is speed an issue?
- Segment, transition, and intersection

Exhibit A-1. Treatment implementation process framework.

TREATMENT SCREENING

Fatal-Flaw Analysis

- Approach type
- Control type
- Physical constraints
- Cost
- Noise
- Maintenance

Detailed Treatment Evaluation

Target Speed

- Design
- Posted
- Operating

Approach Type

- Major or minor
- Stop-controlled
- Signalized
- Uncontrolled
- Yield-controlled

Type of Treatment

- Isolated
- Continuous
- Combination

Effects

- Speed effects
- Safety effects
- Maintenance

Potential Secondary Impacts

- Capacity
- Pedestrians/bicycles
- ADA
- Land use
- Economics
- Enforcement needs
- Construction

TREATMENT IMPLEMENTATION

Design

- Geometric and operational influence areas
- Opportunities to reinforce existing treatments/features
- Distance required for speed transition
- Perception–reaction distance
- Driver workload
- Opportunities to combine treatments

Implementation

- Address public education and awareness
- Consider construction impacts
- Create evaluation plan

Exhibit A-1. **(Continued).**

APPENDIX B

Case Studies

APPENDIX B1

Whiskey Hill Road/Meridian Road

The site of this case study was the intersection of Whiskey Hill Road and Meridian Road in Clackamas County, Oregon.

B1.1 Pre-Screening

Clackamas County identified this intersection because of speed and safety concerns. In particular

- Meridian Road: Complaints were made regarding people running the northbound stop sign.
- Whiskey Hill Road: Horizontal curves, grade, and limited sight distance made it difficult to anticipate the upcoming intersection.
- Special condition: There is a school adjacent to intersection, which motorists also had difficulty anticipating.

Note: Crosswalks near the school make this location especially sensitive to speed.

B1.1.1 Intersection Characteristics

B1.1.1.1 Traffic Volumes

There is approximately 2,100 average daily traffic (ADT) during a typical weekday on Whiskey Hill Road. There is approximately 1,300 ADT during a typical weekday on Meridian Road.

Note: Low volume provided an opportunity for drivers to travel at free-flow speeds.

B1.1.1.2 Traffic Composition

There is a high percentage of agricultural truck traffic and school buses traveling through the area.

B1.1.1.3 Intersection Features

This is a two-way, stop-controlled intersection, with stop signs on the north and south approaches of Meridian Road.

Whiskey Hill and Meridian roads are two-lane roadways.

The west approach of Whiskey Hill Road features a horizontal curve, sight distance issues, and grade changes.

B1.1.1.4 Speed Data

Speed is defined according to the "basic rule."

Note: Basic Rule is, "No person shall drive a vehicle at a speed greater than is reasonable and prudent under the conditions and having regard to the actual and potential hazards then existing."

A speed study conducted in August 2005 found

Whiskey Hill Road

- 85th-percentile speed = 48.7 mph
- Percent exceeding 45 mph = 28%

Meridian Road

- 85th-percentile speed = 56.2 mph
- Percent exceeding 45 mph = 66%

Note: Clackamas County staff said speeds in this area were not extremely high, but drivers were traveling faster than desired. They also reported multiple complaints of drivers running the stop sign northbound on Meridian Road. This may have been caused by drivers' inability to adapt to the intersection influence area and having insufficient distance to stop.

In addition, staff from the adjacent school had received complaints of vehicles driving too fast. There are 25 mph school zones on the north approach of Meridian Road and the east approach of Whiskey Hill Road.

B1.1.1.5 Crash Records

One crash was reported in 2004 and involved a vehicle running the stop sign.

B1.1.1.6 Environment

The surrounding area is rural.

An elementary school is located on the northeast corner of the intersection.

Lenhardt Airport is located north of the elementary school on Meridian Road.

A convenience store is located on the intersection's southeast corner.

Single-family residences are situated adjacent to, and east of, Meridian Road and south of Whiskey Hill Road.

B1.2.1 Assess Data

Is speed the primary issue? Are speed reduction treatments needed?

- No speed limit is posted; therefore, the basic rule applies.
- Given the residential driveways and school zone on Meridian Road, and the horizontal curvature, grade changes, and limited sight distance on Whiskey Hill Road, 45 mph is a reasonable speed for these roadways.
- Based on the speed data for Meridian Road and Whiskey Hill Road, approximately 66% and 28% of drivers exceeded 45 mph, respectively.

Note: Based on discussions with the county, a speed of 45 mph was reasonable for each intersection approach.

On which approaches is speed reduction needed?

- Based on crash data and public complaints, there was a need to reduce speeds in the northbound direction on Meridian Road to eliminate stop sign violations.

- Based on complex roadway geometry and limited sight distance, there was a need to reduce speeds in the eastbound direction of Whiskey Hill Road prior to the intersection and school.

Note: The school is more visible to approaching drivers traveling in the southbound and westbound directions. Therefore, no speed reduction treatments are needed on those approaches.

B1.2 Treatment Screening

Potential treatments are

- Reduced lane width,
- Visible shoulder treatments,
- Speed tables,
- Rumble strips,
- Roadway environment,
- Approach curvature,
- Roundabouts,
- Splitter islands,
- Longitudinal pavement markings,
- Transverse pavement markings, and
- Dynamic warning sign.

B1.2.1 Fatal Flaws

Note: Clackamas County was interested in a treatment that would be implemented quickly and easily. However, the county had limited funding available for the treatment project.

Reduced Lane Width—Existing lane width is 11 ft.

Visible Shoulder Treatment—Existing study roadways have no shoulders.

Exhibit B1-1 illustrates the limited shoulder and narrow cross section on Meridian and Whiskey Hill Roads.

Speed Tables—The 85th-percentile speeds are greater than 45 mph. Therefore, speed tables were not appropriate for these high-speed study roadways.

Rumble Strips—Clackamas County was not interested in installing rumble strips at this location due to potential noise impacts on nearby residences and the school.

Figure B1-2 illustrates the residences near Whiskey Hill and Meridian Roads.

Roadway Environment—Existing vegetation and a continuous drainage ditch adjacent to the roadway made it difficult to install effective roadway environment treatments such as landscaping.

Exhibit B1-3 illustrates the existing roadway vegetation on Meridian and Whiskey Hill Roads.

Approach Curvature—Existing roadways have a narrow cross section and right-of-way is constrained.

Roundabout—Clackamas County did not have funding available to consider a roundabout as a potential intersection treatment. In addition, existing roadways have narrow cross sections and right-of-way is constrained.

Splitter Island—Existing roadways have narrow cross sections and right-of-way is constrained.

(a) Meridian Road

(b) Whiskey Hill Road

Exhibit B1-1. Shoulders and cross sections on Meridian and Whiskey Hill Roads.

Dynamic Warning Signs—Clackamas County did not have funding available to consider dynamic warning signs as a potential treatment. In addition, the rural location made it difficult and expensive to provide power to the signs.

B1.2.2. Evaluate Potential Treatments

After the research team identified the "fatal flaw" treatments that were not feasible to install at this intersection (reduced lane width, visible shoulder treatments, speed tables, rumble strips, roadway environment, approach curvature, roundabouts, splitter islands, and dynamic warning sign), two potential treatments remained: longitudinal and transverse pavement markings. At this point, the research team reviewed past research and evaluated each potential treatment to assess its effectiveness and determine which was the most appropriate.

B1.2.2.1. Longitudinal Pavement Markings

No research had been conducted to show this as an effective speed reduction treatment. Additionally

- This treatment requires a large amount of pavement marking material, depending on the treatment boundary.
- Longitudinal pavement markings may conflict with multiple adjacent driveways.
- This solution may be more effective in areas with speed adaptation issues or a large number of elderly drivers.

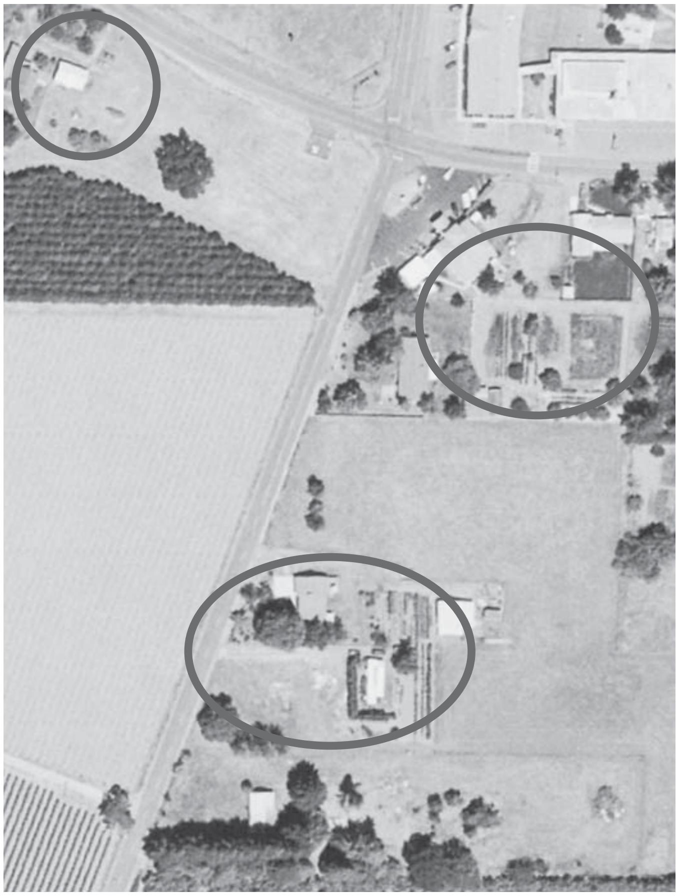


Exhibit B1-2. Residences near Whiskey Hill and Meridian Roads.

B1.2.2.2. Transverse Pavement Markings

Past research has shown this treatment to be effective at reducing speeds. In addition to reviewing past research and treatment information, the research team also reviewed the objectives for the speed reduction, including the target speed and locations where speed reduction was desired.

How much speed reduction is desired?

- Eastbound direction: 45 mph is a safe speed to maneuver the curves and grade.
- Northbound direction: 45 mph at stopping sight distance (SSD) was recommended to reduce speeds at the intersection's approach and throughout the school zone.

Where should speed be reduced?

Speed reduction was needed at the eastbound and northbound intersection approaches, beginning approximately 500 ft SSD from the intersection.

B1.3 Selecting Treatments

B1.3.1 Implementation—Treatment Layout

Based on the review of treatment information and the objectives for reducing speeds, the research team selected transverse pavement markings for this site.

(a) Whiskey Hill Road

(b) Meridian Road

Exhibit B1-3. Existing roadway vegetation on Meridian and Whiskey Hill Roads.

Exhibit B1-4 illustrates a schematic of the proposed treatment layouts at the Whiskey Hill Road/Meridian Road intersection.

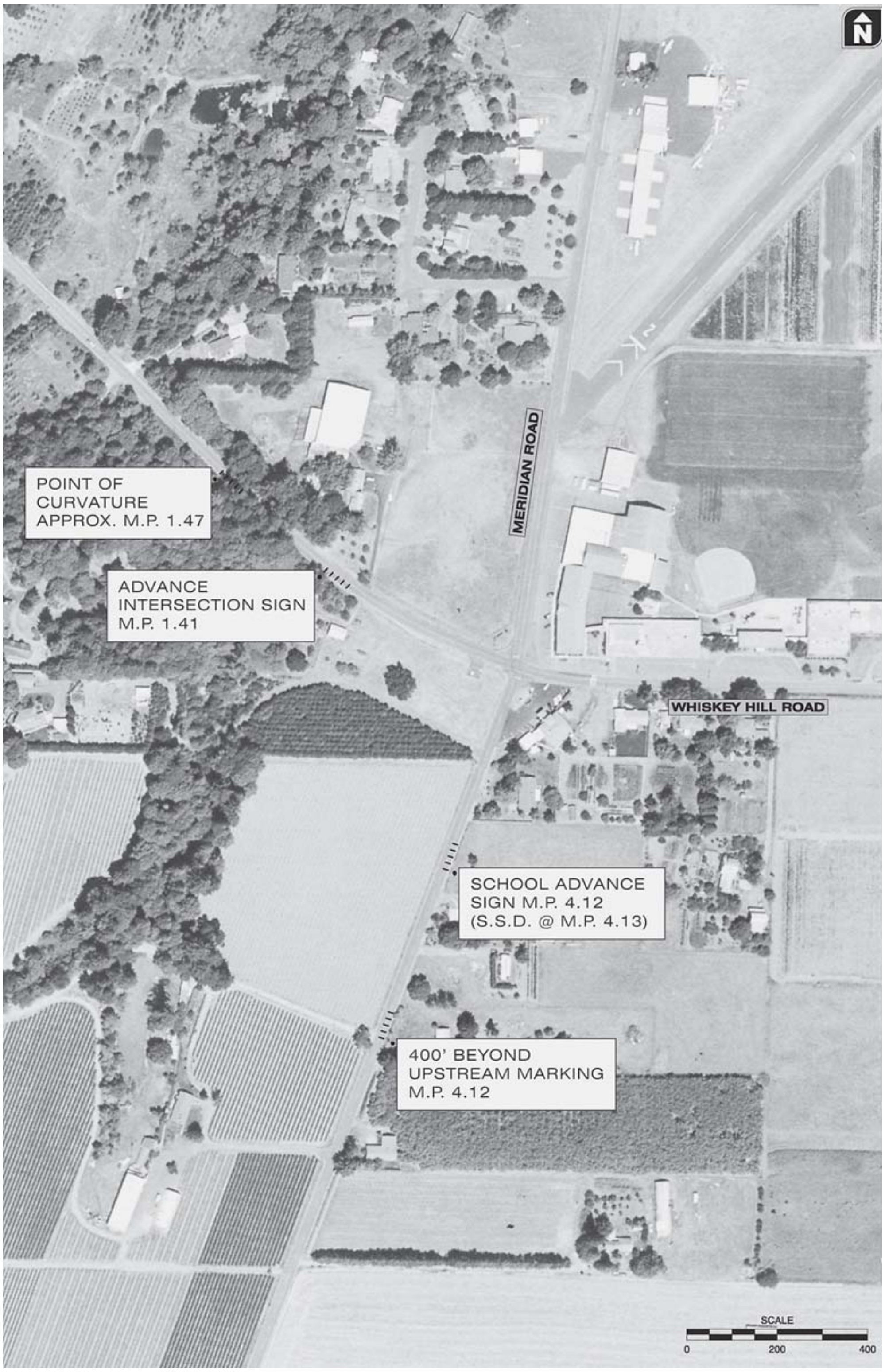
Meridian Road (south approach)

- Treatment Location 1: School Ahead sign at mile post 4.12,
- SSD at 55 mph is also near mile post 4.12 (approximately 500 ft from the intersection), and
- Treatment Location 2: 400 ft downstream of the School Ahead sign and after the existing driveways on Meridian Road.

Whiskey Hill Road (west approach)

- Treatment Location 1: Intersection Ahead sign at mile post 1.41,
- Treatment Location 2: Approximate point of curvature at mile post 1.47, and
- The installation points closest to the intersection (mile posts 4.12 and 1.41) were chosen because of the existing signs at those locations and because the signs are near the SSD for 55 mph (495 ft, Exhibit 3-1 in the "Green Book" [AASHTO, 2004]). The existing signs currently serve to alert drivers of the upcoming intersection. The markings have the potential to draw additional attention to those warning signs and encourage drivers to reduce their speeds as they approach the intersection.

The installation points beyond the upstream treatments are located where the roadway environment changes, such as the approximate point of curvature (Whiskey Hill Road, mile post 1.47) or presence of driveways (Meridian Road, mile post 4.21). In addition, placing a treatment at the end of the tangent at the point of curvature on a roadway allowed drivers a consistent view of the treatment ahead.



| | | | | POTENTIAL TREATMENT LOCATION

Exhibit B1-4. Schematic of Whiskey Hill Road/Meridian Road intersection proposed treatment layouts.

B1.3.2 Treatment Design Options

Full transverse bars

- These are more noticeable to drivers and, therefore, potentially more effective at reducing speeds.
- In some cases, there have been reports of motorcycles slipping on the markings while decelerating.

Peripheral transverse bars

- These require less maintenance than full transverse bars.
- They are less expensive to install due to limited material.
- They potentially create a narrowing effect of the travel way.

Note: Clackamas County chose to install peripheral transverse bars due to the potential safety issues for motorcycles and the decreased need for maintenance.

B1.3.3 Treatment Design—Peripheral Transverse Bars

- The peripheral bars were designed to extend perpendicularly into the travel way from the edge and center lines, but did not extend into the wheel path of vehicles.
- The design includes five pavement markings placed in a series.
- They are spaced approximately 15 ft apart.
- Each marking is approximately 12 to 24 in. in width and between 18 to 33 in. in length.
- The length of each peripheral bar depends on the existing lane width and the width of the wheel base for vehicles that commonly travel through the area.

Exhibit B1-5 illustrates the proposed peripheral transverse pavement marking design for the Whiskey Hill Road/Meridian Road intersection.

Travel way width = 10’6”

Typical wheel base = 8’6”

Bar dimensions = 12” × 8”

B1.3.4 Treatment Testing and Installation

- April 2006—“Before” testing,
- May 2006—Treatment installation, and
- September 2006—“After” testing.

Exhibits B1-6 and B1-7 illustrate the installed treatments at the Whiskey Hill Road/Meridian Road intersection.

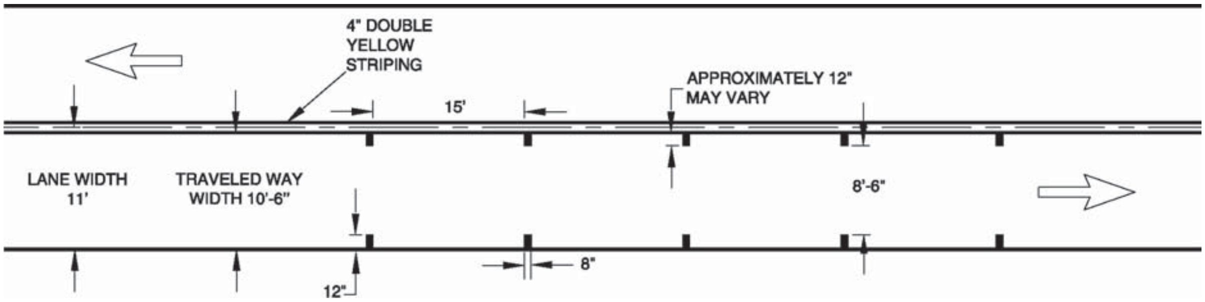


Exhibit B1-5. Peripheral transverse pavement marking design.

Exhibit B1-6. Northbound on Meridian Road near mile post 4.12.

Exhibit B1-7. Eastbound on Whiskey Hill Road near mile post 1.41.

APPENDIX B2

SR 20/Marysville Road

The site of this case study was the intersection of SR 20 and Marysville Road in Marysville, California.

B2.1 Pre-Screening

The California Department of Transportation (Caltrans) identified this intersection as having speed and safety issues.

> SR 20 and Marysville Road—Rear-end crashes resulted from high speeds through the intersection, and there was inadequate intersection visibility or awareness.

B2.1.1 Intersection Characteristics

B2.1.1.1 Traffic Volumes

No traffic volume data was available for this site.

B2.1.1.2 Traffic Composition

The intersection accommodates commuter traffic traveling to and from Marysville and Yuba City.

Note: A gas station at the intersection's northeast corner creates a high number of pass-by trips turning off and on the highway.

B2.1.1.3 Intersection Features

This is a two-way and stop-controlled intersection, with a stop sign on Marysville Road.

SR 20 and Marysville Road are two-lane roadways.

An eastbound left-turn lane and westbound right-turn lane exist on SR 20.

Note: The slight curvature and/or location of the stop sign may make it difficult for vehicles to see the upcoming T-intersection. *Stop Ahead* signing and pavement legends have been installed at the intersection approach.

B2.1.1.4 Speed Data

The posted speed is 55 mph on SR 20 and Marysville Road. A speed study conducted on SR 20 revealed critical speeds of 66 mph.

Note: Commuter drivers are familiar with the area and may not feel the need to reduce speeds at the side-street intersections, such as Marysville Road.

B2.1.1.5 Crash Record

Crash history indicates multiple rear-end crashes involving southbound vehicles on Marysville Road, and multiple broadside crashes involving eastbound and westbound vehicles on SR 20. Both crash types at this location have caused injuries.

Note: The rear-end crashes on Marysville Road may be a result of inadequate visibility of the approaching intersection. Broadside crashes on SR 20 may be a result of vehicles not being aware of upstream vehicles slowing down to make turning movements at the intersection.

B2.1.1.6 Environment

The surrounding area is rural and open.

A small commercial development exists at the intersection's northeast corner.

Note: Open fields are south of the intersection; therefore, the openness may create intersection visibility issues and may provide a more comfortable environment for higher speeds. In addition, this could prevent drivers from identifying and changing speeds in the intersection influence area.

B2.1.2 Assess Data

Is speed the primary issue? Are speed reduction treatments needed?

> A speed study indicated vehicles were exceeding the speed limit by over 10 mph.
>
> Commuter traffic and the open environment create a comfortable environment for high speeds.

On which approaches is speed reduction needed?

> Based on crash history and discussions with Caltrans staff, speeds need to be reduced in the southbound direction on Marysville Road and in the westbound direction on SR 20.

B2.2 TREATMENT SCREENING

Potential treatments are

- Reduced lane width,
- Visible shoulder treatments,
- Speed tables,
- Rumble strips,
- Roadway environment,
- Approach curvature,
- Roundabouts,
- Splitter islands,
- Longitudinal pavement markings,
- Transverse pavement markings, and
- Dynamic warning sign.

B2.2.1 Fatal Flaws

Due to issues with visibility and awareness of the upcoming intersection, Caltrans and the research team decided that a visual treatment may be appropriate for this intersection. In addition,

(Credit: Caltrans)

Exhibit B2-1. Existing shoulders on SR-20.

the agency was sensitive to cost, which eliminated the potential for roundabouts and approach curvature. Therefore, the team narrowed the list of treatments to the following:

- Visible shoulder treatments,
- Roadway environment,
- Dynamic warning signs,
- Transverse pavement markings, and
- Longitudinal pavement markings.

As shown in Exhibits B2-1 through B2-3, visible shoulder treatments, roadway environment, and longitudinal pavement markings are also "fatal flaw" treatments due to the existing roadway conditions.

> Visible Shoulder Treatments—Existing study roadways have minimal shoulders.
>
> Roadway Environment—There is existing vegetation prior to the intersection in the westbound direction. The open cross section and environment would have required significant changes to the roadway environment to be an effective speed reduction treatment.

(Credit: Caltrans)

Exhibit B2-2. Existing roadway environment on SR-20.

(Credit: Caltrans)

Exhibit B2-3. Existing turn lanes on SR-20.

Longitudinal Pavement Markings—The existing intersection turn lanes would have made wider longitudinal pavement markings less effective or required more complex striping.

B2.2.2 Evaluate Potential Treatments

After the research team identified the fatal flaw treatments that were not feasible to install at this intersection, two potential treatments remained: transverse pavement markings and dynamic warning sign. At this point, the research team reviewed past research and evaluated each potential treatment to assess its effectiveness and determine which was the most appropriate.

B2.2.2.1 Transverse Pavement Markings

Past research has shown this treatment to be effective at reducing speeds. This treatment was chosen for the Marysville Road southbound approach to supplement existing signing and *Stop Ahead* pavement markings.

B2.2.2.2 Dynamic Warning Sign

Past research also has shown this treatment to be effective at reducing speeds and making drivers more aware of an upcoming intersection or roadway features. This treatment was chosen for the westbound approach of SR 20 due to the significant visual treatment that was needed to be effective at reducing speeds in a complex and open roadway environment.

How much speed reduction is desired?

Westbound Direction—The goal was to have drivers become more aware of the intersection and travel at or below the 55 mph posted speed limit.

Southbound Direction—The goal was to reduce vehicle speeds prior to the intersection and intersection influence area, which contain the commercial land uses. Therefore, a target speed may be 55 mph or less at the stopping sight distance (SSD) to reduce speeds at the intersection approach.

Where should speed be reduced?

Speed reduction was needed at the southbound and westbound intersection approaches, no closer than approximately 500 ft SSD from the intersection. This would allow drivers adequate time to stop safely at the intersection or avoid any conflicts prior to the intersection approach.

B2.3 Selecting Treatments

B2.3.1 Implementation—Treatment Layout

B2.3.1.1 Marysville Road—Peripheral Transverse Pavement Markings

One set of markings would be located near an existing *Stop Ahead* sign that alerts drivers of the intersection. The markings at this location have potential to draw additional attention to those warning signs, increase drivers' awareness of the impending intersection, and encourage drivers to reduce their speed as they approach SR 20.

Another set of markings was proposed at approximately 500 ft from the intersection, which is the SSD at 55 mph, calculated based on the posted speed, using "Green Book" Exhibit 3-1. (AASHTO, 2004)

B2.3.1.2 SR 20—Dynamic Warning Sign Activated by Speed

In the westbound direction on SR 20, a *Marysville Road* sign is approximately 865 feet from the intersection. This is a reasonable distance for the radar unit (which will activate the dynamic warning sign) because it would capture drivers still exceeding the maximum speed threshold even after seeing that sign. Therefore, drivers who did not reduce their speeds after viewing the road sign would have another warning approximately 370 feet later with the dynamic warning sign. The maximum speed threshold would most likely be 65 mph, based on discussions with Caltrans.

The recommendation was to place the dynamic warning sign approximately 500 ft from the intersection, based on the SSD at 55 mph. This distance also allows drivers 200 ft of perception–reaction time and 200 ft of deceleration using the "Green Book" Exhibit 3-1 (AASHTO, 2004) before reaching the approximate intersection influence area, which could extend approximately 100 ft from Marysville Road.

Exhibit B2-4 illustrates a schematic of the proposed treatment layouts at the SR 20/Marysville Road intersection.

B2.3.2 Treatment Design Options

Full transverse bars would be more noticeable to drivers and therefore potentially more effective at reducing speeds. Some agencies have received complaints from motorcyclists slipping on the markings while decelerating.

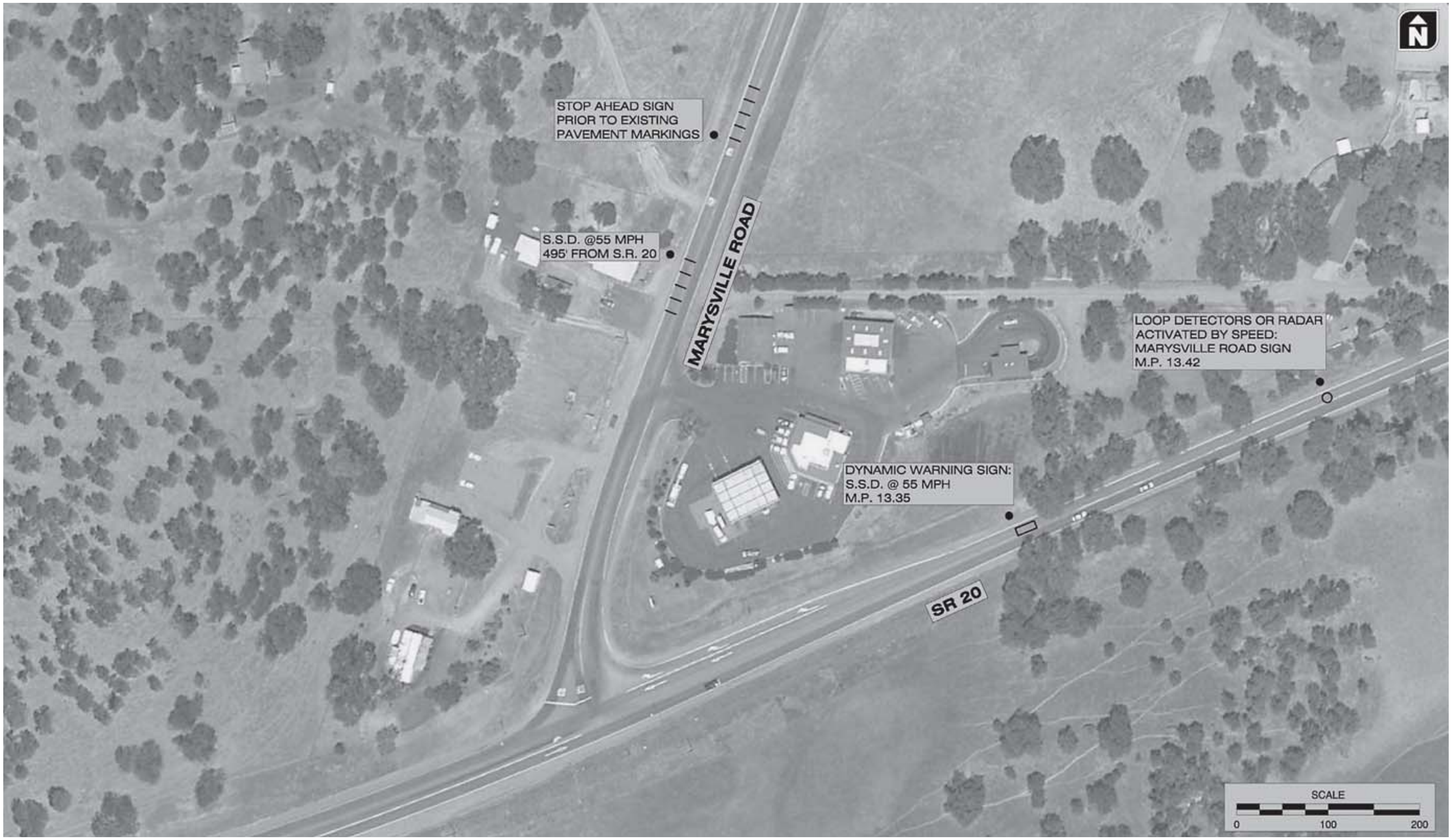
Peripheral transverse bars require less maintenance than full transverse bars, are less expensive to install than full transverse bars (due to limited material), and potentially create a narrowing effect of the travelway.

Note: Caltrans was interested in testing the effectiveness of peripheral transverse bars because of the simple installation and decreased maintenance associated with them.

B2.3.3 Treatment Design

Peripheral Transverse Bars

The peripheral bars were designed to extend perpendicularly into the travelway from the edge and centerlines, but would not extend into the wheel path of vehicles.

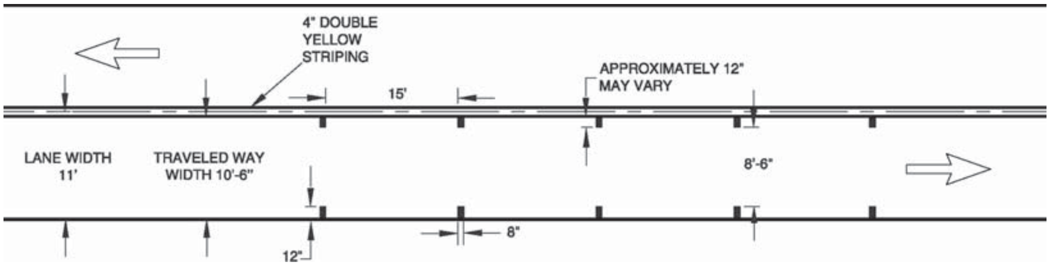


| | | | | POTENTIAL TRANSVERSE PAVEMENT MARKING LOCATION

▭ POTENTIAL DYNAMIC WARNING SIGN LOCATION

○ POTENTIAL LOOP DETECTOR OR RADAR UNIT LOCATION

Exhibit B2-4. Potential treatment layout for SR 20/Marysville Road.



Travelway width = 10’-6”
Typical wheel base = 8’-6”
Bar dimensions = 12” x 8”

Exhibit B2-5. Peripheral transverse pavement marking design.

They include five pavement markings placed in series.

Peripheral bars are spaced approximately 15 ft apart.

Each marking is approximately 12 to 24 in. wide and 18 to 33 in. long.

The length of each peripheral bar depends on the existing lane width and width of the wheel base of vehicles that typically use the roadway.

Exhibit B2-5 illustrates the proposed peripheral transverse pavement marking concept for the Marysville Road/SR 20 intersection.

(Credit: Caltrans)

Exhibit B2-6. Potential dynamic warning sign design.

Dynamic Warning Sign Activated by Speed

Exhibit B2-6 illustrates the dynamic warning sign Caltrans purchased for this intersection. This treatment includes

- A speed limit sign and
- A dynamic sign showing the speeds of vehicles as they pass the detection point.

Note: This is a typical sign that Caltrans has installed at other locations throughout the state.

B2.3.4 Treatment Testing and Installation

Caltrans was not able to install the treatments in time to be included in the research testing. However, the agency plans to implement and monitor the treatments to observe their effectiveness at reducing speeds and increasing driver awareness at the intersection.

APPENDIX B3

SR 26/SR 24/S. First Avenue

The site of this case study was the intersection of SR 26/SR 24/ S. First Avenue in Othello, Washington.

B3.1 Pre-Screening

The Washington Department of Transportation (WSDOT) identified this intersection as having speed and safety issues.

- This intersection had a significant crash history, including two fatalities.
- WSDOT implemented reduced speed zones through this corridor due to drivers not complying with posted speed limits prior to this intersection.
- 85th-percentile speeds were approximately 5 to 6 mph over the posted speed limits.

B3.1.1 Intersection Characteristics

B3.1.1.1 Traffic Volumes

No traffic volume data were available for this site.

B3.1.1.2 Traffic Composition

- SR 26, a state facility south of, and parallel to, Interstate 90, is a secondary route that serves traffic traveling east–west through eastern Washington.
- South of SR 26, S. First Avenue serves as a frontage road to SR 24. North of SR 26, S. First Avenue serves existing commercial and industrial development adjacent to the state highway.
- SR 26 featured relatively high truck volumes.

B3.1.1.3 Intersection Features

This intersection has a two-way stop-control, with stop signs on S. First Avenue.

SR 26 is a limited-access, two-lane facility.

An eastbound left-turn lane, and westbound left- and right-turn lanes, are provided on SR 26.

B3.1.1.4 Speed Data

The posted speed limit on SR 26 was 50 mph in the vicinity of S. First Avenue.

- In September 2005, the posted speed limit changed from 60 mph to 50 mph.
- The speed change to 50 mph occurred 0.75 miles east of S. First Avenue in the westbound direction, and 0.90 miles west of S. First Avenue in the eastbound direction.

- A speed study was conducted on SR 26 in the vicinity of S. First Avenue in October 2005 (after the speed limit change).

  West of Railroad Bridge (west of S. First Avenue)
- In both directions, the mean speed was 50.64; the 85th-percentile speed was 56.63.

  WSDOT Maintenance Shed (east of S. First Avenue)
- In both directions, the mean speed was 50.48; the 85th-percentile speed was 55.43.

B3.1.1.5 Crash Records

Between 1999 and 2005, 74 crashes occurred at this intersection, with one fatality each in 1999 and 2004. The majority were angle crashes and those that involved vehicles traveling in opposite (i.e., left-turn and through vehicles) directions. The majority of crashes resulted in personal injury.

B3.1.1.6 Environment

The environment is semi-rural, with industrial and commercial developments adjacent to SR 26 and S. First Avenue.

B3.1.2 Assess Data

Was speed the primary issue? Were speed reduction treatments needed?

- Speed limit reduction from 60 to 50 mph occurred before this intersection, and 85th-percentile speeds exceeded the posted speed limit by 5 to 6 mph in both directions.

On which approaches was speed reduction needed?

- SR 26 is the major roadway.
- East and west approaches required speed reduction before the intersection with S. First Avenue.
- S. First Avenue is a low-volume, low-speed facility.

B3.2 Treatment Screening

Potential treatments are

- Reduced lane width,
- Visible shoulder treatments,
- Speed tables,
- Rumble strips,
- Roadway environment,
- Approach curvature,
- Roundabouts,
- Splitter islands,
- Longitudinal pavement markings,
- Transverse pavement markings, and
- Dynamic warning sign.

B3.2.1 Fatal Flaws

Reduced Lane Width—The existing lane width was 12 ft with a minimal shoulder and guardrail. Potential risks existed because of high truck volumes.

Visible Shoulder Treatment—Existing shoulders (see Exhibit B3-1) featured a fairly steep slope behind the guardrail, which prevented effective visual shoulder treatments.

(Credit: WSDOT)

Exhibit B3-1. Existing shoulders on SR 26.

Note: WSDOT staff indicated a fill slope of approximately 1.5:1. Therefore, shoulder treatment was not feasible.

Speed Tables—Since 85th-percentile speeds were greater than 55 mph, speed tables would not be appropriate for this high-speed roadway.

Rumble Strips—A high volume of truck traffic and several adjacent industrial and commercial land uses exist.

Note: WSDOT was not interested in installing rumble strips on SR 26 due to the freeway-like conditions.

Roadway Environment—The existing guardrail, narrow shoulders, and steep grades made it difficult to install effective roadway environment treatments such as landscaping.

Approach Curvature—Right of way and lane geometry was constrained.

Roundabout—An imbalance of traffic volumes existed between SR 26 and S. First Avenue. In addition, the south approach would have required complex geometry. WSDOT also did not have the funds to build this type of treatment.

Splitter Island—This treatment is typically used on stop-control approaches.

B3.2.2 Evaluate Potential Treatments

After the research team identified the fatal flaw treatments that were not feasible to install at this intersection, three potential treatments remained: longitudinal pavement markings, transverse pavement markings, and a dynamic warning sign. At this time, the research team reviewed past research and evaluated each potential treatment to assess its effectiveness and determine which one was the most appropriate.

B3.2.2.1 Longitudinal Pavement Markings

Research did not show these to be effective speed reduction treatments because

- They require a large amount of pavement material, depending on the treatment boundary.
- They are possibly more effective in areas with speed adaptation issues or a large number of elderly drivers.

B3.2.2.2 Transverse Pavement Markings

Past research had shown this treatment to effectively reduce speeds.

The eastbound left-turn lane and wider intersection pavement made it difficult to design treatments near the intersection approach.

B3.2.2.3 Dynamic Warning Signs

WSDOT had funds to purchase and install a dynamic warning sign.

- This type of treatment had been effective in reducing vehicle speeds in similar roadway environments.
- WSDOT was interested in designing a dynamic warning sign that combined a speed limit and *Intersection Ahead* sign with a dynamic message sign.

How much speed reduction is desired?

In the eastbound and westbound directions, the desired speed was 50 mph to meet posted speed guidelines.

The target speed (maximum speed threshold) to activate the sign was set at 54 mph, based on the posted speed limit and the existing 85th-percentile speeds.

Where should speed be reduced?

Speed reduction was needed at the eastbound and westbound intersection approaches, no closer than approximately 500 feet (SSD) from the intersection.

B3.3 Selecting Treatments

B3.3.1 Implementation—Treatment Layout

Exhibit B3-2 illustrates a schematic of the proposed treatment layouts at the SR 26/SR 24/ S. First Avenue intersection.

SR 26 eastbound and westbound approaches

- Dynamic warning signs were located approximately 850 ft from the intersection in both directions.
- The sign location was based on the estimated perception-reaction time, deceleration, and stopping sight distance from S. First Avenue. Sign location also was determined based on constraints with the steep shoulder grades and existing bridge.
- The radar unit was placed on the sign to detect vehicle speeds in advance of the sign.

Note: WSDOT also observed that a power source existed near this location, making installation feasible.

B3.3.2 Treatment Design Options

Potential Options

Various treatment design options for this dynamic warning sign existed, including:

- *Your Speed Is XX*,
- *Slow Down*, or
- *Caution*.

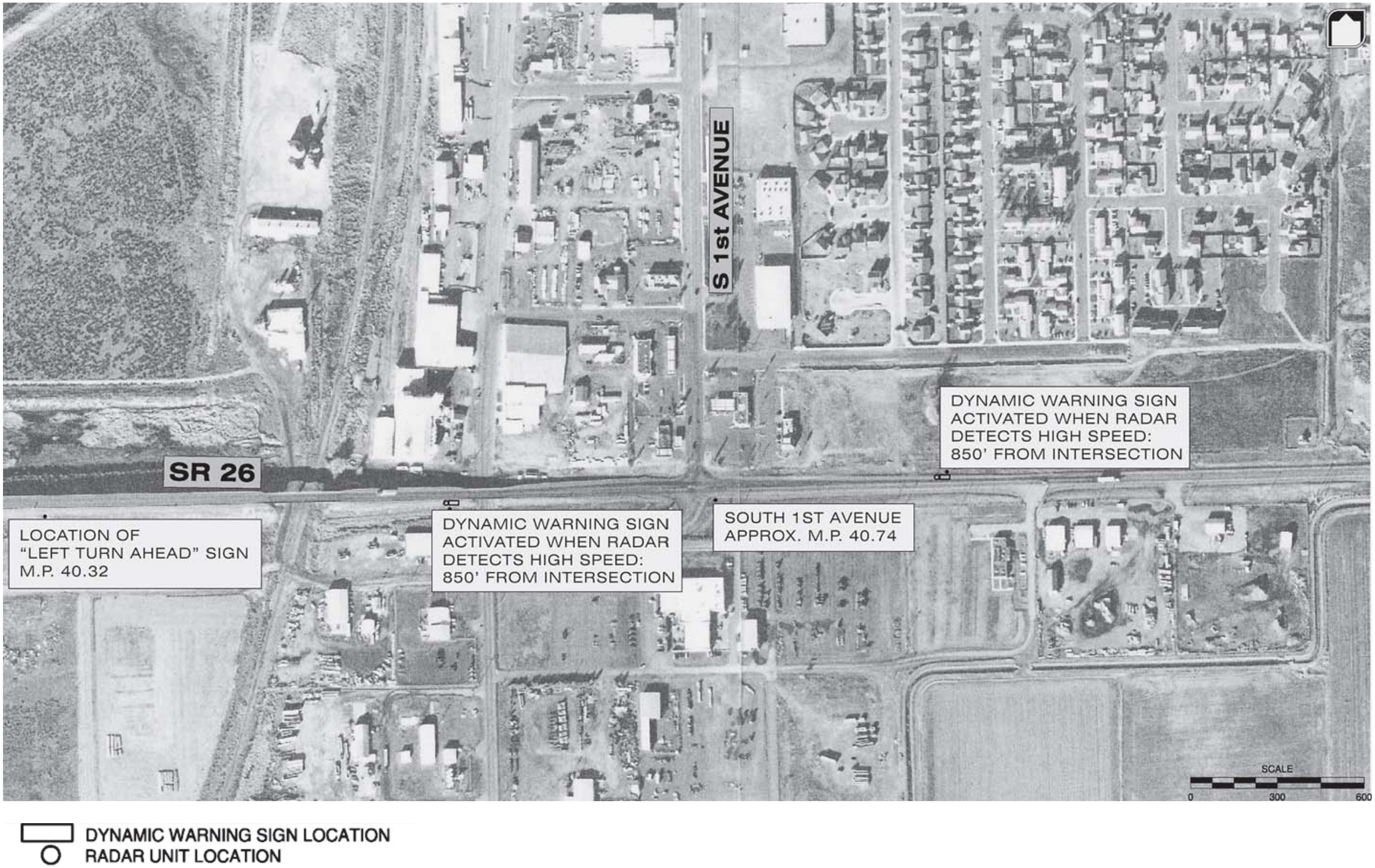
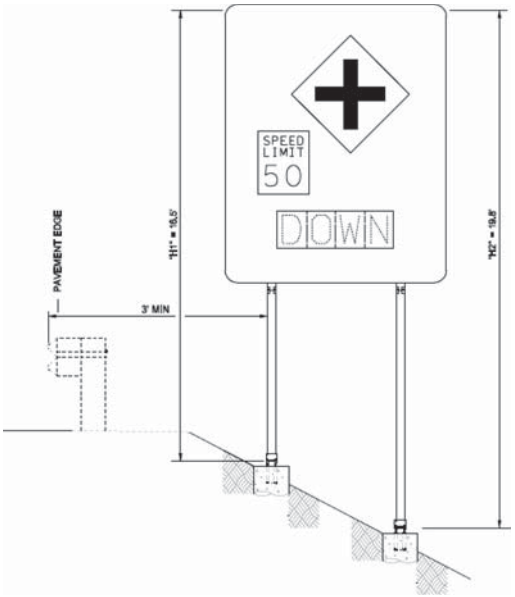


Exhibit B3-2. Preliminary treatment layout for SR 26/S. First Avenue.



(Credit: WSDOT)

Exhibit B3-3. Dynamic warning sign design.

WSDOT Sign Design

The dynamic warning sign at this location is shown in Exhibit B3-3 and was designed to include the messages, *Speed Limit 50* and *Intersection Ahead.* A dynamic message also flashes *SLOW* (1.5 seconds), *DOWN* (1.5 seconds) and then is blank for 1.5 seconds.

Radar Unit

The radar unit was attached to the sign, as shown in Exhibit B3-4.

The maximum speed threshold for the radar unit was set at 54 mph.

(Credit: WSDOT)

Exhibit B3-4. Radar unit.

B3.3.4 Treatment Testing and Installation

- May 2006—“Before” testing,
- September 2006—Treatment installation, and
- March 2007—“After” testing.

Note: Traffic control was required during the before-and-after testing due to high volumes and speeds on SR 26.

The dynamic message attached to the overall sign was not shipped to WSDOT until late August. Therefore, the sign was not installed until September 2006.

Due to the late installation date and desired acclimation period, “after” testing was conducted by the research team in March 2007. This provided an acclimation period of approximately six months.

Exhibit B3-5 illustrates the installed dynamic warning signs along eastbound and westbound SR 26.

(Credit: WSDOT)
(a) Eastbound

(Credit: WSDOT)
(b) Westbound

Exhibit B3-5. Dynamic warning signs along SR 26.

APPENDIX B4

Macksburg Road/Canby-Marquam Highway

The site of this case study was the intersection of Macksburg Road and Canby-Marquam Highway in Clackamas County, Oregon.

B4.1 Pre-Screening

Clackamas County identified this intersection as having speed and safety issues. These issues included run-off-the-road crashes northbound on Canby-Marquam Highway.

B4.1.1 Intersection Characteristics

B4.1.1.1 Traffic Volumes

Canby-Marquam Highway has higher traffic volumes than Macksburg Road. Canby-Marquam Highway has approximately 6,800 to 7,000 ADT during a typical weekday.

Note: Moderate volume provides opportunities for drivers to travel at free-flow speeds, especially during non-peak periods.

B4.1.1.2 Traffic Composition

A high percentage of agricultural truck traffic exists at this site.

B4.1.1.3 Intersection Features

This is a stop-controlled, T intersection, with a stop sign on the east approach of Macksburg Road.

- Canby-Marquam Highway and Macksburg Road are two-lane roadways.
- No dedicated left-turn lanes exist on Canby-Marquam Highway.
- Macksburg Road forms an intersection in the middle of a curve on Canby-Marquam Highway.

B4.1.1.4 Speed Data

The posted speed is the “Basic Rule.”

Note: Although the county does not have speed data for this intersection, they believe that reducing vehicle speeds may decrease intersection crashes.

B4.1.1.5 Crash Record

No intersection crash data was provided for this intersection.

Note: Based on discussions with the county, there is a history of run-off-the-road crashes in the northbound direction. Drivers involved in crashes did not anticipate the existing curve at the intersection, which resulted in vehicles running off the road into the residential property at the intersection's northeast corner.

B4.1.1.6 Environment

The surrounding area is rural and open.

Farms are located on the northeast corner and across from the intersection west of Canby-Marquam Highway.

B4.1.2 Assess Data

Is speed the primary issue? Are speed reduction treatments needed?

- A closer review of the roadway geometry (see Exhibit B4-1) revealed that the run-off-the-road crashes were most likely due to the roadway curvature at the intersection, rather than high speeds.
- The alignment of the curvature made it difficult for drivers to observe the approaching roadway.
- The actual presence of an intersection may not have impacted the crashes.
- Although a speed reduction treatment would help reduce vehicle speeds in advance of the intersection, the team did not move forward with this candidate site because speed was not the primary problem and a segment issue may have existed rather than an intersection issue.
- Installing chevrons along the curve or other signage may make drivers more aware of the existing roadway curvature.
- In the long term, the roadway and intersection may need to be realigned to provide a more gradual curve radius for vehicles traversing the road.

Exhibit B4-1. Aerial view of Macksburg road.

APPENDIX C

Testing Results

Three speed reduction treatments were tested at 19 intersection approaches to determine the effectiveness of each treatment at reducing speeds on high-speed intersection approaches. The treatments included transverse pavement markings, rumble strips, and dynamic warning signs.

Speed data were collected at four locations along each intersection approach before and after treatment installation. The speeds measured at these four locations established a speed profile that could be used to estimate the speed of a vehicle at any point on the intersection approach. Sensors were placed at the same locations before and after a treatment was installed, so that direct comparisons could be made between vehicle speeds on each intersection approach.

The following three types of analyses were conducted:

- Analysis by location to determine the speed reduction observed at each data collection location (i.e., at each of the four locations along an intersection approach),
- Analysis by intersection approach to determine the overall speed reduction observed along an intersection approach, and
- Analysis by treatment type to quantify the effect of each treatment across all intersection approaches at which it was installed.

The results of each analysis are summarized below.

C.1 Analysis by Location

An analysis by location was conducted to determine the speed reduction observed at each data collection location (Locations A, B, C, and D) on an intersection approach as a result of the treatment installed on that approach. Before-and-after speed comparisons were made for 51 individual locations. Key findings from this analysis include the following:

- At approximately 75% of the locations, reductions in speed of up to 3.2 mph were observed (with one anomaly speed reduction of 8.7 mph).
- At approximately 25% of the locations, increases in speed of up to 1.8 mph were observed.
- Of the 51 before-and-after speed comparisons, 34 were statistically significant.

C.2 Analysis by Intersection Approach

An analysis by intersection approach was conducted to determine the overall speed reduction observed along an intersection approach as a result of the treatment installed on that approach. Fourteen intersection approaches (eight with transverse pavement markings, three with rumble strips, and three with dynamic warning signs) were included in this analysis. Key findings include the following:

- At 11 of the 14 intersection approaches, the estimated speed difference from before to after treatment installation was negative (i.e., speeds decreased after treatment installation). The estimated speed reductions were statistically significant at the 5% significance level.
- At 3 of the 14 intersection approaches, the estimated mean speed difference was positive (i.e., speeds increased); however, only one of these speed differences was statistically significant.
- All three intersection approaches on which dynamic warning signs were installed experienced a statistically significant mean speed reduction.
- Speed reductions appeared to be greatest where dynamic warning signs were installed.
- Changes in 85th percentile speeds were comparable in magnitude to changes in mean speeds at all 14 intersection approaches.

C.3 Analysis by Treatment Type

An analysis by treatment type was conducted to quantify the effect of a specific speed reduction treatment across all intersection approaches at which it was installed. Nineteen intersection approaches (10 with transverse pavement markings, 5 with rumble strips, and 4 with dynamic warning signs) were included in this analysis. Key findings include the following:

- Dynamic warning signs were the only treatment to have a statistically significant overall effect at the 5% significance level in reducing mean speeds from before to after installation, with a mean speed reduction of 1.7 mph.
- Transverse pavement markings had a statistically significant overall effect at the 10% significance level in reducing mean speeds from before to after installation, with a mean speed reduction of 0.6 mph.
- Rumble strips did not have a statistically significant overall effect in reducing mean speeds from before to after installation at the 10% significance level.
- All three treatment types were effective in reducing mean speeds at Location C (intersection perception/response speed location) with mean speed reduction of 0.9 mph for transverse pavement markings; 1.3 mph for rumble strips; and 2.3 mph for dynamic warning signs.
- Dynamic warning signs were effective in reducing mean speeds at Location B (accident avoidance speed location) with a mean speed reduction of 2.8 mph.
- Dynamic warning signs resulted in the largest speed reduction when compared to all other treatments.
- The changes in 85th percentile speeds were comparable in magnitude to those in mean speeds for all three treatment types. The reduction was significant at the 5% level for transverse pavement markings (0.9 mph) and for dynamic warning signs (1.4 mph). The reduction of 0.7 mph due to rumble strips was not significant at the 10% level. It should be noted that a comparison of 85th percentile speeds is not as statistically rigorous as a comparison of mean speeds.

C.4 Key Findings

Key findings from the testing results include the following:

- All three treatment types may reduce speeds on high-speed intersection approaches; however, that speed reduction is likely to be minimal (i.e., less than 3 mph).
- The three treatment types appear to be most effective at reducing speeds at Location C (intersection perception/response speed location), which is the point where the intersec-

tion would first become visible to the driver or where the driver might first react to the intersection.

- Of the three treatment types, dynamic warning signs may be the most effective at reducing speeds. However, this conclusion is based on only three intersection approaches.
- Transverse pavement marking also appears to be potentially effective at reducing speeds.
- Based on a limited number of sites, rumble strips do not appear to be as effective at reducing speeds as dynamic warning signs or transverse pavement markings.

APPENDIX D

Supplemental References

This section provides supplemental references for projects and final reports that also looked at speed reduction treatments at intersections, through varying methods described in the report. Data from some but not all of the following papers were included in Sections 3 and 4. The purpose of this section is to provide readers with additional sources of information for further research or insight into possible speed treatments both at intersections and on roadways.

- Arnold, Jr., E. D. and K. E. Lantz, Jr. *Evaluation of Best Practices in Traffic Operations and Safety: Phase 1: Flashing LED Stop Sign and Optical Speed Bars*. Virginia Transportation Research Council, Charlottesville, 2007.

This report looks at the impacts of flashing LED signs and optical speed bars at intersections and road segments identified as "unsafe." Initial results found limited statistically significant speed reduction. Researchers recommend that both flashing LED stop signs and optical speed bars be considered as safety countermeasures at appropriate locations where higher than expected numbers of crashes, crash rates, or excessive speeding occur.

- Federal Highway Administration. *Pavement Marking Demonstration Projects: States of Alaska and Tennessee.* FHWA Project 475980-00001, http://ttiresearch.tamu.edu/b-kuhn/ pmdemo/PMDemo-index.html (accessed August 2007).

Using field tests of volunteers and simulator studies, this study tested the impact of brightness of pavement markings and edge line width on driver speeds along rural road segments. The analysis of driver preference rankings from both the field and simulator studies led to the subjective finding that drivers favor more and brighter markings as they negotiate curves on two-lane rural roads at night. In conjunction with FHWA, Texas Transportation Institute is looking to evaluate the multiple impacts of pavement markings using sites in Alaska and Tennessee. Scheduled for completion in 2009, this study is mandated by Section 1907 of SAFETEA-LU. Further information can be found on the project website at: http://ttiresearch.tamu.edu/b-kuhn/pmdemo/PMDemo-index.html.

- Fylan, Fiona and Mark Conner. *Effective Interventions for Speeding Motorists*. Road Safety Research Report No. 66. Department for Transport, London, 2006.

This report reviews human psychological factors for speeding, components of interventions that are most likely to change this behavior, and the effectiveness and extent of identified interventions. This paper presents a list of components that national speed awareness schemes should include, and how such schemes should be evaluated.

- Gannett Fleming, Inc. *Collision Avoidance System Evaluation Report*. PennDOT, Harrisburg, 2004.

An analysis of the collision avoidance systems (CASs) utilized at two locations in Pennsylvania to address limited sight distance concerns at rural unsignalized intersections is provided. The

CAS was effective in reducing speeds for drivers approaching an intersection with a lit sign. Once users understood the system, speeds increased at the intersection approach with an unlit sign. Stakeholders and users considered this system an effective way of alerting drivers of oncoming traffic without signalizing the intersection.

- Joerger, Mark. *Adjustment of Driver Behavior to an Urban Multi-Lane Roundabout*. Oregon Department of Transportation, Salem, 2007.

This analysis of the first multi-lane roundabout installed in Oregon looked at possible reduction of speed variability on approach from the previous signalized intersection and reduction of driving errors as drivers became accustomed to the new installation. Researchers found that there was no consistent change in speed variability at approaches to the roundabout from the previous signalized intersection. As was hypothesized, however, driving errors and confused behavior declined in the six months studied.

- Rakha, Hesham Ahmed, Bryan Katz, and Dana Duke. *Design and Evaluation of Peripheral Transverse Bars to Reduce Vehicle Speed*. Transportation Research Board, National Research Council, Washington, D.C., 2006.

This research project examined whether perceptual countermeasures such as pavement marking patterns have the potential to reduce vehicle speeds. The markings resulted in a decrease in overall vehicle speeds. There also were reductions in speed with vehicles traveling with headways greater than four seconds. Reductions were found to be higher on interstate and arterial roadways than on local road sites.

- Ullman, Gerald L. and Elisabeth R. Rose. *Effectiveness of Dynamic Speed Display Signs in Permanent Applications*. Texas Transportation Institute, College Station, 2004.

An analysis of the effectiveness of dynamic speed display signs (DSDSs) installed in a variety of speed zones was presented in this report. Overall, average speeds were reduced by 9 mph at the school speed zone, although elsewhere the effect of the DSDSs was less dramatic, with average speeds reduced by 5 mph or less. The results of this project suggest that DSDSs can be effective at reducing speeds in permanent applications if appropriate site conditions apply.

- Vest, Adam, Nikiforos Stamatiadis, Adam Clayton, and Jerry Pigman. *Effect of Warning Signs on Curve Operating Speeds*. Research Report KTC-05-20/ SPR-259-03-1F. Kentucky Transportation Center, University of Kentucky, Lexington, 2005.

This study evaluated the use of several warning signs and methods to identify those that have the most significant impact on reducing vehicle speeds when traversing a horizontal curve. The most effective treatments were found to be transverse lines, the new combination horizontal alignment/advisory speed sign, and flashing lights on both existing and new signs. For all three treatments, a reduction in the average of the speeds over the 85th percentile was observed.

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation